Properties of ultra high performance concrete containing superfine cement and without silica fume
Rui Xiao, Zon-Cai Deng, Chenliang Shen
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Rui Xiao¹, Zong-cai Deng² and Chenliang Shen³

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Abstract

To avoid the disadvantages caused by using silica fume, by using superfine cement (SC) to substitute silica fume, a new kind of ultra high performance concrete (SC-UHPC) was prepared and introduced. The influence of component types and dosages on the mechanical properties of SC-UHPC was investigated. The results show that 40% ground granulated blast furnace slag (GGBFS) or 10% fly ash (FA) & 30% GGBFS replacing SC are the most appropriate proportions to get high strength with satisfied workability and low cost. A suitable amount of defoaming agent (DA) in superplasticizer (SP) effectively reduced the void ratio in the UHPC. To optimize the strength and fluidity, the rational natural sand distribution with lowest clay particles amount can be used. The small sized steel fibers added into the mixture effectively improved the flexural behavior of SC-UHPC. Multiple nonlinear analysis show that, with sufficient calcium silicate hydrate (C-S-H gel) and enough mixture fluidity, the compressive strength of UHPC is closely related to the water to binder ratio and void ratio, and increases linearly with the incremental fiber amount. Microstructure analysis proved that the microstructure of SC-UHPC has ultra high density and homogeneity.

1. Introduction

Ultra high performance concrete, as new cement based material, has been rapidly developed and utilized especially in bridges and some other special structures recently (Schmidt and Fehling 2005; El-Hacha et al. 2010; Corinaldesi and Moriconi 2012; Yi et al. 2012) since the Reactive Powder Concrete (RPC) was firstly reported by Bouygues’ laboratory in France (Richard and Cheyrezy 1995). Compared to the ordinary and high strength concrete, the following impressive advantages of mechanical properties of UHPC have been proved (Richard and Cheyrezy 1995; Wang et al. 2008; Zhang et al. 2008; Tai 2009; Yang et al. 2009): ultra high compressive strength, high tensile strength and ductility by adding special fibers, outstanding abilities to absorb energy and resist impulsive loading by incorporating high volume fraction of steel fibers.

Yang et al. (2009) compared the mechanical properties by using aggregates of silica sand, 2 types of local natural sand, and recycled glass cullet. They found that, the natural grading of fine natural sands does not significantly influence the properties of UHPC compared to using the expensive silica sand, the properties of UHPC with recycled glass cullet is much lower than with other aggregates because the particle shape or particle size distribution reduced the bulk density. By investigating the mechanical properties of UHPC with replacing the cement amount by mineral admixtures of fly ash (FA) and ground granulated blast furnace slag (GGBFS) under different curing conditions, Yazıcı et al. (2007, 2008, 2009, 2010) found that mineral admixtures can substitute a part of cement amount to maintain the properties and reduce cost. Park et al. (2012) investigated the tensile behavior of UHPC with hybrid fibers and found that the shape of tensile stress-strain curves of UHPC is mainly dependent on the type of macro-fiber; the micro-fibers improved multiple cracking and strain hardening behaviors. By studying the flexural and tensile behaviors of UHPC with different fiber distribution characteristics, it was found that the effect of the fiber orientation distribution on post-cracking behavior is significant but very small on pre-cracking behavior (Kang et al. 2011; Kang and Kim 2011). Kim et al. (2011) researched the flexural behavior of UHPC with hybrid fibers and found that macro-fibers with twisted geometry provided the best performance of UHPC with respect to post cracking strength, strain capacity and multiple micro-cracking behavior, whereas long, smooth macro-fibers exhibited the worst performance. Wille et al. (2011) established the expression with factors of the water to cement ratio and air amount to calculate the compressive strength of UHPC.

Nevertheless, there are some problems of using silica fume in UHPC: the quality of silica fume is not easy to control, and the yield is not adequate for concrete industry, which results in high price in China. To resolve the above problems, the test of preparing UHPC with superfine cement and without silica fume was put for-
ward. The effect of component types and dosages on the mechanical properties and rheology of SC-UHPC was studied to acquire the optimized mixtures’ proportion.

