Abstract

Over time, several mix design methods have been developed to obtain a self-compacting concrete (SCC) with suitable fresh and hardened concrete properties. The very fluid concrete with no need for external compaction is achieved by using a higher powder content and the use of chemical admixtures. Segregation and bleeding are prevented by either an appropriate yield stress, a high plastic viscosity, or intermediate values of both (assuming the Bingham model). To avoid rejection of batches, it is important for an SCC to have a sufficient robustness: the ability to withstand small variations in the mix proportions, material properties, and methods of casting. This experimental study examined the effect of two VMA’s with different working mechanisms on the robustness of SCC mixtures. The influence of attapulgite clay, diutan gum, and no VMA addition on the robustness of the slump flow, V-funnel time, sieve stability, and rheological parameters of a SCC mixture stabilized by a relatively high yield stress and a SCC mixture stabilized by a high plastic viscosity is studied in this experimental program.

1. Introduction

1.1. Self-compacting concrete (SCC)

Self-compacting concrete, also referred to as self-consolidating concrete or SCC, is a highly flowable type of concrete not requiring any external compaction. A high powder content and the use of chemical admixtures in this type of concrete allow the air bubbles to escape under the weight of the fresh concrete after casting. Eliminating the need of labor-intensive and energy-consuming vibration of the fresh concrete, this type of concrete becomes very suitable for the precast industry and applications in which external compaction would result in big difficulties and risks, such as massive foundations or casting with complex formwork [1].

1.2. The robustness of fresh SCC

In spite of the many advantages, self-compacting concrete has not a lot of market share. Besides the fact a high powder content makes concrete more expensive and sometimes more susceptible to shrinkage cracks, the higher sensitivity to small variations in the mix proportions and material properties affects the choice between SCC and vibrated concrete. This higher sensitivity, also referred to as a lower robustness, results from a more complex mix design with in general more constituents and a lower yield stress which increases the risk of segregation [2, 3]. Starting with a proper mix design, the robustness against small changes in the water content can be improved by optimizing the grading curve of the aggregates [4-6], the right choice of superplasticizer [7], and the use of a VMA [5, 8-16]. However, VMA’s can also reduce the robustness of SCC [8, 16].
1.3. The rheology of fresh SCC

As illustrated in the generally accepted graph of appropriate Bingham parameter combinations for SCC (Figure 1, originally made by Olafur and Jon Wallevik [17]), different stability mechanisms can be achieved to meet both the contradictory demands of a sufficient flowability and sufficient stability against segregation and bleeding.

![Figure 1: Range of suitable rheological characteristics of SCC [17]](image)

Results of an earlier experimental study in which no VMA’s were included [18] gave the impetus for the investigation described in this paper. SCC mixtures with a low plastic viscosity and relatively high yield stress (left side of the graph) are mainly stabilized by their high yield stress and therefore especially the robustness of this yield stress is important for the probability of acceptance of these mixtures. The flowability and segregation resistance of SCC mixtures with a high plastic viscosity and a low or even no yield stress (on the right side of the graph) is governed by their high plastic viscosity. The robustness of this high plastic viscosity therefore determines the robustness of such a mixture [18].

This paper investigates whether the influence of two VMA’s on the robustness of a SCC mixture with high yield stress and low plastic viscosity is the same as on a SCC mixture with low yield stress and high plastic viscosity. Changes in the water content of ± 10 l/m³ were applied to the SCC mixtures to study the robustness.

2. Materials and methods

2.1. Materials

All SCC mixtures were made with Portland cement CEM I 52.5 N (density 3116 kg/m³ and a Blaine fineness of 368 m²/kg), limestone powder (density 2674 kg/m³), a PCE superplasticizer (concentration of 35%), Rhine sand, river gravel 2/8, and river gravel 8/16 (density respectively 2575, 2668, and 2658 kg/m³). The grading curves of the aggregates, cement and limestone powder are shown in Figures 1 and 2. The chemical compositions of the cement and limestone filler are given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Cement [%]</th>
<th>Limestone filler [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>63.01</td>
<td>0.00</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>0.00</td>
<td>98.8</td>
</tr>
<tr>
<td>SiO₂</td>
<td>18.55</td>
<td>0.11</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.83</td>
<td>0.04</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.09</td>
<td>0.04</td>
</tr>
<tr>
<td>MgO</td>
<td>1.22</td>
<td>0.32</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.53</td>
<td>0.01</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.97</td>
<td>0.02</td>
</tr>
<tr>
<td>S</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>0.086</td>
<td>&lt;0.008</td>
</tr>
<tr>
<td>L.O.I.</td>
<td>1.24</td>
<td>-</td>
</tr>
<tr>
<td>Insoluble</td>
<td>0.94</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of the cement
Two types of VMA are used in this experimental program: diutan gum and purified attapulgite clay. Diutan gum is a high molecular weight microbial polysaccharide, fixing part of the mixing water with hydrogen bonds. The polymer chains entangle at rest and align during shear flow [9, 19]. Attapulgite clay consists of small needles with negative charges along its main axis and pH-dependent charges at the ends, strongly increasing the floc strength in cement pastes [20, 21].

