- SELF-COMPACTING CONCRETE -
PRESSURE ON FORMWORK
AND ABILITY TO DEAERATE

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SUMMARY

Self-compacting concrete (SCC) is already common in the fabrication of precast concrete products. This success is based on the high quality of these products as well as the reached economic advantages. To make SCC interesting for other applications, in particular as a ready mix concrete, the higher material expenses in comparison to normal concrete must be reduced. Further, it is necessary to cast SCC on the building site reliable and with the accepted level of quality. Relating to this, the ability to deaerate is very important. The expenses merely due to cosmetic work on the bubble holes on the concrete-surfaces are significant. Besides the higher material-expenses (cement, fly ash, superplasticizer), an extra charge for the stronger formwork has to be considered so far, primarily in case of placing on building site. The necessity of stronger formwork results from assuming a hydrostatic concrete pressure in the calculation.

1. INTRODUCTION

A intensive development of self-compacting concrete began approximately 20 years ago in Japan. The new product SCC represents a milestone in the concrete research. Essential technical and economic advantages were achieved by the loss of the additional mechanical compaction and the high flowability. The SCC must fill the formwork completely without large bubbles, enclose the reinforcement, deaerate with the force of gravity and must not segregate.
The following technical advantages can be listed for SCC, when professionally applied:

- enlargement of the architectural variety through realisation of any forms
- better quality in the area of reinforcement concentration
- high und very homogeneous quality of the concrete, very dense concrete-structure
- optically appealing surface
- durability against chemically medias, early strength

Also the economic reasons for the application of SCC are very interesting:

- simplification of the casting process, increase of the moulding-performance
- increase of efficiency, reduction of staff
- improvement of working-conditions
- advantages for the environment and the conditions at work (noise)
- lower investment costs and higher lifespan of the formwork

It can be stated that the rationalisation in the process of fabrication, connected with an increase of the product-quality, will compensate the higher material costs. Above all, SCC is applied in precast plants, where special conditions are available (regarding the procurement of the material, the concrete production and processing as well as the supervision of the quality).
2. PRESSURE ON FORMWORK

2.1 General remarks on formwork pressure

Talking about fresh conventional concrete, approximately eighteen parameters influence the pressure on vertical formwork. All parameters, according to the respective conditions, affect the pressure with different intensity [1] (table 1). The parameters 1.3, 1.4, and 2.4 will become void if SCC is applied.

Tab. 1: Influences on the formwork pressure

<table>
<thead>
<tr>
<th>1. First-order</th>
<th>2. Second-rate</th>
<th>3. Third-rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 velocity of pouring</td>
<td>2.1 time of solidification</td>
<td>3.1 type of casting</td>
</tr>
<tr>
<td>1.2 density of concrete</td>
<td>2.2 cement-additives</td>
<td>3.2 aggregates and maximal grain size</td>
</tr>
<tr>
<td>1.3 type of compaction</td>
<td>2.3 pore water pressure</td>
<td>3.3 type of cement</td>
</tr>
<tr>
<td>1.4 type of vibration/depth of vibration</td>
<td>2.4 time of vibration</td>
<td>3.4 temperature of the environment</td>
</tr>
<tr>
<td>1.5 consistency of concrete</td>
<td>2.5 design of the formwork</td>
<td>3.5 height of pouring and total height</td>
</tr>
<tr>
<td>1.6 temperate of the fresh concrete</td>
<td>2.6 permeability of the formwork</td>
<td>3.6 construction of reinforcement</td>
</tr>
</tbody>
</table>

The concrete pressure on the formwork extends from the time of placing to the internal stability of the structure. It depends on the existing vertical pressure and the ratio of the horizontal to the vertical pressure (\(\lambda\)). The formwork pressure increases with the rising of the concrete level (respective vertical pressure), the increment of the pressure is declining in the process of the setting and solidification (reduction of \(\lambda\)). For the self-compacting concrete, in the time of placing, \(\lambda\) is approximately 1.

To calculate formwork-pressure, so far only approximated and on empirical values based methods and standards are available. The calculation for normal concrete takes differently parameters into account (figure 1). The most important parameter is always the pouring velocity.

Fig. 1: Analysis of formwork pressure for a flowable consistency according to various design rules, specific gravity of fresh concrete $\gamma = 25$ kN/m³, temperature of fresh concrete $T = 15^\circ$, end of solidification $t_E = 5$ h

2.2 Formwork pressure with application of SCC

Using SCC, the calculation basing on normal concrete are not valid any more. The absence of the vibration is decreasing the pressure; the changed consistency does increase the loads. An important factor beside the changed consistency is the behaviour of setting. It can be influenced significantly by the use of very effective superplasticizers and stabilizers.

