THE INFLUENCE OF THE TEMPERATURE ON THE RHEOLOGICAL PROPERTIES OF SELF-COMPACTING CONCRETE

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ABSTRACT: An important factor, which up to now has not received the attention it deserves, is the temperature of fresh Self-Compacting Concrete (SCC). Compared with vibrated concrete, the range of suitable temperatures for fresh concrete is not as broad in the case of SCC. Both, low and high temperatures can trigger phenomena in fresh concrete which make it impossible to cast the concrete properly. The problem here is that the transition from suitable to unsuitable consistencies is not smooth but very abrupt. All it takes for the concrete to lose its self-compacting properties completely is a 1°C difference in the temperature of the fresh concrete. In practice, the sensitivity to temperature is often attributed to the type of the applied superplasticizer based on polycarboxylate-ether (PCE). Therefore investigations with different types of PCE were carried out. The investigated PCE differ with regards to their molecular structures, i.e. its different length of the main (backbone) and side chains. In this paper the results of the investigations are presented.

KEYWORDS: Self-Compacting Concrete, superplasticizer, rheology, temperature

1. INTRODUCTION

Owing to its manifold fields of application the importance of Self-Compacting Concrete (SCC) increases /BRA01a, BRA01b, BRA01c/. Apart from the mechanical properties and the durability, the rheological properties are the main features of an SCC. Rheological properties adapted to the building measure assure that, under the given preconditions, the SCC fills the formwork without segregation and a vibration is not necessary /BRA03a, UEB00/. The influence of the fresh concrete temperature on these fresh concrete properties of SCC was, however, up to now, only scarcely examined /HAU00/. A variation of the fresh concrete temperature is the precondition which can lead to an unsuitable SCC. If the fresh concrete temperature rises, a liquefying of the SCC maybe induced, which can lead to sedimentation of the coarse aggregate and to a cloudy surface structure (see figure 1), as well as to a total segregation of the SCC. If the fresh concrete temperature decreases for instance due to low outdoor temperatures and/or a low temperature of the formwork, a stiffening of the mixture maybe observed and the SCC does not accurately de-air (see figure 2). These phenomena may occur when the fresh concrete temperature decreases or increases by only a few degrees. In practice, superplasticizers (SP) on the basis of polycarboxylate-ether (PCE), which enable the production of SCC in the first place, are held responsible for this behaviour, without knowing the exact causes.

PCE are complex molecules which are build from several functional groups with main-(backbone) and side chains of varying lengths. In contrast to usual plasticizers based on lignin, naphthalene or melamine, which mainly induce an electrostatic effect, the action of the PCE-superplasticizers is additionally based on a steric effect /HAU00/.
Owing to the practical experience with SCC, a very different behaviour of the SCC is known depending on the PCE used as well as on the fresh concrete temperature. For the application of these superplasticizers in SCC, it is, however, important to know the temperature-induced properties of the different PCEs. Therefore, in the following the results of systematic investigations concerning the temperature-sensitivity of different PCEs are presented.

2. INVESTIGATIONS

The investigations were conducted on a mortar for SCC. This is an SCC without coarse aggregate and with a maximum grain size of 2 mm. This refers to a mortar of a SCC with a general technical approval, which one needs to use this kind of concrete in Germany /BRA02/. For the concrete with this mortar, experiences of many site castings with different outdoor temperatures exist. An ordinary Portland cement CEM I 32,5 R according to DIN EN 197-1 /DIN01a/ and a limestone powder according to DIN 4226-1 and DIN EN 197-1 /DIN01a, DIN01b/ were used. The mix proportion of the mortar is given in table 1. The investigations were conducted with six different superplasticizers based on PCE (SP A - F, see table 2). The superplasticizers differ with regards to the length of the backbone and the side chains, respectively (see table 2). SP A and B have the same main-chain and side-chain lengths and differ only regarding their side-chain density. SP B has a higher side chain density than SP A. SP C is a special superplasticizer which is to ensure a high early strength for the production of precast elements. SP A, B and C are defoamed PCE raw materials, SP D is a PCE raw material, which incorporates no defoamer, so that the defoamer was added in the laboratory. SP E and F are ready-mixed formulations which are available on the German market. The distinctly lower content of ingredients and the higher dosage of SP E and F also indicate that these are ready-mixed formulations (see table 2). The water content of the superplasticizers was taken into consideration in the mortar mix design.
Table 1: Mix proportion of the investigated SCC mortar