2. Basic principles and differences between SC-UHPC and conventional UHPC

There are mainly 4 basic principles that should be followed for preparing UHPC (Richard and Cheyrezy 1995; Reda et al. 1999; Yang et al. 2009):

- Eliminating coarse aggregates to improve the homogeneity;
- Adding silica fume to increase compactness of binder;
- Improving the ductility by blending special small sized fibers;
- High temperature curing to reach satisfied early age strength.

In addition, silica fume was regarded as necessary component for the follow functions (Richard and Cheyrezy 1995):

- Filling the voids of the larger class particles of cement;
- Enhancing rheology by the lubricating effect from the particles’ perfect spherical shape;
- Generating secondary hydrates by pozzolanic reaction with lime from primary hydration.

In chemical reaction mechanism, the reaction of superfine cement (SC) is basically same to ordinary Portland cement (OPC) because there is no much difference in component between the 2 kinds of cement. This reaction mode is favored for increasing UHPC strength in the early age in normal environmental temperature. And the SC obtained by the cement clinker pulverized by using the conventional ball mill also has good voids filling effect due to the small particle size (the specific surface is over 500 m²/kg). Hence, it is doable to take the superfine cement as the smallest class particles together with the OPC and other mineral admixtures as the binder to prepare UHPC (the binder constitutes SC, OPC and mineral admixtures in the mixture).

In this study, SC and mineral admixtures were used to prepare the UHPC without silica fume. It proved that it is feasible to prepare UHPC without silica fume because the basic function of silica fume can be substituted by SC. Meanwhile, the amounts of water, sand, defoaming agent (DA), mineral admixtures were changed to investigate their effect on the compressive strength, spread value, and void ratio. And the relationships among their properties were analyzed. Then, the compressive and flexural behavior of the SC-UHPC specimens with different steel fiber volume fractions based on the optimized SC-UHPC mortar were tested and evaluated. At last, the microstructure of UHPC was investigated.

3. Experimental program

3.1 Materials

4 types of cementitious materials including SC, OPC, FA and GGBFS were used. The chemical composition and physical properties are given in Table 1. The different size ranges of a type of river sand used for components are shown in Fig. 1. The sand range in other specimen mixtures not in A series were used the same sand range as A12. Polycarboxylate based superplasticizer (SP) was used to minimize the dosage of water while keeping good

<table>
<thead>
<tr>
<th>Chemical composition (%)</th>
<th>SC</th>
<th>OPC</th>
<th>FA</th>
<th>GGBFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>57.34</td>
<td>58.69</td>
<td>4.15</td>
<td>34.54</td>
</tr>
<tr>
<td>SiO₂</td>
<td>28.01</td>
<td>22.45</td>
<td>52.36</td>
<td>36.67</td>
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<tr>
<td>Al₂O₃</td>
<td>4.60</td>
<td>6.04</td>
<td>31.73</td>
<td>14.85</td>
</tr>
<tr>
<td>MgO</td>
<td>3.78</td>
<td>4.64</td>
<td>0.78</td>
<td>8.91</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.58</td>
<td>4.28</td>
<td>1.00</td>
<td>2.30</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.31</td>
<td>2.35</td>
<td>5.87</td>
<td>0.37</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.13</td>
<td>1.13</td>
<td>1.66</td>
<td>0.58</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.08</td>
<td>0.05</td>
<td>0.35</td>
<td>-</td>
</tr>
<tr>
<td>Na₂O</td>
<td>-</td>
<td>0.14</td>
<td>0.55</td>
<td>0.42</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>-</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F·CaO (%)</td>
<td>0.58</td>
<td>0.92</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical properties</th>
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<tr>
<td>Specific gravity</td>
<td>3.07</td>
<td>3.06</td>
<td>2.23</td>
<td>2.86</td>
</tr>
<tr>
<td>Specific surface (m²/kg)</td>
<td>570</td>
<td>350</td>
<td>340</td>
<td>410</td>
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<tr>
<td>Initial setting time (min)</td>
<td>40</td>
<td>170</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final setting time (min)</td>
<td>120</td>
<td>235</td>
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</table>

<table>
<thead>
<tr>
<th>Compressive strength of cement (MPa)</th>
<th></th>
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<tr>
<td>2 days</td>
<td>33.7</td>
<td>25.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 days</td>
<td>49.5</td>
<td>36.8</td>
<td></td>
<td></td>
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<tr>
<td>28 days</td>
<td>53.1</td>
<td>44.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Physical, chemical and mechanical properties of SC, OPC, FA and GGBFS.

