Original Article

Dosage effect of superplasticizer on self-compacting concrete: correlation between rheology and strength

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Abstract

This study presents the relationship between the rheology and the compressive strength of self-compacting concrete (SCC). The concrete mixes contained eight different dosages of superplasticizer. The used rheology measurements are the slump flow, V-funnel, L-box, yield stress and plastic viscosity. The used mechanical tests are the compressive strength. The superplasticizer effect on these rheological and mechanical properties will be studied in more details.

Based on experimental tests, the results obtained show that the slump-flow diameter, L-box ratio, V-Funnel time, yield stress, plastic viscosity and compressive strength were correlated at a high level. At 1 day, the best fit-curve representing this relationship is given by:

Compressive strength value (MPa) = [−1.19 × slump flow diameter value] + 120;

Compressive strength value (MPa) = [1.82 × V – Funnel time value] + 9;

Compressive strength value (MPa) = [−148.4 × H2/H1 ratio value] + 167;

Compressive strength value (MPa) = [0.71 × Yield stress value] + 18;

Compressive strength value (MPa) = [0.20 × Viscosity value] + 18.

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1. Introduction

The self-compacting concrete (SCC) can be considered as a Bingham fluid. This complex interaction is described in several works [1–6]. Data from recent studies on the mechanical and rheological properties showed that the SCC has a better performance compared to the ordinary concrete [7–17]. Influence of organic products on the rheological properties of concrete mixture was the subject of many studies by authors [1,9,18–26] who showed that the improvement of the rheological and mechanical properties by the superplasticizer is due to the release the water between cement particles and the increase of the water films coating the mixture particles.

Authors [27–29] have showed that the propagation diameter measured by slump-flow test is correlated with the yield stress. The studies presented in [30] shown that the time of flow the mixture measured by V-Funnel test is directly proportional to the plastic viscosity. The passing ability and the resistance to segregation of SCC are evaluated by the L-box and J-ring tests [31–35].

In this work, the water contents of the mixes have a constant water/binder (W/B) ratio of 0.37 and a constant total binder content of 520 kg/m³ (cement amount = 350 kg/m³ and Limestone filler amount = 170 kg/m³). The main objective of this paper is to characterize the dosage effect of superplasticizer on the fresh and hardened properties of the mixes. Then, the relationships between the used rheology tests (slump flow, V-funnel, L-box, yield stress, and plastic viscosity) and compressive strength are deduced.

2. Experimental program

2.1. Concrete mixtures, materials and mixing procedure

Nine types of concrete were made: 1 normally-vibrated concrete and 8 self-compacting concrete, using different percentage of superplasticizer (SP). Chemical composition and physical properties of the cement CEM I 52.5 R and the superplasticizer are given in Table 1. The proportions of mixtures are presented in Table 2. The nomenclature used to identify each type of concrete refers to: self-compacting concrete (SCC), normal (N) type concrete or concrete with different percentage of superplasticizer (SCC-SP). All these concretes are mixed in the same way [36].

The used cement in this study is manufactured by Calcia cement society according to European Standard EN 197–1. The mineral addition is Limestone Filler marketed by Carmeuse France society according to European Standard EN 12620. The mixtures fluidity is ensured by ViscoCrete Krono 20 HE manufactured by Sika France society according to European Standard EN 480-8. The granular skeleton of the mixtures is formed by the crushed sand 0/2 mm and the crushed gravel 4/10 mm with a specific gravity of 2.65.

2.2. Test program and methodology

2.2.1. Tests on fresh SCC properties

The slump flow, V-funnel and L-Box tests were described by the AFGC (French Association of Civil Engineering) and the standard ENARC [37,38]. The values of yield stress and plastic viscosity are measured by a concrete rheometer [36] and summarized in Table 3. The average of five tests was calculated for each property.

2.2.2. Tests on hardened SCC properties

The compressive strengths of various SCCs are presented in Table 4. The average of five tests was measured for each property.