<table>
<thead>
<tr>
<th>Component/Value</th>
<th>by Mass</th>
<th>by Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/m³</td>
<td>m³/m³</td>
</tr>
<tr>
<td>1 Cement</td>
<td>463</td>
<td>0.152</td>
</tr>
<tr>
<td>2 Limestone Powder</td>
<td>432</td>
<td>0.161</td>
</tr>
<tr>
<td>3 Water</td>
<td>255</td>
<td>0.255</td>
</tr>
<tr>
<td>4 Sand 0 – 2 mm</td>
<td>1097</td>
<td>0.417</td>
</tr>
<tr>
<td>Air Content¹)</td>
<td>-</td>
<td>0.015</td>
</tr>
<tr>
<td>w/c</td>
<td>0.55</td>
<td>1.68</td>
</tr>
<tr>
<td>w/p (&lt; 125 µm)</td>
<td>0.28</td>
<td>0.81</td>
</tr>
</tbody>
</table>

¹) theoretical air content

Table 2: Characteristics of the superplasticizers and fresh mortar properties

<table>
<thead>
<tr>
<th>Superplasticizer</th>
<th>Qualitative Length</th>
<th>Ingredients</th>
<th>Dosage¹)</th>
<th>Slump Flow¹)</th>
<th>V-Funnel Time¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Backbone</td>
<td>Side Chain</td>
<td>Content</td>
<td>% by volume</td>
<td>% by mass²)</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SP A</td>
<td>medium</td>
<td>short</td>
<td>35</td>
<td>2.40</td>
<td>275</td>
</tr>
<tr>
<td>SP B</td>
<td>medium</td>
<td>short</td>
<td>50</td>
<td>3.00</td>
<td>270</td>
</tr>
<tr>
<td>SP C</td>
<td>short</td>
<td>long</td>
<td>30</td>
<td>2.14</td>
<td>270</td>
</tr>
<tr>
<td>SP D</td>
<td>long</td>
<td>medium</td>
<td>40</td>
<td>2.51</td>
<td>265</td>
</tr>
<tr>
<td>SP E</td>
<td>medium</td>
<td>short + long</td>
<td>18</td>
<td>4.20</td>
<td>265</td>
</tr>
<tr>
<td>SP F</td>
<td>medium</td>
<td>long</td>
<td>17</td>
<td>5.28</td>
<td>275</td>
</tr>
</tbody>
</table>

¹) fresh mortar temperature 20°C
²) of cement

With this superplasticizer the mortar mixtures were adjusted to achieve a definite mortar consistency at a fresh mortar temperature of 20°C, characterised by a mortar slump flow of 270 mm and a flow time through the mortar V-funnel of 7 s. The effective slump flows and V-funnel times are given in table 2. With the dosage of superplasticizer necessary for the workability at 20°C the investigations at the other mortar temperatures of 5, 10, 15 and 30°C have been carried out. The fresh mortar temperature of 5°C indicates a lower limit which is usually not reached in practice in Germany.

The examinations were carried out using a rotation viscometer Viskomat NT. This device is a modified coaxial cylinder viscometer whose inner cylinder was replaced by a concentric measuring paddle (see figure 3). This entails the advantage that sedimentation can not occur. Furthermore, mortars with a grain size of 2 mm can be investigated because a wall-slip effect is minimized. The Viskomat NT is equipped with a tempering device, so that steady state conditions are ensured during the investigation time of e. g. 90 min. The investigations
described in this paper were conducted with a constant shear rate (single point investigation). This constant shear profile was chosen to visualise continuously the liquefying and stiffening effect. The shear stress was applied with a constant shear rate of 120 rpm. This relatively high shear stress was chosen in order to quickly dissolve a possible initial flocculation and to compare the results with other investigations.