Fig. 1 The sand size distribution and ranges used in mixtures.
rheology of mixture. The DA which is commonly con-
tained in SP was independently researched to identify the
best dosage. In this experiment, the silicone polyether
based DA with excellent effect to reduce entrained air
content in mortar was used. Brass coated steel fibers
manufactured by Shanghai Bekaert-Ergang Co., Ltd.
were used and the characteristic parameters are length 8
mm, diameter 0.12 mm, and at least 2850 MPa tensile
strength.

3.2 Mix proportions
First, the mix proportions of the SC-UHPC mortar
without steel fibers were designed and adjusted to opti-
mize compressive strength and rheology. The tested
SC-UHPC mortars’ proportions are presented in Table 2.
Then, steel fibers were added into the optimized mortar
and the mechanical properties tested. The mixtures with
the same alphabet of specimen number in Table 2 means
one kind of components varied while the others remain
constant. The meanings of the alphabets representing
variable components are: W, water amount; S, sand
amount; D, DA amount; SP, SP amount; A, aggregate
types; P, replacing amount of SC by OPC; F, replacing
amount of SC by FA; G, replacing amount of SC by GGBFS; SF, steel fiber amount.

3.3 Specimen preparation
The mixtures were blended by a two-speed mortar mixer.
First, the cementitious materials and aggregates were
dry-mixed at low speed for 1 min. Then the mixtures
were mixed for 2 min (the water and SP were gradually
added into the pre-mixed mixtures in the first 30 s). After
that, the mortar was mixed at high speed for 3 min. At
last, the mortar continued to be mixed at low speed for 1
min (in this time, fibers, if any, can be slowly added, and
additional 2 min mixing at high speed was needed to
keep them evenly distributed throughout the mortar).
After that, the fresh mixture was cast into steel moulds
and compacted by a vibrating table. The specimens were
kept in the moulds in condition of 20 °C, 100% RH for
48h. After demoulding, the specimens were steam cured
at 90 °C, 100% RH for 48 h.

3.4 Test methods
The method of evaluating the rheology of the fresh
mortar was performed by testing the spread value fol-
lowing the China standard of GB/T 2419-2005. The glass
plane plate substituted as the base plate without impact-
ing was used, and the measure time after raising the
mould was 30 s.

Specimens of dimensions 40 × 40 × 160 mm were used
to determine the compressive strength according to the
China standard of GB/T 17671-1999, in which the
compressive area of specimens is 40 × 40 mm. The flexural
behavior of specimens with steel fibers was also
tested. The loading rate for flexural behavior test was set
at 0.5 mm/min, and the max mid-span deflection of 3.0
mm was set, which was loaded under a closed-loop
closeup test procedure. The distance between two sup-
ports of specimens is 100 mm, the cross section of the
specimen is 40 × 40 mm, and the specimens were loaded
at the mid-span. After the test, flexural load-deflection
curves were drawn according to the results closest to the
average flexural performance.

The specimens’ amount of void ratio was got by the
actual density from measuring the weight and the volume

Table 2 Mix proportions and results.

