Design and Performance of 3D Printable UHPC Using Locally Available Materials

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Extended Abstract

The advancement of 3D printing (3DP) technology in construction has been limited by the overreliance on conventional Portland cement and the absence of internal reinforcement. This is particularly evident in certain structures where large amounts of raw materials need to be sourced from far-off locations. This research aims to overcome these challenges by developing an eco-friendly and printable ultra-high-performance concrete (UHPC) that can achieve high strength and toughness by utilizing locally available material, such as fly ash (FA), slag cement (SC), silica fume (SF), and conventional concrete sand. To achieve this, a step-by-step approach was employed to select indigenous materials and optimize fiber volume for the UHPC ink material at cement paste, mortar, and fiber-reinforced mortar scales. The optimized binder combinations were identified through the spread-flow test at the paste level and further narrowed down based on the radar chart approach at the mortar level. This study involved investigations on the key properties, such as superplasticizer (SP) demand, plastic viscosity, forced bleeding, final setting time, and 3-d compressive strength were determined. The 6-mm steel fiber was then incorporated into the mortar made with the selected binder combination, and the key fresh and hardened properties were evaluated. Finally, the printability of the resulting non-proprietary UHPC mixture was validated through an extrusion-based 3D printer. Developing a print material with high strength and toughness can improve the cost-effectiveness of 3DP in construction and extend 3DP technology to remote, isolated, and expeditionary environments.

In the first step, the flow characteristics of paste mixtures made with the various SCMs and their combination were systematically evaluated, as shown in **Figure 1**. The minimum water content (MWC) refers to the required water for the onset of flow, which is closely related to the packing density of the powder particles. The relative water demand (RWD) indicates the sensitivity of flow regarding water addition. Thus, a paste made with a given binder having low MWC and high RWD can be considered a desirable binder. The FA replacement decreased the

MWC and RWD simultaneously, which decreased gradually as their replacement rates increased. While for paste mixtures made with SC, their MWC and RWD also showed a decrease with increasing substitution rates; however, low substitution rates, such as the SC30 and SC40 binder exhibited higher MWC. On the other hand, the use of SF resulted in a significant increase in MWC and RWD as the substitution rate increased. It should be noted that the main index used in selecting the desired binder combinations is a low MWC (i.e., low SP demand and lower viscosity) that can result in better extrudability. Thus, SC30 and SC40 mixtures with higher MWC were eliminated.

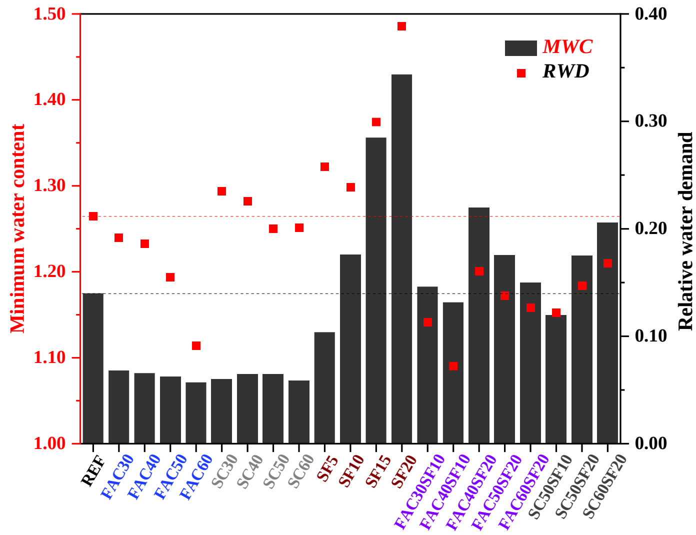

Figure 1. Systematic investigation of effect of SCMs/filler on MWC and RWD

In the second step, the radar chart approach was adopted to narrow down the optimized binder candidates using key fresh and hardened properties, namely SP demand, final setting time, forced bleeding capacity, plastic viscosity, and 3-d compressive strength. The selected test methods are closely related to the 3DP performance. The FAC30, FAC40, SC50, FAC30SF10, FAC40SF20, FAC50SF20, and SC50SF20 mixtures were chosen based on the radar chart, as illustrated in **Figure 2**. These mortar mixtures are considered desirable for 3D printing. The FAC30, FAC40, and FAC30SF10 mixtures showed higher radar areas compared with the reference mixture made with only Type III cement and can be considered as candidate mixtures for further evaluation.