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**Table 1 – Chemical and physical properties of the used materials.**

<table>
<thead>
<tr>
<th></th>
<th>CEM</th>
<th>LF</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃S (%)</td>
<td>67</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C₃S (%)</td>
<td>12</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C₄AF (%)</td>
<td>9</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C₆A (%)</td>
<td>9</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SiO₂ (%)</td>
<td>20.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>2.6</td>
<td>0.04</td>
<td>–</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>5.0</td>
<td>&lt;0.4</td>
<td>–</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>65</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>1.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SO₃ (%)</td>
<td>3.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Loss on ignition (%)</td>
<td>1.2</td>
<td>43.10</td>
<td>–</td>
</tr>
<tr>
<td>Na₂O eq. (%)</td>
<td>0.43</td>
<td>–</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>0.01</td>
<td>–</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>3.15</td>
<td>2.70</td>
<td>1.06</td>
</tr>
<tr>
<td>Blaine (cm²/g)</td>
<td>4750</td>
<td>5550</td>
<td>–</td>
</tr>
<tr>
<td>pH</td>
<td>–</td>
<td>–</td>
<td>6</td>
</tr>
<tr>
<td>Dry extract (%)</td>
<td>–</td>
<td>–</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 2 – Mixture proportions of concretes.**

<table>
<thead>
<tr>
<th>Mix</th>
<th>W/B</th>
<th>Cement (kg/m³)</th>
<th>Limestone filler (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>SP %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>–</td>
</tr>
<tr>
<td>SCC-SP1</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>–</td>
</tr>
<tr>
<td>SCC-SP2</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.3</td>
</tr>
<tr>
<td>SCC-SP3</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.4</td>
</tr>
<tr>
<td>SCC-SP4</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.5</td>
</tr>
<tr>
<td>SCC-SP5</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.6</td>
</tr>
<tr>
<td>SCC-SP6</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.7</td>
</tr>
<tr>
<td>SCC-SP7</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>0.8</td>
</tr>
<tr>
<td>SCC-SP8</td>
<td>0.37</td>
<td>350</td>
<td>170</td>
<td>890</td>
<td>900</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 3 – Results of the mixture fresh properties.

<table>
<thead>
<tr>
<th>Mixtures SCC’s</th>
<th>Slump flow diameter (cm)</th>
<th>V-Funnel flow time (s)</th>
<th>L-Box H2/H1 ratio</th>
<th>Yield stress (Pa)</th>
<th>Viscosity (Pa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>25</td>
<td>–</td>
<td>–</td>
<td>85.8</td>
<td>288</td>
</tr>
<tr>
<td>SCC-SP1</td>
<td>64.2</td>
<td>20.8</td>
<td>0.812</td>
<td>39.44</td>
<td>139.36</td>
</tr>
<tr>
<td>SCC-SP2</td>
<td>66.56</td>
<td>17</td>
<td>0.86</td>
<td>33.06</td>
<td>127.64</td>
</tr>
<tr>
<td>SCC-SP3</td>
<td>68.76</td>
<td>13.6</td>
<td>0.894</td>
<td>23.88</td>
<td>78.44</td>
</tr>
<tr>
<td>SCC-SP4</td>
<td>73.72</td>
<td>10</td>
<td>0.904</td>
<td>21.96</td>
<td>56.42</td>
</tr>
<tr>
<td>SCC-SP5</td>
<td>78.28</td>
<td>8.4</td>
<td>0.932</td>
<td>12.86</td>
<td>37.88</td>
</tr>
<tr>
<td>SCC-SP6</td>
<td>81.18</td>
<td>8</td>
<td>0.968</td>
<td>5.76</td>
<td>24.64</td>
</tr>
<tr>
<td>SCC-SP7</td>
<td>83.76</td>
<td>7.8</td>
<td>1</td>
<td>4.12</td>
<td>19.68</td>
</tr>
<tr>
<td>SCC-SP8</td>
<td>86.16</td>
<td>6.6</td>
<td>1</td>
<td>2.24</td>
<td>18.16</td>
</tr>
</tbody>
</table>

Table 4 – Compressive strength on 160 mm diameter × 320 mm high cylindrical specimens.

<table>
<thead>
<tr>
<th>Mixtures SCC’s</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 day</td>
</tr>
<tr>
<td>N</td>
<td>29.4</td>
</tr>
<tr>
<td>SCC-SP1</td>
<td>45.2</td>
</tr>
<tr>
<td>SCC-SP2</td>
<td>50.64</td>
</tr>
<tr>
<td>SCC-SP3</td>
<td>35.3</td>
</tr>
<tr>
<td>SCC-SP4</td>
<td>32.24</td>
</tr>
<tr>
<td>SCC-SP5</td>
<td>29.24</td>
</tr>
<tr>
<td>SCC-SP6</td>
<td>26.64</td>
</tr>
<tr>
<td>SCC-SP7</td>
<td>18.88</td>
</tr>
<tr>
<td>SCC-SP8</td>
<td>15.04</td>
</tr>
</tbody>
</table>

Finally, Table 3 and Fig. 4 show that the measurement of yield stress and plastic viscosity decreases with the dosage of SP [39–41].