<table>
<thead>
<tr>
<th>No.</th>
<th>SC:OPC: FA:GGBFS</th>
<th>S/B</th>
<th>W/B</th>
<th>SP, DA (%)</th>
<th>Fibers (vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.15</td>
<td>2, 2</td>
<td>0</td>
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<tr>
<td>W2</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.16</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>W3</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>W4</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.18</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>W5</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.19</td>
<td>2, 2</td>
<td>0</td>
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<tr>
<td>W6</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.20</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>S1</td>
<td>1:0:0:0</td>
<td>1:1</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>S2</td>
<td>1:0:0:0</td>
<td>1:1.05</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
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<tr>
<td>S3</td>
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<td>1:1.1</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>S4</td>
<td>1:0:0:0</td>
<td>1:1.15</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
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<tr>
<td>S5</td>
<td>1:0:0:0</td>
<td>1:1.2</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
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<tr>
<td>S6</td>
<td>1:0:0:0</td>
<td>1:1.25</td>
<td>0.17</td>
<td>2, 2</td>
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<td>D1</td>
<td>1:0:0:0</td>
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<td>2, 0</td>
<td>0</td>
</tr>
<tr>
<td>D2</td>
<td>1:0:0:0</td>
<td>1:1.1</td>
<td>0.17</td>
<td>2, 2</td>
<td>0</td>
</tr>
<tr>
<td>D3</td>
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<td>1:1.1</td>
<td>0.17</td>
<td>2, 4</td>
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<tr>
<td>D4</td>
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<tr>
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<td>0.17</td>
<td>2, 10</td>
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<tr>
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<td>2, 6</td>
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<tr>
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<td>1:1.1</td>
<td>0.17</td>
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<td>0.17</td>
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<td>0</td>
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<td>0.17</td>
<td>1.4, 6</td>
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<td>A11</td>
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<td>E0</td>
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<td>0</td>
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<tr>
<td>P20</td>
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<td>P60</td>
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<td>0.17</td>
<td>1.5, 6</td>
<td>0</td>
</tr>
<tr>
<td>F20</td>
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<td>0.17</td>
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<td>0</td>
</tr>
<tr>
<td>F40</td>
<td>0.6:0:0:4:0</td>
<td>1:1.1</td>
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<td>1.5, 6</td>
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</tr>
<tr>
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<td>1.5, 6</td>
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</tr>
<tr>
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<td>1.5, 6</td>
<td>2</td>
</tr>
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<td>0.17</td>
<td>1.5, 6</td>
<td>4</td>
</tr>
</tbody>
</table>
4. Results and discussion

4.1 Influence of the raw materials amount on the performance of SC-UHPC mortars

(1) Water to binder ratio

The compressive strength and the corresponding spread value and void ratio of SC-UHPC mortars with different amounts of raw materials are presented in Fig. 2. According to Fig. 2(a), when the water to binder ratio increased from 0.15 to 0.17, the fluidity increased due to the decrease of the paste yield stress and viscosity. The improved rheology as the main positive influence factor effectively reduced the entrapped air in the mortar and resulted in better packing density, and consequently increasing the compressive strength of the mortar. When the water to binder ratio was higher than 0.18 and continually increased, the growing additional free water became the main passive influence factor, replaced the entrapped air and reduced the compactness of the specimen, and consequently caused the compressive strength to decrease.

(2) Sand to binder ratio

Figure 2(b) shows that, increasing the sand proportion (the sand to binder ratio changed from 1:1 to 1:1.25), the spread value gradually increased while the compressive strength and void ratio of the specimens do not obviously change, which indicates the rheology can be enhanced by reducing the sand amount without influencing the strength of the material. By considering the workability and the cost, the sand to binder ratio was suggested to be controlled at 1:1.1.

(3) Chemical admixtures

The chemical admixtures of DA and SP were added to the SC-UHPC in the mixing stage. It can be seen from Fig. 2(c) that, compared with the mortar without DA, adding 4%–6% DA (the weight proportion of DA to SP), the content of the surfactant, salt and etc. in the DA minimized entrapped air in the mortar and enhanced the rheology, and consequently the compressive strength of the specimen was largely increased. The SP based on polycarboxylate was necessary to avoid particle aggregation and improve the rheological behavior of fresh mixer. Because the side chain lengths have different effect on the particle dispersion (Schröfl et al. 2012), by comparing 5 kinds of SP, the one with the best effect was selected in this test. Figure 2(d) shows that, when the superplasticizer ratio (the ratio of SP to binder) increased from 1.2% to 2.0%, the compressive strength and void ratio were not significantly changed, but the spread value slightly reduced. Using 1.5% SP can get rational retardation time and relative lower cost.

