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Effects of saturated lightweight sand content on key characteristics of ultra-high-performance concrete

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ABSTRACT

In this study, 0 to 75% volume of river sand was replaced by an equivalent amount of pre-saturated lightweight sand (LWS) to enhance mechanical properties and reduce autogenous shrinkage of ultra-high-performance concrete (UHPC). The use of LWS is demonstrated to effectively decelerate and reduce the drop in internal relative humidity and autogenous shrinkage of UHPC. Isothermal calorimetry and thermal gravimetry results showed that the use of LWS promoted cement hydration degree after 28 d of hydration. Mercury intrusion porosimetry and scanning electron microscope analyses revealed that the porosity was decreased and interface properties between sand and cement matrix is enhanced by use of LWS up to 25%. The optimum replacement ratio of LWS to river sand was found to be 25%, which resulted in the highest compressive strength (168 MPa at 91 d), flexural strength (24 MPa at 28 d), and autogenous shrinkage limited to 365 μm/m at 28 d.

1. Introduction

Ultra-high-performance concrete (UHPC) is a new class of cementitious composites that can develop superior mechanical properties and superior durability [1,2]. However, low water-to-binder ratio (w/b < 0.25) of UHPC can result in low degrees of hydration of cement, typically $< 50\%$ [3]. UHPC can have significant amount of unhydrated cement particles that do not effectively contribute to the development of mechanical properties. Low w/b can also lead to significant autogenous shrinkage, which tends to cause cracking in UHPC [4,5]. Self-desiccation increases capillary tension in pore fluid, resulting in autogenous shrinkage in low w/b systems [6]. Supplying additional water facilitates the hydration reactions and reduces self-desiccation. However, due to the significantly high impermeability of UHPC, limited amount of external curing water can penetrate the matrix and sustain cement hydration [7]. Internal curing is a promising alternative to supply addition water to cure cement-based materials for low w/b concrete [1,8–11].

Benefits of internal curing have been shown to include reducing shrinkage of high-performance concrete [12,13], increasing compressive strength [8], reducing potential cracking [14], and increasing durability [15]. Bentz et al. [16] claimed that compared with large internal curing agent, small inclusions can be better dispersed in matrix and more effectively store water during mixing and setting, and then progressively release water for internal curing. De la Varga and Graybeal [1] reported that supplying internal curing by utilizing pre-saturated lightweight aggregate resulted in a significant reduction in autogenous shrinkage of cementitious composites. However, past studies in the literature of UHPC internal curing indicate a trade-off between mechanical properties and autogenous shrinkage of concrete with the use of superabsorbent polymer or rice husk ash. Justs et al. [6] used superabsorbent polymer as internal curing agent to reduce autogenous shrinkage of UHPC. However, employment of superabsorbent polymers was reported to significantly reduce the workability [17] and compressive strength of concrete [6]. Mechtcherine et al. [18] achieved complete autogenous shrinkage reduction by applying internal curing with superabsorbent polymers to a reference UHPC that experienced high autogenous shrinkage of 1100 μm at 7 days (d). However, the high dosages of superabsorbent polymers necessary to reduce shrinkage reduced the compressive strength from 150 MPa to lower than 100 MPa. Zhutovsky and Kovler [15] claimed that the presence of excessively additional pores in internally cured concrete may cause reduction in compressive strength. Rice husk ash was also proven to be a good internal curing agent and pozzolanic material for UHPC [19,20]. Habeeb and Fayyadh [21] stated that fine rice husk ash increased the compressive strength of concrete, but it also increased the autogenous shrinkage. The use of pre-saturated lightweight aggregate is found to offer more effective and longer internal curing than superabsorbent polymers in the system of cement-based materials with low w/b (≤ 0.36) [22]. However, limited information is available on the effectiveness of lightweight sand (LWS) for internal curing of UHPC. There is a concern that the relatively large particle size of lightweight sand can

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Table 1
Chemical and physical properties of cementitious materials and selected sands.

	Type III cement	Class C fly ash	Silica fume	Missouri river sand	Masonry sand	Lightweight sand
SiO_2 (%)	19.72	36.50	95.50	80.30	86.50	57.60
Al_2O_3 (%)	5.10	24.80	0.70	10.50	0.39	19.40
Fe_2O_3 (%)	2.76	5.20	0.30	3.43	1.47	9.60
CaO (%)	64.50	28.10	0.40	1.72	9.42	3.40
MgO (%)	2.30	5.00	0.50	1.70	0	2.60
SO_3 (%)	3.25	2.50	–	1.07	0	0.60
Na_2O eq. (%)	0.33	–	0.40	–	–	5.60
C_3S (%)	65.23	–	–	–	–	–
C_2S (%)	7.33	–	–	–	–	–
C_3A (%)	8.85	–	–	–	–	–
C_4AF (%)	8.40	–	–	–	–	–
Loss of ignition (%)	1.50	0.50	2.00	1.28	0.24	–
Blaine surface area (m^2/kg)	562	465	–	–	–	–
B.E.T. (m^2/kg)	–	–	18,200	–	–	–
Specific gravity, SSD	3.15	2.70	2.20	2.65	2.64	1.80

potentially have adverse effect on mechanical properties of UHPC.