The values of Slump flow diameter and H2/H1 ratio increase with the increase of the superplasticizer amount. On the other, the increase of superplasticizer decrease the V-funnel flow time, the yield stress and the plastic viscosity values. This improvement of the rheological and mechanical properties is due to the release the water between cement particles and the increase of the water films coating the mixture particles.

3.2. Hardened properties of SCC

Compressive strength of the control mixture (N) at 1 day is of 29.4 MPa and it increases to 50.8 MPa at 28 days. Firstly, Table 4 shows that the SCC-SP1 represents the best mechanical characteristics as compared to other SCCs (the compressive strength is about 74.4 MPa). In a general way, Table 4 shows that the compressive strength decreases with the dosage of SP (Fig. 5).

3.3. Correlation between rheological and mechanical properties

According to Tables 3 and 4, for a same water/binder ratio, when the rheology of the mixes improved, the hardened properties of the self-compacting concrete mixes decrease. The relationship between the test results on workability and the 1, 7 and 28 days compressive strengths of self-compacting mixes is described in Figs. 6–10.

Fig. 1 – Results of slump flow test for all mixes.
3.3.1. Correlation between slump flow and compressive strength

Fig. 6 shows that the results obtained in the slump-flow test and the compressive strength was correlated a high level: $R^2 = 0.94$ (28 days), $R^2 = 0.93$ (7 days) and $R^2 = 0.92$ (1 day).

At 7 days, the best fit-curve representing this relationship is given by:

$$\text{Compressive strength value (MPa)} = [-1.59 \times \text{slump flow diameter value}] + 160.$$
Fig. 5 – Values of compressive strength for all mixes.

Fig. 6 – Correlation between slump flow and compressive strength.

3.3.2. Correlation between V-Funnel time and compressive strength

Fig. 7 shows that the results obtained in the V-Funnel test and the compressive strength was correlated a high level: $R^2 = 0.77$ (28 days), $R^2 = 0.88$ (7 days) and $R^2 = 0.83$ (1 day).

At 7 days, the best fit-curve representing this relationship is given by:

\[
\text{Compressive strength value (MPa)} = [2.50 \times V – \text{Funnel time value}] + 12.
\]

Fig. 7 – Correlation between V-Funnel time and compressive strength.

Fig. 8 – Correlation between L-box ratio and compressive strength.

3.3.3. Correlation between L-box ratio and compressive strength

Fig. 8 shows that the results obtained in the L-box test and the compressive strength was correlated a high level: $R^2 = 0.91$ (28 days), $R^2 = 0.95$ (7 days) and $R^2 = 0.95$ (1 day).

At 7 days, the best fit-curve representing this relationship is given by:

\[
\text{Compressive strength value (MPa)} = [-197.17 \times \text{H2/H1 ratio value}] + 222.
\]

Fig. 9 – Correlation between yield stress and compressive strength.
3.3.5. Correlation between plastic viscosity and compressive strength

This relationship is given by:

Compressive strength value (MPa)

\[ Y = 0.30x + 36 \quad R^2 = 0.82 \]

Compressive strength value (MPa)

\[ Y = 0.27x + 23 \quad R^2 = 0.91 \]

Compressive strength value (MPa)

\[ Y = 0.20x + 18 \quad R^2 = 0.85 \]

Compressive strength value (MPa)

\[ Y = 0.30x + 36 \quad R^2 = 0.82 \]

Compressive strength value (MPa)

\[ Y = [1.86 \times \text{slump flow diameter value}] + 195 \]

Compressive strength value (MPa)

\[ Y = [2.71 \times V - \text{Funnel time value}] + 23 \]

Compressive strength value (MPa)

\[ Y = [-223.84 \times H2/H1 \text{ ratio value}] + 261 \]

Indeed, based on the results of our procedure achieved on more than 40 different compositions, the compressive strength of SCC can be estimated from its rheological tests.

Conflicts of interest

The authors declare no conflicts of interest.

References


[10] Sahmaran M, Yaman IÖMT. Transport and mechanical properties of self consolidating concrete with high volume