(4) Aggregate sizes

By considering the convenience of construction, the river sand was used to replace the quartz sand as the aggregate.

Fig. 2 Influence of raw materials amount on the compressive strength, spread value and void ratio of SC-UHPC mortars.
in UHPC. According to Fig. 3, the average compressive strength of the specimens A01, A02 and A03, with aggregate particle sizes smaller than 0.16 mm was lower than A11, A12 and A13 without the particle sizes of below 0.16 mm. The corresponding standard deviations of the former ones were wider than the latter, and the spread values of the former ones were lower. Whereas, the void amounts of these specimens were all limited in a small ratio of below 0.9%. Moreover, the fluidity of composition A01, with the lowest sand range and highest volume proportion of soil amount, was lowest. This is because the particles size below 0.16 mm containing much clay particles reduced the average compressive strength, increased the range of the standard deviation value and decreased the fluidity of the mortars. In addition, the composition A11, with the aggregate particle size range of 0.16 to 0.63 mm had the highest average compressive strength, the smallest standard deviation and the largest spread value. The above test results proved that, by reducing the defects caused by clay and coarse aggregate amounts, the compressive strength and fluidity were increased due to the enhanced homogeneity of the UHPC.

(5) OPC, FA or GGBFS
The OPC, FA and GGBFS were independently mixed in SC-UHPC mortars to partly replace SC. Figure 4 shows that, the replacement of SC by OPC caused the compressive strength of SC-UHPC mortar to drop; the corresponding void ratios were higher than the one without other admixtures; whereas the corresponding spread values of the specimens were no much different to the SC-UHPC mortar without admixtures. It implies that the void in SC-UHPC cannot be effectively filled by mixing SC and OPC.

When the SC was replaced by 20% FA, the compressive strength of the SC-UHPC mortar was maintained, but the compressive strength was slightly smaller when the amount of FA reached 40%. The spread value decreased with the increase of FA, and the void ratio in both replacement amounts were smaller compared with the one without the substitution.

When the SC was substituted by 20% and 40% GGBFS, the compressive strength of specimens was higher than the specimen without admixtures. The beneficial effect of GGBFS replacing 40% of OPC in UHPC was reported by Yazıcı (2007), because more capillary pores were filled with low density C-S-H gel generated by GGBFS than only using OPC (Arya and Xu 1995; Glass et al. 2000). According the test results above, it can be inferred that the GGBFS has the same effect in replacing SC. The corresponding void ratios were all controlled within 0.2% when the replacing amount of GGBFS was not higher than 40%, and the fluidity can...
satisfy the workability requirement. However, the high replacement amount of 60% FA or GGBFS caused the retardation time lagging and was not suitable for using.

The specimens with the highest and second highest compressive strengths are the ones with total replacement of 40% mineral admixtures, including the one with 30% GGBFS and 10% FA and the one with 40% GGBFS. The corresponding compressive strengths were 160 MPa and 158 MPa, 106.0% and 104.6% of the one without substitution respectively. Moreover, the spread values of the two corresponding specimens were 277 mm and 266 mm respectively, which were higher than the others. By considering the strength, workability and cost of the SC-UHPC, the above 2 kinds of mixture proportions are suggested.

4.2 Influence of steel fiber amount on the properties of SC-UHPC

Figure 5 shows the compressive strength, flexural strength, spread value and void ratio of SC-UHPC with different steel fiber amounts. It was found that, by increasing steel fiber volume fraction from 1% to 4%, the compressive strength and flexural strength of SC-UHPC increased from 172 MPa to 206 MPa, and 17.2 MPa to 31.4 MPa, respectively. Hence, the incorporation of steel fibers improved the compressive strength and flexural strength of SC-UHPC. Whereas, by increasing the steel fiber amount, the spread value dropped from 259 mm to 188 mm because the overlap of steel fibers increased the paste yield stress and viscosity of the mortar, consequently caused a slight increase of SC-UHPC’s void ratio. However, the workability of the SC-UHPC mortar with 4% fiber amount was good and the void ratio was controlled in 1.2% which is comparatively low. Moreover, when the volume fraction of steel fibers increased from 1% to 4%, the ratio of flexural strength to compressive strength increased from 9.4% to 15.2%; so increasing the steel fiber amount has greater effect on the flexural strength than the compressive strength.