![Figure 3: Measuring principle Viskomat NT](image)

A transfer of the results into the practice was ensured by means of separate investigations, which are described in /BRA02, UEB03, BRA03b/.

3. RESULTS

When examining SCC mortars with a single point investigation using a constant shear rate, the torque always shows a characteristic course during the investigation time of 90 minutes (see figure 4). At the beginning of the test the mixtures show a liquefying displayed by a decreasing torque, the so-called liquefying period. After the liquefying period a steady-state period is observed, where the torque is constant. Finally, an increase of the torque is visible caused by a stiffening of the mixture. The different periods are more or less marked, depending on the superplasticizer and the temperature.

Figure 5 shows the course of the torque up to 90 minutes under laboratory conditions at 20°C. Starting the examinations the torque of all mixtures amounted to approx. 60 to 80 Nmm. The mixtures with SP A, B and C show a distinct liquefying. The reason for this behaviour is probably a delayed adsorption of the superplasticizer on the surface of the cement particles. This liquefying of SCC with superplasticizers based on the raw materials of SP A, B and C is also observed when this SCCs are applied on the building site, depending on the cement. SP A and SP B - both have short side chains - keep their consistency constant until the end of the investigation and show no stiffening. The mixture with SP F shows a slight, the mixture with SP C a strong and the mixture with SP E a very strong stiffening. The early stiffening of SP E was regular, as already mentioned. The mixture with SP E remains in the steady-state section for only 10 minutes. Therefore using this superplasticizer it is difficult to cast the
concrete in practice at 20°C. SP C, SP E and SP F possess long side chains. This may indicate that long side chains lead to an early stiffening. A possible reason may be that the steric effect is more stable with short side chains than with long side chains. Regarding its liquefying and stiffening, the mixture with SP D is the most balanced and remains in the steady-state period during the entire investigation. An influence of the higher density of side chains of SP B to SP A cannot be verified.

![Characteristic course of the torque during the single point investigation](image)

**Figure 4:** Characteristic course of the torque during the single point investigation

![Rheological investigation of different superplasticizers (SP) with a constant shear rate at a fresh mortar temperature of 20°C](image)

**Figure 5:** Rheological investigation of different superplasticizers (SP) with a constant shear rate at a fresh mortar temperature of 20°C
In figure 6 the results at a fresh mortar temperature of 30°C are shown. With a range of approx. 50 Nmm, the initial values for all mixtures besides SP F are lower than those of a fresh mortar temperature of 20°C. The mixture with SP F has in general a higher viscosity than the other mixtures. The liquefying of mixtures with SP A, B and C is less distinct than at 20°C, so that at a higher temperature the adsorption processes of the superplasticizer on the surface of the cement particles seems to be accelerated. Mixture SP B shows no stiffening, SP A and SP D only a slight one. The higher side-chain density of SP B seems to have a positive influence reaching a constant consistency. For a duration of approx. 20 minutes, the mixtures with SP C and SP F remain in the steady-state period, which is sufficient for the application in a precast element plant. After 30 minutes a very strong stiffening is observed. During the entire investigation time, the mixture with SP E stiffens, so that this mixture is not applicable in practice at a temperature of 30°C. The stiffening of this mixture is so strong that the results of this investigation should not be quantified after 70 minutes duration.

It is well known from practice that at fresh concrete (mortar) temperatures of approx. 15°C, superplasticizers which are sensitive to low temperatures change their effectiveness. This becomes obvious with SP C which delivers a very high torque of 160 Nmm at the beginning of the test (see figure 7). The torque of SP F amounts to approx. 110 Nmm, of all others at approx. 80 Nmm, respectively, so the initial values are about 20 Nmm higher compared to the values at 20°C. Thus, the investigations show that a lower fresh mortar temperature at an early fresh mortar stadium induces a higher viscosity, a higher temperature induces a lower viscosity.

