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Effect of macro-mesoporous rice husk ash on rheological properties of mortar formulated from self-compacting high performance concrete

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HIGHLIGHTS

- The effect of rice husk ash on rheological properties of mortar was investigated.
- Rice husk ash/silica fume increased superplasticizer saturation dosage of mortar.
- Rice husk ash predominantly increased the yield stress and viscosity of mortar.
- Mortar formulated from SCHPC was a shear-thickening material.
- Rice husk ash/silica fume decreased the shear-thickening degree of mortar.

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ABSTRACT

In the present study, effect of macro-mesoporous rice husk ash (RHA) on rheological behavior and flowability of mortar formulated from self-compacting high performance concrete (SCHPC) was investigated. For comparison, the investigation was also conducted on samples containing silica fume (SF). The results reveal that the incorporation of RHA/SF decreased mini-slump flow, and increased superplasticizer adsorption, superplasticizer saturation dosage, yield stress and plastic viscosity of mortar. The effect of RHA on yield stress and plastic viscosity is significantly stronger than that of SF, especially when the coarser RHA or the higher content of RHA is used. Interestingly, the increase in particle size or content of RHA predominantly increased plastic viscosity and yield stress rather than decreased mini-slump flow of mortar, especially 60 min after water addition. Fresh mortar in this study is a shear-thickening material. The shear-thickening degree decreased over time. The incorporation of RHA/SF decreased the shear-thickening degree where the effect of SF is much stronger than that of RHA. It is suggested that the rheological behavior of mortar is attributable to the capacity and progress of the water adsorption of RHA.

1. Introduction

Self-compacting concrete is a concrete that can flow and consolidate under its own weight, pass through the spaces between the reinforcement bars to completely fill the formwork, and simultaneously maintain its stable composition [1–3]. Self-compacting high performance concrete (SCHPC) is defined as a new generation of concrete on the basis of the concepts of self-compacting concrete (SCC) and high performance concrete (HPC) [4]. As a result, SCHPC possesses adequate self-compactability (filling ability, passing ability and segregation resistance) of SCC and high strength and good durability of HPC. In order to fulfill these requirements, a high volume of Portland cement, a very high dosage of chemical admixtures and reactive supplementary cementitious materials (SCMs), e.g. silica fume (SF), are used. Therefore, SCHPC is very expensive and has an adverse ecobalance. Normally, cement is partially replaced by cheaper SCMs, such as fly ash or limestone powder. The performance of SCHPC with these SCMs is not comparable to that of SCHPC with SF. SF is expensive due to the limited availability, especially in developing countries. Rice husk ash (RHA) with a high amorphous silica content is a very good replacement for SF

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with regards to compressive strength and durability of concrete [4–9]. The reactive RHA is the residue of under proper conditions completely incinerated rice husk. Rice husk, the outer covering of a rice kernel, is an agricultural waste from the milling process of paddy. Rice husk is abundant in many rice cultivating countries, e.g. Vietnam, India and China. Each ton of paddy rice can produce approximately 200 kg of rice husk, which on combustion produces about 40 kg of ash [6]. According to ''Rice market monitor'' report [10], the global rice paddy production in 2011 was about 723 million tons which produces approximately 145 million tons of rice husk. Normally, rice husk from paddy rice mills is disposed directly into the environment or sometimes is burnt in open piles on the fields. This results in serious environmental pollution, especially when it is disintegrated in wet conditions. Substitution of less-expensive RHA for SF as a partial cement replacement not only improves the sustainability of SCHPC but also reduces environmental pollution from the disposal of rice husk and increases the benefit of rice cultivation.

The addition of RHA increases the water demand of the blended cement paste and concrete [11–14]. An increase in a partial cement replacement by RHA results in a higher water demand or a higher superplasticizer (SP) dosage to maintain a given workability of concrete [6,14–16]. The similar effect of RHA content on the workability of ultra high performance concrete is obtained [17,18]. Decreasing mean particle size (MPS) of RHA from 31.3 to 11.5 μm increases the water demand or the SP dosage to reach a given workability when a partial cement content is replaced by 20 wt.% RHA [13]. However, the SP dosage needed for a given workability of ultra high performance concrete is reduced proportionally with the decrease in MPS of RHA from 15.5 to 3.6 μm [9]. RHA is a porous material different from SF [5,18]. The variation in MPS of RHA results in a change in the pore structure, specific surface area (SSA) thus water absorption of RHA [17,18]. These parameters will dramatically influence properties of fresh concrete containing RHA. Therefore, increasing MPS of RHA might increase or decrease the workability of concrete. This effect of RHA will be investigated in detail in this study.

