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ABSTRACT

This article presents a way to use silica fume (SF) in the production of highly flowable mortar containing untreated rice husk ash (RHA) and a way to evaluate the characteristic rheological and compressive strength development of this kind of mortar. Mortar mixtures were made with RHA used to replace cement at 0%, 10%, and 30% by mass without any treatment. SF was used in the percentage of 5%, 10% and 15% of the total binder materials (cement, RHA, and SF) to produce nine mortar mixtures, each of which had a water-binder materials ratio of 0.38 and a binder-sand ratio of 1:1. The mixtures were adjusted based on a slump flow diameter in the range of 25 ± 2.5 cm. The rheological properties were tested, including the mini slump flow and the V-funnel flow time, and compressive strength development was also investigated. The results indicate that a significant percentage of silica fume can be used to produce flowable mortar containing RHA. Further, the resulting mortars have good rheological properties but decreased compressive strength as compared with control flowable mortar.

KEYWORDS: Silica fume, Rice husk ash, Self-compacting mortar, Cement replacement, Rheological

1. Introduction

Self-compacting mortars, as new technology products, are principally used in the rehabilitation and repair of reinforced concrete structures. To place the fresh mortar without any external compaction and at the same time without causing any segregation, the water-cementitious materials ratio of the mortar and the type of chemical admixtures should be determined. In other words, the paste phase rheology of repair mortar should have suitable properties from the viewpoint of flowability and segregation. In addition, the self-compactability of the resulting mortars may provide considerable advantages over conventional mortar such as reducing construction time and labor costs and enhancing the filling capacity of highly congested structural members [1]. High cement content is needed in self-compacting mortars to increase their flowability and stability, and inert fillers and supplementary cementitious materials are usually added for this purpose [2]. An appropriate supplementary cementitious material can be used to improve the segregation resistance of self-compacting mortars, while maintaining excellent flowing ability in the fresh state. In fact, most common supplementary cementitious materials such as fly ash, silica fume and limestone powder have been used to produce self-compacting mortar with good flowing ability [3].

Silica fume (SF) is a powder by-product resulting from the manufacture of ferrosilicon and silicon metal. It has a high content of glassy silicon dioxide (SiO2) and consists of very small spherical particles. Given its extreme fineness and very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material. The addition of silica fume influences the thickness of the transition phase in mortars and the degree of the orientation of the calcium hydroxide (Portlandite, CH) crystals in it. Because of this, silica fume is popular as a mineral admixture for use in high-strength concrete. However, silica fume is expensive compared to both Ordinary Type I Portland cement (OPC) and fly ash [4,5]. Silica fume is expensive due to its limited availability, especially in developing countries [6].

In 2013, Thailand produced nearly 39 million tons of rice. Rice husk, a by-product of rice paddy and a major agricultural waste product, is used as a fuel in boilers in rice mills and electric power plants, in small plants to generate electricity, and for brick burning. When rice husks are burned under controlled conditions, ash is produced in the form of partial non-crystalline or amorphous silica with a cellular structure [7]. When this agro-waste is incinerated, crystalline or non-crystalline (amorphous) RHA can be obtained depending on the burning time and temperature. Uncontrolled incineration at a high temperature (>800 ºC) produces crystalline RHA, which has a poor pozzolanic property. Conversely, the controlled incineration of rice husks at between 500 and 800ºC results in non-crystalline RHA, which has a very high content of amorphous silica. Due to this high silica content, the amorphous RHA is highly pozzolanic; therefore, it is more suitable than crystalline RHA for use in concrete [3]. The pozzolanic activity of RHA depends on its silica content, its silica crystallization phase, size and surface area. An appropriate particle size for RHA can be achieved by grinding—although this can only performed at a considerable cost. Most related research has considered the use of unground RHA, which may be used in normal-strength concrete if the component materials are appropriately incorporated during the mixing process [8]. Untreated RHA can also be used as a cement or fine aggregate replacement [7-9]. The substitution of less expensive RHA for SF as a partial cement replacement not only improves the sustainability of self-compacting high-performance concrete but also reduces environmental pollution from the disposal of rice husk and increases the benefit derived from rice cultivation [6].