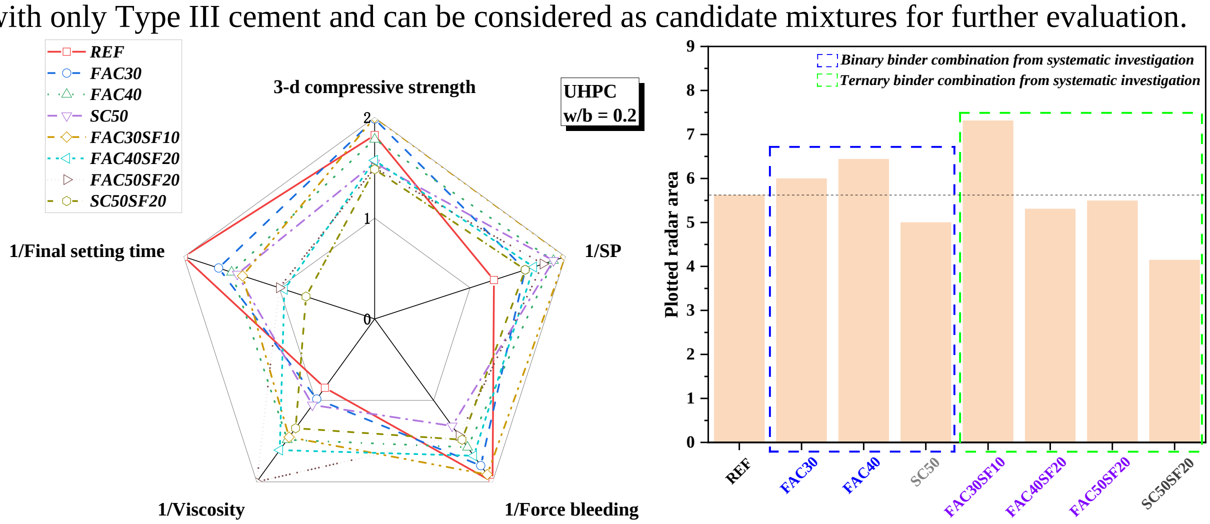

Figure 2. Radar chart diagram and plotted radar area of UHPC mortars

In the third step, different volumes of 6-mm steel fibers (1%, 1.25%, 1.5%, 1.75%, and 2%) were added to selected mortar mixtures and the performance of fiber-reinforced mortars was assessed. The hardened properties (i.e., 28-d compressive strength and flexural properties) of fiber-reinforced mortars made with the selected binder combination (FAC30SF10) with varying fiber volumes are shown in **Figure 3**. An increase in compressive strength, flexural strength, and toughness can be observed with the increase in fiber volume. This can be attributed to the positive effect of short steel fibers on bridging microcracks and the mechanical interlocking of the fibers. The 28-d compressive and flexural strengths of the FAC30SF10 mixture prepared with 2% fiber met the performance specifications of minimum f'_c and f_f of 120 and 18MPa, respectively, as well as high flexural toughness of 24 J. Excessive fiber volume can increase cost and lead to fiber agglomeration, which is detrimental to mechanical properties. Therefore, the use of 2% fiber volume is recommended for this application.

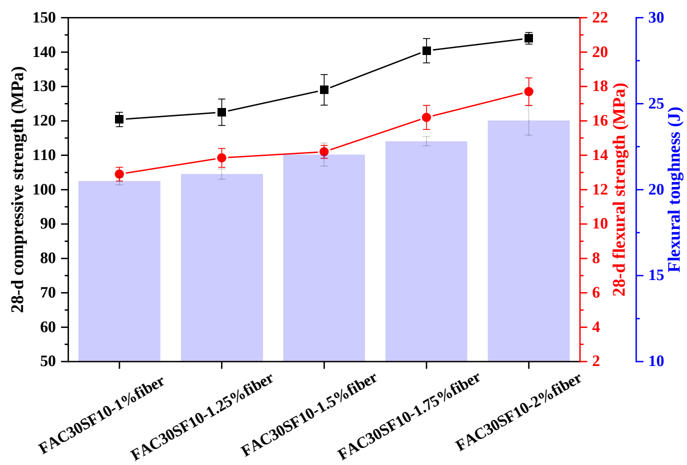

Figure 3. 28-d compressive and flexural strengths and toughness of optimized UHPC mortars

The printability of the selected UHPC mixture made with the optimized binder combination and optimal fiber volume was evaluated using a 3D printer. As shown in **Figure 4**, the freshly developed UHPC can be successfully extruded without any clogging, segregation, and bleeding, and possessed superior shape stability. After extrusion, no signs of vertical distortion, collapse, or excessive deformation among layers were noted.

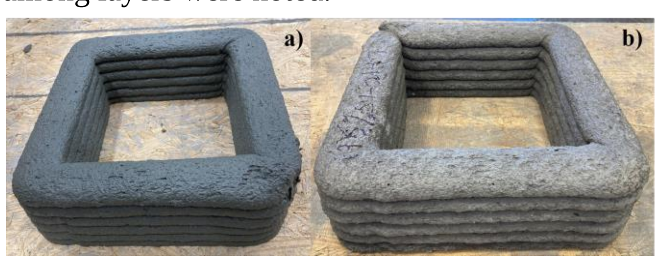

Figure 4. Printability of optimized UHPC; (a) captured before setting and (b) captured after hardening

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