Figure 1: The particle size distributions of the aggregates

Figure 2: The particle size distributions of the cement and limestone filler

### 2.2. Mix proportions
The mixture compositions of this test program are summarized in Table 2. As recommended by the manufacturer, the dosage of diutan gum was chosen as 0.05% of the water weight and the dosage of attapulgite clay was chosen as 0.15% of the cement weight. When diutan gum was added, the superplasticizer dosage was adjusted in order to obtain an optimum flowability for this mixture. The robustness is studied by changing the water content with ±10 l/m³ water.

### 2.3. Methods
All mixtures are made in a planetary pan mixer of 50 liters using a fixed mixing procedure and timing of the workability tests to eliminate additional influences:

- The aggregates, cement, and limestone powder are mixed for 1 minute;
- The water is added to the mixer and mixing continues for 1 minute;
- The superplasticizer is added and mixing continues for 1 minute. When a VMA is included in the mix design, it is added 30 seconds after adding the superplasticizer during this step;
- 3 minutes of rest;
- Start of the workability tests: measurement of the slump flow, the V-funnel time, the sieve stability index (S.S.I.), the density and air content, and the rheological parameters of the produced mixture.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mix A [kg/m³]</th>
<th>Mix B [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>River gravel 8/16</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>River gravel 2/8</td>
<td>266</td>
<td>265</td>
</tr>
<tr>
<td>Rhine sand 0/5</td>
<td>835</td>
<td>834</td>
</tr>
<tr>
<td>Limestone filler</td>
<td>160</td>
<td>250</td>
</tr>
<tr>
<td>Cement</td>
<td>390</td>
<td>350</td>
</tr>
<tr>
<td>Water</td>
<td>195</td>
<td>175</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>1.86</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Table 2: Mixture compositions

Figure 3: The rotational velocity profile applied during the rheometer tests.
The rheological parameters were determined in an ICAR rheometer with a 6-bladed vane with a diameter of 127 mm and a height of 127 mm in a ribbed cylindrical bucket with a diameter of 286 mm. The torque necessary to rotate the vane according to a fixed rotation speed profile including a segregation point, as illustrated in Figure 3, is measured. The data measured during the last 2 seconds of every rotational velocity step was used to calculate the Modified Bingham rheological parameters [22] (Eq. 1). When plug flow occurred, a plug flow correction was applied during the analysis [22].

\[ \tau = \tau_0 + \mu \cdot \gamma + c \cdot \gamma^2 \]  
(Equation 1)

3. Results and discussion

Table 3 summarizes the fresh properties of the reference mixtures A and B in which diutan gum, attapulgite clay, and no VMA were added. Two mixtures in which diutan gum is added to mix B were considered: one with a lower superplasticizer dosage which was very sensitive to a decrease of the water content, and one with a higher superplasticizer dosage which was very sensitive to an increase of the water content and suffered from bleeding.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>SP dosage [l/m^3]</th>
<th>Slump flow [mm]</th>
<th>V-funnel time [s]</th>
<th>S.S.I. [%]</th>
<th>Densit y [kg/m^3]</th>
<th>Air conten t [%]</th>
<th>Yield stress (\tau_0) [Pa]</th>
<th>Mod. B. pl. visc. (\mu) [Pa s]</th>
<th>Mod. B. 2nd ord. coëff. (c) [Pa s](^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix A</td>
<td>1.86</td>
<td>720</td>
<td>3.8</td>
<td>10.8</td>
<td>2350</td>
<td>1.6</td>
<td>29</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>Mix B</td>
<td>4.00</td>
<td>705</td>
<td>9.5</td>
<td>14.5</td>
<td>2360</td>
<td>2.0</td>
<td>0</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Mix A – Diutan Gum</td>
<td>3.29</td>
<td>680</td>
<td>7.6</td>
<td>11.9</td>
<td>2350</td>
<td>1.8</td>
<td>37</td>
<td>69</td>
<td>0</td>
</tr>
<tr>
<td>Mix B – Diutan Gum 1</td>
<td>6.57</td>
<td>695</td>
<td>14.8</td>
<td>15.0</td>
<td>2360</td>
<td>2.0</td>
<td>23</td>
<td>81</td>
<td>6</td>
</tr>
<tr>
<td>Mix B – Diutan Gum 2</td>
<td>8.00</td>
<td>785</td>
<td>10.9</td>
<td>21.2</td>
<td>2370</td>
<td>1.7</td>
<td>8</td>
<td>49</td>
<td>4</td>
</tr>
<tr>
<td>Mix A – Attapulgite clay</td>
<td>2.00</td>
<td>675</td>
<td>4.6</td>
<td>8.2</td>
<td>2360</td>
<td>1.7</td>
<td>51</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>Mix B – Attapulgite clay</td>
<td>3.14</td>
<td>660</td>
<td>10.1</td>
<td>9.4</td>
<td>2370</td>
<td>2.6</td>
<td>34</td>
<td>60</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3: The fresh state properties the SCC mixes