The objective of the present study is to investigate the influence of silica fume used as a partial replacement for Portland cement on the rheological characteristics and hardened properties of self-compacting mortar incorporating untreated RHA mixtures.

2. Materials and methods

2.1 Materials

In this study, the cementitious materials used were an Ordinary Type I Portland cement (OPC) conforming to the ASTM C150 [10]. The imported brands of condensed SF, in powder form contained 85.98%, which exceeds the 85% limit of silica fume set by ASTM C1240 [11] that was followed in this experimental program. RHA was obtained from an electric power plant in Chainat province, located in the central region of Thailand. The only treatments to which the RHA was subjected prior to its use were drying and homogenization. Also, the summation of silica, alumina, and iron oxide in the RHA was about 93.83%--a percentage that significantly exceeds the 70% limit for Class N raw and natural pozzolans, according to ASTM C618 [12]. The chemical composition and physical properties of Portland cement and mineral admixtures are given in Table 1.

Table 1 Chemical composition and physical properties of OPC, SF, and RHA.

Oxides (%)	OPC	RHA	SF
Silicon dioxide (SiO_2)	20.22 ± 0.35	93.44 ± 3.24	85.98 ± 1.01
Alumina oxide (Al_2O_3)	4.49 ± 0.05	0.21 ± 0.01	0.88 ± 0.12
Ferric oxide (Fe_2O_3)	3.20 ± 0.01	0.18 ± 0.02	2.31 ± 0.05
Magnesium oxide (MgO)	1.03 ± 0.02	0.43 ± 0.02	1.21 ± 0.04
Calcium oxide (CaO)	61.42 ± 0.41	0.76 ± 0.03	2.69 ± 0.06
Sodium oxide (Na_2O)	0.28 ± 0.02	0.05 ± 0.01	0.14 ± 0.01
Potassium oxide (K_2O)	0.54 ± 0.01	1.98 ± 0.21	1.17 ± 0.05
Sulfur trioxide (SO_3)	4.18 ± 0.03	0.16 ± 0.02	0.32 ± 0.01
$SiO_2+Al_2O_3+Fe_2O_3$	27.91 ± 0.22	93.83 ± 4.02	89.17 ± 1.74
Loss on ignition	4.07 ± 0.37	1.27 ± 0.14	2.65 ± 0.26
Specific gravity	3.15 ± 0.04	2.24 ± 0.12	2.20 ± 0.02
Mean particle size (μm)	22.65 ± 1.45	39.34 ± 2.75	153.44 ± 4.91
Specific surface area (cm^2/g)	8,100 ± 32.98	3,700 ± 22.14	1,080 ± 12.23

The fine aggregate used was natural river sand with a maximum size of 4.75 mm, which met the requirements of ASTM C33 [13]. The fine aggregate had a fineness modulus of 2.59, a specific gravity of 2.65 and water absorption of 0.71%, respectively. Further, to achieve the desired workability in all the mortar mixtures, the following were used as the chemical admixtures: various percentages of SF and RHA as a pozzolanic material and a polycarboxylate-type new-generation high-range water-reducing admixture (HRWR) conforming to ASTM C494 [14] standard type G with a specific gravity of 1.05 and a solid content of 42%.

2.2 Mix proportions of mortar

To cover the range of mixture variations, 9 mortar mixtures were designed, each with a water-binder ratio of 0.38. A constant paste volume of 60 vol.% (including air content of 1 vol.) and a constant fine aggregate volume of 40 vol.%. The reference concrete (Control) was made with only OPC as the binder, whereas the remaining mixtures incorporated binary (OPC + RHA) and ternary (OPC + RHA + SF) cementitious blends in which a proportion of OPC was replaced with the mineral admixtures. The proportions of sand, cement, RHA/SF, and water in the mortars were identical to the corresponding concretes. The mixture proportions of the mortars are shown in Table 2. The mixing procedure was shown in Figure 1.

Table 2 Self-compacting mortar mixtures proportions.