The flexural behaviors of specimens with steel fiber volume fractions from 1% to 4% were observed and the load-deflection curves are presented in Fig. 6. The first crack strength of specimens with steel fiber volume fractions of 1%, 2%, 3% and 4% was 17.2 MPa, 16.3 MPa, 21.8 MPa and 23.6 MPa, and the flexural strength was 17.2 MPa, 19.0 MPa, 27.5 MPa and 31.4 MPa, respectively. The load-deflection curve of specimen with 1% steel fibers increased linearly at the beginning of loading. When the first crack load was reached, the peak load was observed, and a single fine crack appeared in the mid bottom of the specimen, the curve first dropped sharply and then slowly decreased, while the deflection increased subsequently. The load-deflection curve of specimens with steel fibers more than 1% also increased linearly at the beginning of loading. When the first crack load reached, the load was gradually increasing until the peak load reached, then the curve slowly decreased along with the increasing deflection. As shown in Fig. 6, it can be found that higher steel fiber amount can effectively enhance the toughness as well as the first crack strength and the flexural strength because steel fibers bridged on macro-cracks and arrested them.

4.3 Regression modular for predicting compressive strength of UHPC

By comparing and analyzing the test data, the compressive strength of SC-UHPC mortar was found to be highly influenced by the water to binder ratio and the void ratio. Based on the regression equation defined by the water to cement ratio and void ratio proposed by Wille et al. (2011), the following expression is established to predict the compressive strength of SC-UHPC mortar:

\[ R_c = a\left(W/B\right)^{b} + c \]  

where \( R_c \) is the compressive strength of UHPC mortar.
according to the standard of GB/T 17671-1999 (MPa), \( W/B \) is the water to binder ratio, and \( V \) is the void ratio (%). The coefficients \( a \), \( b \) and \( c \) are -1016, 0.064 and 309 respectively by multiple nonlinear regression analysis, and the adjusted \( R \) square is 0.80. The fitted curve and the test data are shown in Fig. 7. According to the figure, it is effective to predict the compressive strength of SC-UHPC mortar by using the water to cement ratio and the void ratio. The value that deviated farthest from the fitted curve belongs to specimen F20G30, in which 30% GGBFS and 20% FA were used to replace the SC. Because the replacing amount of mineral admixtures is high, and the hydration reaction activity of FA is relatively low, the converted C-S-H gel was not as much as other specimens, which caused the lower strength of the matrix, and the interface between the matrix and aggregate. Hence sufficient C-S-H gel amount should be ensured to avoid the compressive strength loss.

When the steel fibers were blended and the spread value was higher than 180 mm (too low fluidity can cause the pouring problem), the relation between the fiber amount and the compressive strength of the SC-UHPC was linear given that the dimension of fibers, preparation method and curing environment conditions were appropriate. The compressive strength of SC-UHPC can be expressed by the SC-UHPC mortar and steel fiber amount equation:

\[
R_{cf} = R_c (1 + d \rho_f)
\]

where \( R_{cf} \) is the compressive strength of SC-UHPC according to the standard of GB/T 17671-1999 (MPa), and \( \rho_f \) is the volume fraction of fiber in SC-UHPC. The coefficient \( d \) is 7.2 by regression analysis in this experiment.

4.4 Microstructure analysis

The microstructure of the SC-UHPC mortar mixtures of E0, F20 and G20 was investigated by using FEI Quanta 200 electron microscope (SEM). Samples were taken from the inner part of specimens and dried at 90 °C. The SEM study was carried out by using an accelerating voltage of 30 kV.