This is confirmed by the investigations at a fresh mortar temperature of 10°C (see figure 8). The initial torque again is slightly higher than that at a fresh mortar temperature of 15°C. The liquefying effect is now very distinct for all examined superplasticizers. The adsorption of the superplasticizers on the surface of the cement particles seems to be strongly influenced by the temperature. With decreasing temperature the liquefying effect increases, whereas the duration of the liquefying period remains nearly constant.
The investigations show that SP C and SP F are very sensitive to low temperatures (see figure 8). At the start of the viscometer tests, the initial torque values are quite higher at low temperatures than for the other superplasticizers. In the entire testing programme only these superplasticizers have long side chains. The length of the side chains not only influences the stiffening behaviour of these mixtures but also their sensitivity to cold temperatures. This is possibly caused by a diminished steric effect in the case of long side chains. Therefore a delayed liquefying occurs.
The stiffening of these mixtures (SP C, SP F) is less distinct than at higher temperatures (see figure 8).

Essentially, this is confirmed by the test on mortars with a temperature of 5°C (see figure 9). Contrary to tests with higher fresh mortar temperatures, a stiffening of the mixture with SP E can no longer be discerned.

![Figure 9](image.png)

*Figure 9: Rheological investigation of different superplasticizers (SP) with a constant shear rate at a fresh mortar temperature of 5°C*

It follows that SP E is suitable for temperatures lower than 15°C, SP C and SP F are suited for temperatures above 15°C. SP A, B and D are applicable in the complete range of the investigated temperatures, when the temperature-depending liquefying of SP A and SP B, possibly caused by a delayed adsorption of the superplasticizers on the surface of the cement particles, is taken into account.

4. **SUMMARY AND OUTLOOK**

The investigations demonstrate, that the superplasticizers (PCE) feature very different rheological characteristics at different temperatures differing from usual properties of other plasticizers. So SP A, B und C tend very much to liquefy in combination with the cement used. This may be caused by the temperature-depending delay of the adsorption of the superplasticizer on the surface of the cement particle. Low temperatures have a distinct effect on this delay.

SP A, B and D show a slight stiffening at all temperatures. At temperatures above 15°C, SP E shows such a strong stiffening that it cannot be applied in practice. This behaviour seems to depend on the lengths of the side chains. SP C, E and F, with their long side chains, feature an early stiffening, whereas the superplasticizers with only short side chains cause a constant consistency of the mortar. This might be due to the steric effect which is more stable for superplasticizers with short side chains than that with long side chains.
On the other hand the mixtures with SP C and SP F are very sensitive to low temperatures. This behaviour seems also to depend on the lengths of the side chains. Superplasticizers with only long side chains (SP C, SP F) are much more sensitive to cold temperatures than superplasticizers with short side chains or superplasticizers with a combination of short and long side chains. A possible reason for this behaviour is caused by a diminished steric effect in the case of long side chains, so that a delayed liquefying occurs.

The conducted single point investigations with a constant shear rate show that this method is well-suited to characterise the liquefying and stiffening. It is, however, not suited to quantify the influence of the temperature on the rheological characteristics, the yield value and the dynamic viscosity. Here, multipoint investigations must be carried out. The results of these tests will be presented in /BRA03c/.

Furthermore, the influence of the cement has to be examined, e.g. the cement type and the chemical and mineralogical composition of the clinker phases.

On the whole the investigations demonstrate that two decisive conditions must be fulfilled when choosing a superplasticizer for the production of SCC. First the effectiveness of the superplasticizer with the chosen cement must be proven. Second the superplasticizer has to be carefully chosen with regards to temperatures occurring in the respective application case to ensure a proper casting of the SCC.

5. ACKNOWLEDGEMENTS

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