Mixtures	Paste : Sand (vol.%)	OPC (wt.%)	RHA (wt.%)	SF (wt.%)	w/b	HRWR (%)
Control	60 : 40	100	-	-	0.38	0.75
10%RHA	60 : 40	90	10	-	0.38	1.38
10%RHA 5%SF	60 : 40	85	10	5	0.38	2.50
10%RHA 10%SF	60 : 40	80	10	10	0.38	3.25
10%RHA 15%SF	60 : 40	75	10	15	0.38	4.00
30%RHA	60 : 40	70	30	-	0.38	4.00
30%RHA 5%SF	60 : 40	65	30	5	0.38	6.00
30%RHA 10%SF	60 : 40	60	30	10	0.38	7.50
30%RHA 15%SF	60 : 40	65	30	15	0.38	9.50

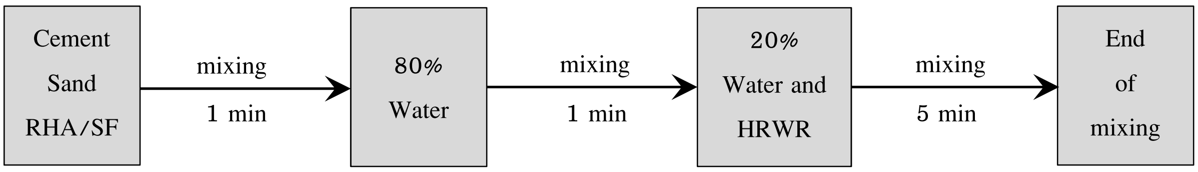
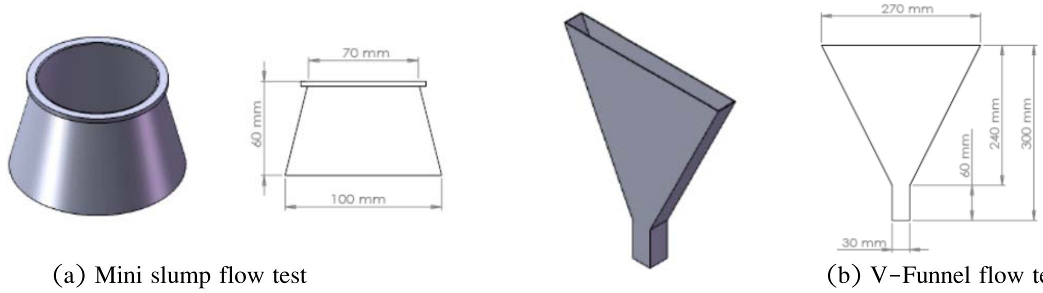


Figure 1 Mixing procedure for self-compacting mortar.

2.3 Testing procedures

The experimental investigation consisted of two stages. In the first stage, flow diameter, V-funnel flow time and setting time measurements were conducted on fresh mortar. In the second stage, compressive strength was determined on 50 x 50 x 50 mm cubes at 7, 14, and 28 days. All the test specimens were stored in a water tank saturated with lime at a temperature of (23 ± 2) °C until the test age.

2.3.1 Fresh properties test, including the time of setting, using the needle of the modified Vicat apparatus to determine the stipulated penetration. The time required to obtain the stipulated penetration with the modified Vicat needle is the time of setting specified in ASTM C807 [16]. Slump flow tests were performed by using the mini slump test of self-compacting mortar, which consists of a mold in the form of a cone frustum, 60 mm high with a diameter of 70 mm at the top and 100 mm at the base as shown in Figure 2(a). The mortar spread was checked visually for any segregation or bleeding, according to the procedure outlined in EFNARC [15]. V-funnel flow time, suggested by the procedure outlined in EFNARC [15], was used to select a suitable water-powder ratio in the mix design. The funnel was filled with 1.1 liters of mortar, the gate was then opened and the stopwatch simultaneously started. The watch was stopped when light first appeared, looking down into the funnel from above. The flow time (in seconds) was then recorded as shown in Figure 2(b).