In this study, LWS is for the first time employed as an internal curing agent to prepared UHPC, aiming to reduce autogenous shrinkage and increase mechanical properties. The mechanisms of the effects of LWS on material properties of UHPC are systematically evaluated. The kinetics of cement hydration, evolution of internal relative humidity (IRH), autogenous shrinkage, compressive and flexural properties, and microstructure were investigated for UHPC mixtures with LWS contents between 0 and 75% substitutions by volume of river sand.

2. Materials

2.1. Raw materials

Type III Portland cement, Class C fly ash (FAC), and silica fume (SF), well-graded river sand (NS), masonry sand (MS), and expanded shale LWS were employed to produce UHPC. The chemical compositions and physical characteristics of these materials are listed in Table 1.

The particle size distributions of the three types of sand (NS, MS, and LWS) are shown in Fig. 1. The water absorption values of NS and MS were respectively measured to be 0.14% and 0.06% in accordance with ASTM C128 [23]. The water absorption value of LWS after soaking in water for 24 h (h) and the relative desorption of the LWS using centrifuge method was determined to be 17.6% and 96.4%, respectively, in accordance with ASTM C1761 [23]. The 72 h water absorption was also measured as 18.4%. In addition, Henkensiefken et al. [14] reported that 96% of water in this type of LWS was lost at a 92% RH, implying that water can be effectively transported from the LWS to cement paste at a high RH for internal curing. The moisture content of the bulk LWS was measured in accordance with ASTM C128 [23]. The rest amount of water to be added in the LWS was calculated by subtracting the water content in the LWS from the total water demand of the LWS to secure a saturated-surface-dry (SSD) condition. After adding the rest amount of water to the LWS, the LWS was homogenized with water and then placed in a sealed plastic bag for 24 h before batching to secure the SSD condition [11,12].

A polycarboxylate-based high-range water reducer (HRWR) with a solid mass content of 23% and a specific gravity of 1.05 was used. The selected HRWR enhanced the fluidity retention and fiber distribution of the UHPC mixture [24]. An air de-training admixture was employed to reduce the entrapped air content in the UHPC. Steel fibers with 0.2 mm in diameter and 13 mm in length were incorporated. The tensile strength and modulus of elasticity of the fibers were 1.9 and 203 GPa, respectively.

2.2. Mixture design

In this study, a UHPC mixture designed by the authors in a previous study was used for the reference mixture [25]. For the binder, the volume percentages of cement, FAC, and SF were 55%, 40%, and 5%, respectively. The contents of MS and NS for the reference mixture were 30% and 70%, respectively, of the total sand volume. The binder-to-sand ratio (b/s) was 1:1, by volume. The w/b was fixed at 0.20, by mass. The mixture designs are listed in Table 2. The dosages of active solid component of HRWR and air de-training admixture were fixed at 1% and 0.8%, respectively, by mass of binder. The volume fraction of 2% of steel fibers was incorporated in all investigated mixtures.

A theoretical model was presented in ASTM C1761 to predict the minimum amount of internal curing agent required to provide additional water to counteract the effects of self-desiccation and chemical shrinkage during the hydration of cement paste [26]. Water introduced by internal curing agent is gradually released to sustain a relatively high IRH, and ensures the capillary porosity in the cement paste is water-filled at the maximum degree of hydration. The hydration

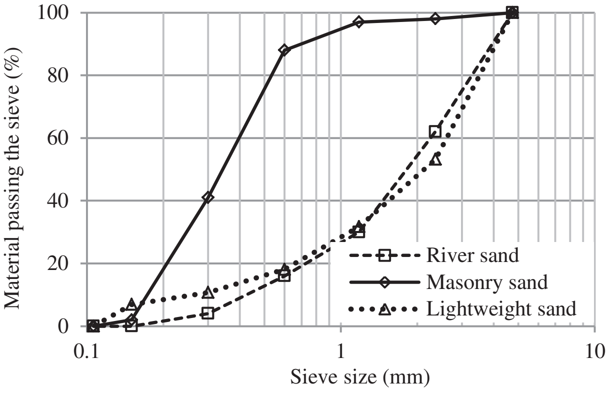

Fig. 1. Sieve analyses of investigated sand.

Table 2
Investigated UHPC mixtures.

Code	LWS/(NS + LWS), (vol%)	Cement (kg/m^3)	FAC (kg/m^3)	SF (kg/m^3)	MS[a] (kg/m^3)	NS[a] (kg/m^3)	LWS[a] (kg/m^3)
LWS00	0	663	367	42	308	703	0
LWS12.5	12.5					615	60
LWS25	25.0					527	120
LWS37.5	37.5					440	180
LWS50	50.0					352	240
LWS75	75.0					176	360

[a] Weighted under the SSD condition.

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