As shown in Fig. 8, the density and homogeneity of the matrix microstructure of SC-UHPC mortars is almost the same to the conventional UHPC at the same steam curing condition of 90 °C (Yazici et al. 2008; Korpa et al. 2009; Yazici et al. 2010), and much higher than that of normal concrete and high performance concrete (HPC). Nevertheless, very low amount of entrapped air pores was found in the SC-UHPC matrix. However they can probably be filled by tobermorite in higher temperature of 200 °C (Cheyrezy et al. 1995). Figure 9 shows that the matrix’s dense microstructure of samples extended to the aggregate boundary and the well-known transition zone of the microstructure gradient of cement paste toward to the aggregate was absent. Although the XRD analysis found the existence of CH, the CH crystal was not detected by the SEM investigation. It can be inferred that the very low water to binder ratio of the mixture resulted in high density and very low porosity of the SC-UHPC mortar and consequently restricted the available space for the CH crystal growth (Reda et al. 1999). Both reacted and non-reacted fly ash particles were detected in Fig. 8 (b) and Fig 9 (b) respectively by scanning F20. In Fig. 9 (b), the regular hemispheroidal voids generated from non-reacted fly ash particles pulled out due to the cutting and splitting force. It can be found from the microstructure of F20 that most fly ash particles in the section surface were non-reacted, which caused the weak bonding interface. So, the compressive strength of specimen was reduced if the SC was replaced by more than 20% FA.
The splinter of SC-UHPC mortar sample G40 was dried, and its porosity tested on the AutoPore IV 9500 porosimeter. Figure 10 shows that, the total cumulative porosity of sample G40 at the pore diameter 3 nm to 5000 nm was 0.0082 mL/g, which is a bit smaller than approximately 0.011 mL/g of the RPC sample cured at 90 °C at the same pore diameter range in Cheyrezy et al.'s research (Chyrezy et al. 1995), and the threshold of above 2 comparative samples' curves are around 10 nm. The above results prove that, with the same curing condition, the cumulative porosity of SC-UHPC can be controlled in the same range as RPC, and result in ultra high durability of SC-UHPC which is mainly influenced by the porosity characteristics.

5. Conclusions

UHPC can be prepared by using cementitious materials of SC without silica fume, because the SC with small particle size has voids filling effect. Moreover, the reaction mode of SC is basically the same as OPC, and does not have negative influence in enhancing early age strength.

In the mixing procedure, the superfine cement can play the whole role of the binder; GGBFS and FA can be added to improve the performance and reduce the cost of preparation. Partly replacing the SC by 20% FA does not cause compressive strength reduction, and the GGBFS can enhance the strength of SC even at 40% replacement ratio. The replacement ratio of 40% GGBFS, and the one with both 30% GGBFS and 10% FA are suggested. However, OPC partly replacing the SC caused the compressive strength reduction.

To maximally reduce the water amount and voids while keeping high compressive strength and rheology, the water should be limited to extremely low level, and high dosages of SP and DA should be used. Nevertheless, the dosage of SP should be controlled because the superfluous SP can delay the setting time.

The sand to binder ratio should be adjusted to avoid too much rheology loss or cementitious material wastage. Clay particles amount and the coarse aggregate caused the average compressive strength reduction and the relative standard deviation increase.

The compressive strength and the flexural behavior were enhanced by blending steel fibers, and these properties improved by increasing the amount of steel fibers up to 4%, which still satisfied the workability requirement.

With enough C-S-H gel generation, the compressive strength of SC-UHPC mortar is the function of the water to binder ratio and void ratio; when the steel fibers are blended into the mixture and without too much fluidity loss, the compressive strength basically increased linearly with the fiber amount increase.

SEM analysis revealed that the characteristic of the microstructure of SC-UHPC is quite similar to the conventional UHPC with high density and homogeneity of the matrix and absence of transition zone. The weak bonding interface due to non-reacted fly ash particles caused the compressive strength reduction. The porosity test results denote that, under the same curing condition, the porosity of SC-UHPC mortar was as low as RPC, so it indicates that SC-UHPC also has ultra high durability.

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