(a) Mini slump flow test (b) V-Funnel flow test

Figure 2 Schematic views of apparatus used in flow tests.

2.3.2 Hardened properties test, after the initial fresh mortar test was complete the mixtures were poured into 50 x 50 x 50 mm steel molds without any vibration or compaction. The specimens were demolded 24 h after casting. After demolding, the specimens were cured in lime water at a temperature of (23 ± 2) ºC until the test age. Average compressive strength was tested after aging for 7, 14, and 28 days, in accordance with ASTM C109 [17].

3. Results and discussion

The results of fresh self-compacting mortar tests and compressive strength concrete of test specimens up to 28 says with different amounts of RHA and RHA+SF addition are presented in Table 3.

Table 3 Properties of fresh self-compacting mortar and compressive strength results.

Mixtures	Fresh properties				Compressive strength (ksc)		
	Initial setting time (h)	Final setting time (h)	Slump flow (cm)	V-Funnel flow (s)	7-days	14-days	28-days
Control	4.0 ± 0.01	16.0 ± 0.03	25.0 ± 0.02	5 ± 0.10	284 ± 7.54	404 ± 10.24	534 ± 16.15
10%RHA	4.5 ± 0.02	16.5 ± 0.02	25.5 ± 0.01	27 ± 0.14	266 ± 8.73	385 ± 14.55	512 ± 15.88
10%RHA 5%SF	6.5 ± 0.02	18.0 ± 0.02	26.0 ± 0.02	20 ± 0.15	252 ± 6.34	364 ± 12.39	484 ± 16.04
10%RHA 10%SF	9.5 ± 0.03	19.0 ± 0.02	25.0 ± 0.02	15 ± 0.10	235 ± 5.21	345 ± 13.66	458 ± 13.24
10%RHA 15%SF	13.0 ± 0.05	20.0 ± 0.01	25.5 ± 0.04	13 ± 0.09	215 ± 5.77	320 ± 9.25	428 ± 12.11
30%RHA	13.5 ± 0.03	18.5 ± 0.02	26.0 ± 0.02	90 ± 0.08	188 ± 9.23	292 ± 8.31	395 ± 10.14
30%RHA 5%SF	14.5 ± 0.02	20.0 ± 0.03	27.0 ± 0.02	58 ± 0.21	164 ± 6.64	258 ± 6.97	363 ± 12.09
30%RHA 10%SF	18.0 ± 0.01	26.0 ± 0.02	26.5 ± 0.01	40 ± 0.16	138 ± 8.73	220 ± 4.27	329 ± 8.15
30%RHA 15%SF	22.0 ± 0.02	32.0 ± 0.01	26.0 ± 0.02	28 ± 0.14	112 ± 6.73	192 ± 5.86	302 ± 7.06
Criteria			25±2.5	2-10			

3.1 Fresh properties of mortar

As shown in Table 2, the superplasticizer dosage produced a controlled slump flow of 25 ± 2.5 cm. In order to maintain the desired slump flow, the mixtures containing RHA and SF required larger amounts of superplasticizer with increasing amounts of RHA and SF. At the 10% RHA replacement level, the superplasticizer dosage varied between 1.4%, 2.5%, 3.3%, and 4.0% with SF replacement of 0%, 5%, 10%, and 15%, respectively. In addition, with increasing RHA content at 30%, the superplasticizer dosage varied between 4.0%, 6.0%, 7.5%, and 9.50% with SF replacement of 0%, 5%, 10%, and 15% respectively. The incorporation of RHA and SF increased the superplasticizer adsorption due to the pore structure and greater surface area of the RHA particles. Moreover, the adsorption of water to the higher SF content resulted in an increase in the superplasticizer required in the mixture [3,6,8]. For the initial and final setting times for the various self-compacting mortars are shown in Table 3. It can be observed that the mortar with binary blends of RHA exhibited a marginal delay in both the initial and final setting times. Moreover, the effect of increasing the replacement level with ternary blends of SF was to increase further the setting times. The reason for this may be due to the greater superplasticizer demand at the higher RHA and SF content [2,6]. The higher percentages had a significant effect on setting time: there was an increase in setting time when OPC was replaced with the higher percentages of SF in this study [5].