The robustness, defined as the capacity of a mixture to tolerate small changes in the water content (±10 l/m^3), was evaluated using three parameters for each workability test: the change of the test response (e.g. ASF), the change of the test response per liter water (e.g. ∆SF / 20 l/m^3) and the ratio of the interval divided by the mean value (e.g. ∆SF / SF\(_{ref}\)). The plastic viscosity listed in Table 4 is the first derivative of the shear stress to the shear rate at 5 s\(^{-1}\) for the mixtures having a Modified Bingham rheological behavior (Equation 2). All test results are plotted in Figures 4 to 7.

\[ \eta_s s^{-1} = \mu + 2 \cdot c \cdot 5 s^{-1} \]  
(Equation 2)
As illustrated in Figure 4, mixtures A, with a high yield stress and low plastic viscosity \( \eta_{5, s^{-1}} \) (the first derivative of the shear stress to the shear rate at 5 s\(^{-1}\)) react different on the inclusion of a VMA in the mix design than the mixtures B, with a high plastic viscosity and low yield stress. The robustness of the yield stress of mixtures A increases significantly when a VMA is included in the mixture. Both diutan gum and attapulgite clay had only a small influence on the robustness of the plastic viscosity of mixtures A. When the superplasticizer dosage was adjusted in order to reach a similar flowability as the original mixture B (low yield stress and high plastic viscosity), both VMA’s decreased the robustness of yield stress and plastic viscosity for mixtures B. Especially a small decrease of the water content had a pronounced effect on the rheology of mixtures B. In order to counteract this high sensitivity, another mixture B was tested, including diutan gum and a larger dose of superplasticizer (slump flow 785 mm). This mixture had an improved robustness of the Bingham parameters, but suffered from severe bleeding and segregation.
Similar trends are observed for the workability tests:

- Slump flow (Figure 5): Adding a VMA increased the slump flow robustness of the mixture A with a high yield stress and low plastic viscosity and decreased the slump flow robustness of the mixture B with a high plastic viscosity and minimal yield stress.

- V-funnel time (Figure 6): Although all other mixtures had a similar V-funnel robustness, the V-funnel robustness of mixture B is significantly affected when diutan gum is added to the mix design: a very viscous mixture was obtained when the water dosage is decreased with 10 l/m³. When the same mixture was produced with a higher dosage of superplasticizer, a similar robustness as for the original mixture was measured.

- S.S.I. (Figure 7): The use of VMA's in mixture A resulted in a more sensitive S.S.I. to an excess of water and a less sensitive S.S.I. to a reduction of the amount of water, resulting in a more or less similar robustness of the sieve stability test. The measured S.S.I. of mixtures B were above the maximum limits for SCC when VMA's were included in the mix design. However, no pronounced segregation or bleeding were observed during the workability tests. Only 'Mixture B - Diutan Gum 2' with a very high superplasticizer dosage suffered from severe bleeding and segregation.
Diutan gum and purified attapulgite clay have different working mechanisms in SCC. The diutan gum polysaccharide molecules dissolve in the mixing water, develop attractive forces, and intertwine with each other [9, 19]. This increases the viscosity of the mixing water at rest, resulting in an increased yield stress and plastic viscosity of the concrete mix. Attapulgite clay particles are charged needles which increase flocculation rate and yield stress of the concrete mixture [20, 21]. The influence of the VMA's on the rheology is partly compensated by an increased superplasticizer dosage. Because mixtures B with a low yield stress and high plastic viscosity are already on the limit of bleeding, an increase of the superplasticizer dosage endangers the stability of the mixtures. The robustness of these mixtures decreases because of the more narrow range of acceptable superplasticizer dosage limited by excessive bleeding and a too viscous mixture. Therefore, small variations in the water content affect this delicate equilibrium and a decrease of the robustness of these mixtures is observed.

For mixtures with a high yield stress and low plastic viscosity, the larger amount of free water allows the fixation of part of the mixing water. The mixtures are less sensible to bleeding and therefore an increase of the superplasticizer content causes less problems. Diutan gum increases the plastic viscosity of SCC, providing more resistance to changes of the water content compared to attapulgite clay.

4. Conclusions
The influence of VMA's on the robustness of the slump flow depends on the mechanisms ensuring the stability of the mixture. Mixtures with a high yield stress and low plastic viscosity, which include more free water, benefit from the fixation of part of the water by diutan gum or an increased floc strength originating from the purified attapulgite clay. The reduced flowability can be compensated with an increase of the superplasticizer content. When VMA’s are included in mixtures with a low yield stress, already on the limit of bleeding, an increase of the superplasticizer dosage reduces the capacity of the mixture to adsorb small variations in the water content.

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6. References


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