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Rice husk ash as both pozzolanic admixture and internal curing agent in ultra-high performance concrete

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ABSTRACT

The present study investigated the effects of mesoporous amorphous rice husk ash (RHA) on compressive strength, portlandite content, autogenous shrinkage and internal relative humidity (RH) of ultra-high performance concretes (UHPCs) with and without ground granulated blast-furnace slag (GGBS) under different treatments. The results were compared with those of UHPCs containing silica fume (SF). Because of the mesoporous structure, RHA can absorb an amount of aqueous phase to decrease the free water content and to supply thereafter water for further hydrations of cementitious materials. Hence, compressive strength of RHA-blended samples is enhanced. The highly water absorbing RHA delays and slows down the decrease in the internal RH (self-desiccation) of UHPCs, and hence strongly mitigates autogenous shrinkage of UHPCs compared to SF. The combination of GGBS and RHA or SF improves the properties of UHPC. These results suggest that RHA acts as both highly pozzolanic admixture and internal curing agent in UHPC.

1. Introduction

Ultra-high performance concrete (UHPC) commonly consists of a high amount of Portland cement, silica fume (SF) with fine grained aggregates and steel fibers for reinforcement. UHPC possesses a very low water to binder ratio (w/b) with the addition of a high superplasticizer (SP) dosage [1–3]. UHPC is a new class of concrete with 28-day compressive strength over 150 MPa and advanced durability properties that has gained a strong interest in research and application in recent years [4,5]. Because of the very high cement and SF content, very low w/b, inherently fine pore structure and extremely dense matrix, UHPC not only is expensive and not environmentally friendly but also possesses a problematically high autogenous shrinkage.

The major part of autogenous shrinkage of UHPC is related to self-desiccation [6–8]. Internal curing agent, i.e. super-absorbent polymer (SAP) is commonly used in UHPC to mitigate autogenous shrinkage. Internal curing agent particles release their absorbed water to delay the internal relative humidity (RH) decrease, and hence to mitigate autogenous shrinkage at an early age [9–13]. However, it has a negative effect on pore structure in the cement matrix and thus on properties of concrete, particularly in UHPC [13,14].

Rice husk ash is produced by burning rice husks, an agricultural waste. It is fondly acknowledged that under suitable burning conditions, reactive rice husk ash (RHA) has a high content of amorphous silica, a high pore volume and specific surface area (SSA) [15–17]. Therefore, RHA possesses a very high pozzolanic reactivity comparable with that of silica fume (SF) [17–19]. It has been proven that RHA is a very good substitute for SF in terms of portlandite consumption and compressive strength of high performance concrete (HPC) [20–22] and UHPC [23,24]. It is reported that RHA normally decreases autogenous shrinkage of cement matrices [24–26]. However, Habeeb and Fayyadh [27] stated that fine RHA results in an increased autogenous shrinkage of sample, even higher than that of a control sample.

With mesoporous structure, the water absorption capacity of RHA is significantly higher than that of SF [17]. It can absorb an amount of free water in RHA-blended Portland cement mixture to improve compressive strength. The absorbed water in the porous structure allows Ca^{2+} ions to diffuse into internal parts of RHA particles to enhance the pozzolanic reactivity and maintains the

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Table 1
Chemical compositions of cementitious materials, (wt.%).

Material	SiO_2	Fe_2O_3	Al_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	LOI
Cement	21.6	5.1	3.7	64.3	0.17	0.36	0.6	2.4	0.9
SF	96.0	0.0	0.1	0.6	0.20	0.69	0.2	0.4	1.2
RHA	87.4	0.3	0.4	0.9	0.04	3.39	0.6	0.4	4.6
GGBS	37.8	0.5	8.0	39.7	0.38	0.74	10.8	0.1	0.2

LOI – Loss on Ignition.

hydration of cementitious materials [17]. RHA may also play as an internal curing agent to mitigate autogenous shrinkage of UHPC. For proving this mechanism, the effect of RHA addition on self-desiccation (i.e. the internal RH change) and autogenous shrinkage during hardening of UHPC should be measured. Furthermore, the effect of the combination of RHA and ground granulated blast-furnace slag (GGBS) on properties of UHPC needs more detailed study.

Therefore, the influence of RHA alone as well as in the combination with GGBS on portlandite (CH) content, compressive strength, autogenous shrinkage and internal RH of UHPC under different treatment conditions was assessed in this study. CH content and compressive strength of UHPC was tested up to one year. Samples for autogenous shrinkage were measured in 24 weeks.

2. Materials and methods

2.1. Materials

Cementitious materials used in this study were ordinary Portland cement (CEM I 52.5 R-HS/NA conforming to DIN EN 1164-10), GGBS, RHA and undensified powder of SF. Quartz powder and quartz sand were utilized as filler and aggregate, respectively. Chemical compositions and physical properties of the materials are given in Tables 1 and 2. The particle size distribution of the materials is present in Fig. 1.