The slump flow ranged from 25 to 27 cm, as shown in Table 3. All the self-compacting mortars were designed to give a slump flow diameter of 25 ± 2.5 cm, which was acquired by adjusting the dosage of the HRWR chemical admixture used. Thus, all the fresh mixtures had a slump flow diameter that conformed with the EFNARC [15] recommendation. That is, it is clear from this result that the flowability of the self-compacting mortars reduced as the percentage of cement replaced by RHA and SF increased. However, the use of a required dosage of the HRWR chemical admixture reduced this effect [2-3, 6]. Moreover, the flowability of the self-compacting mortar was evaluated by means of a mini-v funnel, which was based on the time required for a concrete mixture to flow through a funnel. The results reflect the viscosity and segregation resistance of a concrete mixture. According to Benaded et al. [2], the acceptable range of flow time values is 2–10 s. It is evident from Table 3, that at the 10% RHA replacement level, the V-funnel flow time varied between 27, 20, 15 and 13 s with an SF replacement of 0%, 5%, 10% and 15%, respectively. In addition, at an RHA content of 30%, the V-funnel flow time varied between 90, 58, 40, and 28 s with an SF replacement of 0%, 5%, 10%, and 15%, respectively. These results show that to yield the same workability, mortar with a higher RHA and SF content requires more superplasticizer dosage than does mortar with a lower RHA and SF content as shown in Figure 3. For cement replacement, the minimum value of the V-funnel flow time obtained at 10% RHA with 15% SF content may be due to the more compact nature of SF, which results in a smaller volume of void to be filled, and hence a larger amount of superplasticizer is required for lubrication [1,2]. The maximum value of the V-funnel flow time obtained at 30% RHA content, longer V-funnel time indicates a relatively high level of viscosity. The incorporation of a greater amount of RHA generally made the concrete more viscous and decreased flow resistance [7-9].