RHA has been used as a SCM to produce SCHPC at various w/b ratios of 0.30, 0.35, 0.40 and 0.50. The RHA content used is in the range of 0–30 wt.% [4]. The investigation was conducted on paste, mortar and SCHPC. The results of this study reveal that the increase in RHA content increases the flow time of paste and SCHPC, and decreases the slump flow of mortar, particularly at lower w/b ratios. However, the slump flow of concrete increases considerably with a lower w/b ratio and a greater RHA content. This is ascribed to the increased paste volume and decreased aggregate content of concrete with the lower w/b ratio and the higher RHA content. The partial cement replacement by RHA in weight leads to an increase in paste volume due to the lower density of RHA, thus an increase in the slump flow. In another study [19], the addition of 25 and 50 wt.% RHA to the mixture proportion of SCC leads to a decrease in the w/b ratio from 0.40 to 0.38 and to 0.36 respectively. The experimental results of this study show that increasing RHA content decreases the slump flow and increases the flow time of concrete at the same dosage of SP. Besides, RHA has been used to replace sand in producing SCC [20], as well as to combine with fly ash and ground granulated blast-furnace slag to produce SCC [21]. In order to meet a certain slump flow, increasing RHA content increases the SP dosage or the water demand. The addition of RHA induces a longer flow time, indicating higher viscosity [20,21]. As a summary, the addition of RHA increases flow time, and decreases slump flow of SCC/SCHPC. It is very important to note that the pore structure of RHA as a main factor influencing the self-compacting properties of SCC/SCHPC has not been studied in detail. Furthermore, the effect of RHA on rheological behavior of SCC/SCHPC, i.e. yield stress, viscosity, shear-thickening behavior, and workability retention, is also needed to investigate in detail.

In this study, properties relating to the pore structure of RHA were evaluated by scanning electron microscopy (SEM) images, measurement of SSA, determination of pore volume and pore size in RHA particles, and by water demand test. Subsequently, the effect of RHA on SP adsorption, saturation SP dosage, flowability and rheological behavior of mortar formulated from SCHPC 15 and 60 min after water addition was investigated. RHA with different MPSs and contents was used in this study. The investigations were also conducted on the reference sample and the samples containing SF.

2. Materials and experimental methods

2.1. Materials

Ordinary Portland cement (CEM I 52.5 R conforming to DIN EN 197-1 [22]), undensified SF, RHA, and natural sand with a maximum size of 2 mm were used in this study. The chemical composition and physical properties of the materials are summarized in Tables 1 and 2 respectively. Fig. 1 shows the scanning electron microscope (SEM) images of morphology of RHA and SF particles. Particle size distributions of the materials used in this study are displayed in Fig. 2. In addition, a polycarboxylate-based SP with density of 1.08 g/cm^3 and 40 wt.% solid content was used.

RHA was produced by burning rice husk under proper temperature conditions, i.e. the temperatures measured at 650–700 °C, in a simple incinerator prototype in Vietnam. The incinerator has been designed on the basis of the principle of the atmospheric bubbling fluidized bed [23,24]. In order to analyze characteristics of RHA, the obtained ash was ground in a ball mill for different periods of time. Four types of RHA with different MPSs of 5.7, 7.7, 15.6, and 22.6 μm, designated as RHA5.7, RHA7.7, RHA15.6 and RHA22.6 respectively, were used. The effect of the grinding time on the fineness, pore structure and SSA is summarized in Table 3.

Increasing grinding time generally decreased MPS of RHA, pore volume and mean pore size in RHA particles. SSA of RHA slightly increased with grinding time, regardless of a lower pore volume. Pore size distribution of RHA particles at different grinding periods is shown in Fig. 3a–d by ultra high resolution scanning electron microscope (NanoSEM) imaging and BJH analysis respectively. It can be obtained that the RHA is a porous material including mostly macropores (>50 nm) and mesopores (2–50 nm). It appears that most macro pores collapsed during grinding time (Fig. 3d), resulting in the lower total pore volume and the lower mean pore size in RHA particles (Table 3). It is very important to note that SSA of RHA derives from the internal surface area in pores and the external surface area on the surface of RHA particles. During grinding, most macro-pores collapsed (Fig. 3d) decreasing the internal SSA but increasing the external SSA of RHA. It is very interesting to note that the macro–meso pore size distribution of RHA determined by BJH measurement is consistent with NanoSEM imaging analysis. Normally, pore structure of RHA is theoretically calculated on the basis of results of BET–SSA or BJH measurement [25,26].

Water demand of cement, SF and RHA with different MPSs determined by the Puntke method is displayed in Fig. 4. The water demand of RHA was considerably larger than that of cement and SF. The higher water demand was obtained with the coarser MPS of RHA. This result is closely related to the pore volume in RHA particles (Table 3).

Table 1
Chemical composition (wt.%) of cement, RHA and SF.

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
Cement	19.4	5.3	2.5	61.2	1.2	3.2	0.07	0.61	4.9
RHA	87.0	0.8	0.4	1.2	0.6	0.4	0.4	2.63	3.7
SF	96.6	0.7	0.2	0.3	0.4	0.1	0.16	0.65	0.9

LOI – loss on ignition.

Table 2
Physical properties of materials used in this study.

Parameters	Cement	RHA5.7	SF	Sand
Density (g/cm^3)	3.09	2.27	2.26	2.65
Mean particle size (μm)	7.07	5.70	0.35	–
Specific surface area (BET, m^2/g)	2.07	25.21	18.09	–
Particle shape	Angular	Angular	Spherical	Quite spherical