The fineness of this RHA was chosen in a previous study [23] for UHPC production in terms of economic, technical validity and realization. RHA possesses a larger particle size but a higher specific surface area (SSA) compared to SF (Table 2). This RHA is a kind of mesoporous amorphous siliceous material with 97.4 wt.% amorphous, 2.0 wt.% quartz, 0.6 wt.% calcite (Fig. 2) by quantitative X-ray diffraction analysis (D5000, Bruker), pore size range from about 2 to 50 nm (Fig. 3) and specific pore volume of 120 mm^3/g measured by the Barrett–Joyner–Halenda method (SA 3100, Beckman Coulter). The specific water absorption capacity of the RHA significantly exceeds that of SF (i.e. 0.180 ml/g and 0.073 ml/g, respectively) [17]. Superplasticizer (SP) is polycarboxylate ether polymer with 40% of solid content by weight.

2.2. UHPC production

Based on results of a previous study [23], compositions of four UHPC mixtures with difference in their RHA, SF and GGBS content used in this study are given in Table 3. The ratio W/F_v is volume of water to volume of fine materials (i.e. cement, pozzolans and quartz powder). The volume of RHA and SF in mixtures is equal. Superplasticizer dosage is given as dry weight referred to the amount of cementitious materials (i.e. cement and pozzolans). 1 vol.% of steel fibers (a length of 9 mm and a diameter of 0.15 mm) was added to the mixture for producing prisms to measure compressive strength of UHPC. When fibers were used, volume of quartz sand was equally replaced by volume of fibers.

UHPC was mixed in a Hobart mixer (5 l) at 140 rpm with a total mixing time of 15 min based on the sequence shown in Fig. 4. Samples were casted with 30 s of vibration and were kept in molds at 20 °C, 95% relative humidity (RH) for 48 h. After demolding, three kinds of treatment conditions were applied: Treatment 1: 20 °C and 100% RH until testing; Treatment 2: 65 °C and 100% RH for 48 h; Treatment 3: 90 °C and 100% RH for 48 h. Samples of Treatment 2 and Treatment 3 were stored afterwards at 20 °C and 65% RH until examination.

2.3. Experimental methods

Mini-cone slump flow of UHPC mixtures was tested without stroking. UHPC was tested compressive strength on $4 \times 4 \times 16$ cm^3 sized samples in accordance to DIN EN 196-1.

The CH content in binder matrices (cement, pozzolans and water) of U2-SF and U2-RHA was calculated from the results of thermal analysis (DTA/TG) and the proportions of UHPC mixtures. For the thermal analysis, the samples were ground to a grain size $\leqslant$63 μm after stopping hydration by isopropanol addition and drying at 40 °C. The DTA/TG test was conducted in nitrogen atmosphere at a heating rate of 10 K/min and a nitrogen flow of 100 ml/min (SDT Q600, TA Instruments). The second derivative of DTA was used for identification of the onset of loss weight [28,29].

An experiment setup as shown in Fig. 5 was used to measure the continual free length change and temperature of three $4 \times 4 \times 25$ cm^3 sized samples up to 28 days of hydration at 20 °C. The moveable plate and mold at the ends of samples were fixed in UHPC by fixed plugs. Plastic plate and paraffin wax have been used to avoid any moisture exchange between concrete and environment during the examination. The concrete temperature and length change as well as room temperature were recorded every 6 min by temperature sensors and linear variable differential transformers (LVDT). The long term autogenous shrinkage of UHPC with the different treatment conditions was measured on three sealed $4 \times 4 \times 16$ cm^3 sized bars from 2 days of hydration as specified in DIN 52450.

To illustrate self-desiccation in UHPC, the internal RH in UHPC was measured during hydration. A hole with diameter of 20 mm and 60 mm in depth was created on $10 \times 10 \times 10$ cm^3 sized sample by a free surface steel bar to ensure the free moisture exchange between the concrete matrix and the environment within the hole. After demolding, the samples were immediately sealed with an aluminum foil. The internal RH in the hole during hydration of UHPC was recorded hourly by a RH sensor. Rubber ring and plastic foil were also used as the setup for the RH sensor to avoid any moisture exchange between the environment in the hole and the external environment during testing. For one mixture, two samples were measured (Fig. 6).

Table 2
Physical properties of materials.

	Cement	SF	RHA	GGBS	Quartz powder	Quartz sand
Density (g/cm^3)	3.20	2.30	2.19	2.91	2.64	2.64
Blaine (BET) SSA (m^2/g)	0.462	(21.05)	(52.28)	0.670	0.438	–
Mean particle size (μm)	9.15	0.31	7.41	2.93	14.60	174.50