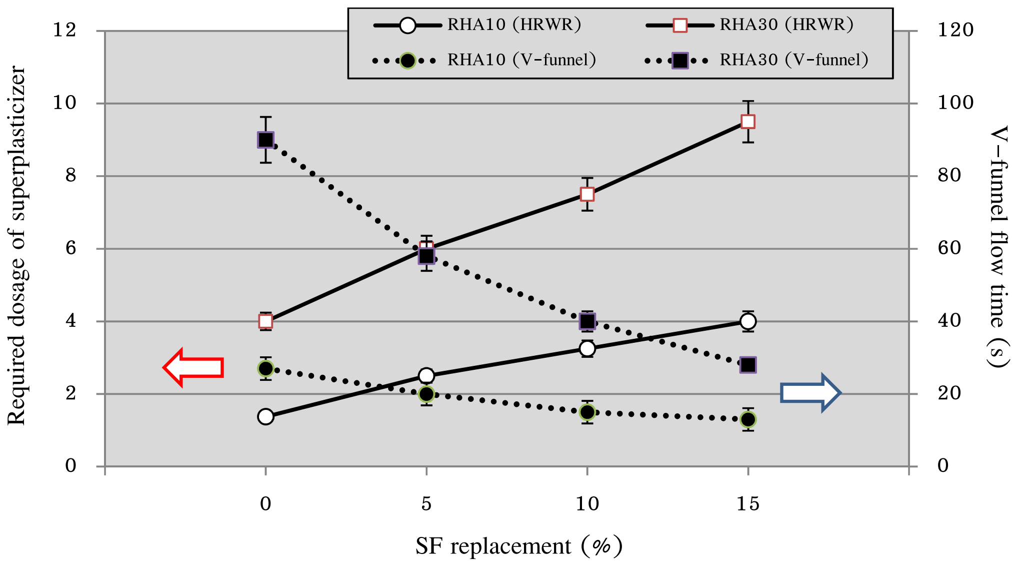


Figure 3 HRWR and V-funnel flow time of self-compacting mortar

3.2 Hardened properties of mortar

The compressive strength development of various self-compacting mortars, tested using sealed-cured 50 mm cubes, continued to increase over the 28-day curing period, as shown in Table 3. The compressive strength of the control mixture at 7 days was measured as 284 ksc, which increased to 534 ksc at 28 days. It is, clear, therefore, that the control mortar performed best of than all the mortar mixtures in the present study. As shown in Figure 4, replacing OPC with RHA and SF contributed to compressive strength decreased of the mortar. At the 10% RHA replacement level, compressive strength after 28 days decreased by 4%, 9%, 14%, and 20% compared to the control mortar mixtures with SF replacement, the compressive strength of which decreased by 0%, 5%, 10%, and 15%, respectively. In addition, with RHA content at 30%, compressive strength after 28 days decreased by 26%, 32%, 38%, and 43% compared to the control mortar mixtures with an SF replacement of 0%, 5%, 10%, and 15% respectively. As increasing percentages of RHA and SF were used to replace cement in the concrete mixture, the decreasing percentage of cement resulted in a lower $Ca(OH)2$ content, which, in turn, reduced the compressive strength of the concrete [4,7].

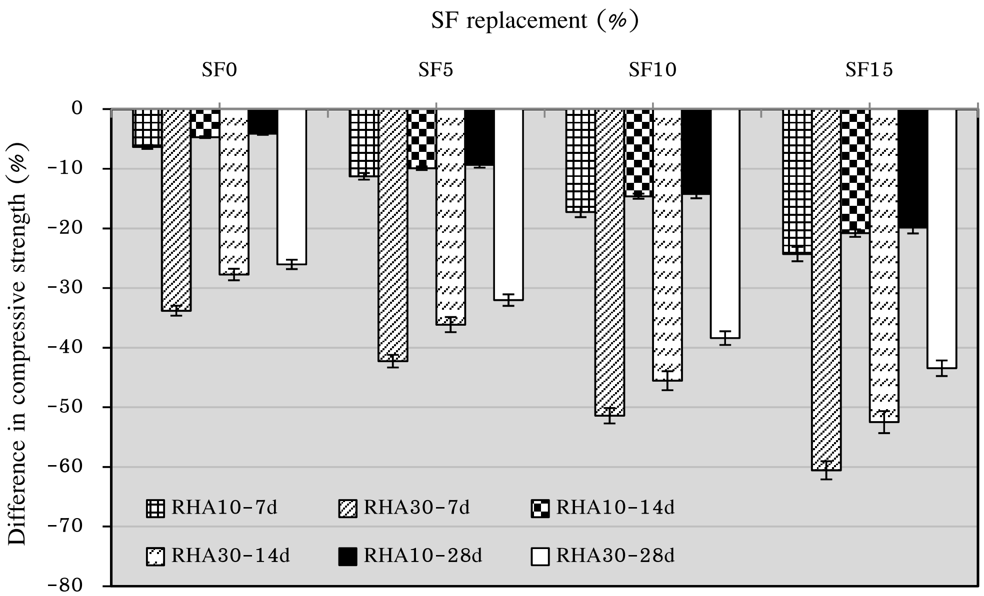


Figure 4 Percent difference in compressive strength of self-compacting mortars.

4. Conclusions

Based on the results of this study, the following conclusions can be drawn:

- As the percentage of OPC replaced with RHA and SF increased, the demand for superplasticizer increased in order to yield the designed slump flow diameter.
- The incorporation of RHA rendered the self-compacting mortars more cohesive, which, in turn, lengthened the V-funnel flow time. In addition, the use of RHA and SF appeared to have a greater influence on the V-funnel flow time of mixtures with relatively high SF content than on those with relatively low SF content.
- There is a clear trend whereby the use of higher RHA and SF content significantly lengthened the initial and final setting times of the self-compacting mortars.
- The compressive strength tests showed that the control self-compacting mortar performed better than all the other mixtures. On the other hand, in the case of the mortars in which 30% RHA was combined with 15% SF, the compressive strength was more than 300 ksc at 28 days. Further research is needed, especially in regard to durability over the long term.

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