The known publications often report about approximately hydrostatic pressure distribution on formwork (assumption of the concrete as liquid) [2]. But sometimes reductions of up to 50% are observed [3]. Vanhove [2] represents interesting calculations, based on the silo theory (friction between the surface of formwork and the concrete).
2.3 Test series

The project, to verify the influence of the casting velocity on formwork-pressure, is supported by the German Committee for Reinforced Concrete (DAfStb). Eleven experimental tests on slender columns have been proceeded to verify the formwork pressure. Ten of the columns were reinforced. All columns had the same cross-section 30/30 cm as well as a uniform height of 4,0 m.

The test-program was divided in three series I, II and III. The varied parameters are represented in table 2.

Series I: Influence of the rising velocity on the formwork-pressure
Series II: Influence of the slump flow value in interaction with the velocity
Series III: Conventional compaction by vibration and the influence of the reinforcement on formwork-pressure

Tab. 2: System of the test series I - III

<table>
<thead>
<tr>
<th>Test series</th>
<th>Nr.:</th>
<th>Velocity of pouring (concrete level in the formwork) (v) [m/h]</th>
<th>Slump flow value (sm – without J-ring) at the begin of pouring [cm]</th>
<th>Time of spreading (t_{500}) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1a</td>
<td>12,5</td>
<td>ca. 75</td>
<td>2,5</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>25,0</td>
<td></td>
<td>2,0</td>
</tr>
<tr>
<td></td>
<td>3a</td>
<td>40,0</td>
<td></td>
<td>2,0</td>
</tr>
<tr>
<td></td>
<td>4a</td>
<td>80,0</td>
<td></td>
<td>2,0</td>
</tr>
<tr>
<td></td>
<td>5a</td>
<td>160,0</td>
<td></td>
<td>2,5</td>
</tr>
<tr>
<td>II</td>
<td>2b</td>
<td>25,0</td>
<td>ca.70</td>
<td>3,0</td>
</tr>
<tr>
<td></td>
<td>2c</td>
<td>25,0</td>
<td>ca.60</td>
<td>5,0</td>
</tr>
<tr>
<td></td>
<td>3b</td>
<td>40,0</td>
<td>ca.70</td>
<td>3,0</td>
</tr>
<tr>
<td></td>
<td>4c</td>
<td>60,0</td>
<td>ca.55</td>
<td>6,0</td>
</tr>
<tr>
<td>III</td>
<td>2b(^1)</td>
<td>25,0</td>
<td>ca.70</td>
<td>3,0</td>
</tr>
<tr>
<td></td>
<td>5r(^2)</td>
<td>160,0</td>
<td>(a = 47,5 \text{ cm (K3)})</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\) Column without reinforcement  
\(^2\) Compaction, using concrete vibrators
The speeds of pouring (columns $v = 25$ to $80$ m/h and walls $v = 10$ to $40$ m/h) are orientated on the values in the practice.

In all these tests the same mixture has been used. It was only negligibly changed (the content of superplasticizer) to influence the slump flow. The concrete took place with a free height of fall up to 4,3 m.

Tab. 3: Mix-design of SCC and normal concrete

<table>
<thead>
<tr>
<th>1 m³ fresh concrete</th>
<th>Normal concrete</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II 52,5R</td>
<td>350 kg</td>
<td>350 kg</td>
</tr>
<tr>
<td>Fly ash</td>
<td>90 kg</td>
<td>90 kg</td>
</tr>
<tr>
<td>Water</td>
<td>190 l</td>
<td>190 l</td>
</tr>
<tr>
<td>SP 1</td>
<td>-</td>
<td>6 l</td>
</tr>
<tr>
<td>SP 2</td>
<td>6 l</td>
<td>-</td>
</tr>
<tr>
<td>Sand 0/2</td>
<td>834 kg</td>
<td>834 kg</td>
</tr>
<tr>
<td>Gravel 2/8</td>
<td>420 kg</td>
<td>420 kg</td>
</tr>
<tr>
<td>Gravel 8/11</td>
<td>465 kg</td>
<td>465 kg</td>
</tr>
</tbody>
</table>

The points of measurement were placed at a distance of 4 m (M1), 3 m (M2), 2 m (M3), and 1 m (M4) related to the top of the column.
2.4 Results

In the test series I almost hydrostatic pressure was determined at all points of measurement. Here the slump flow value was approximately 75 cm. Only for the column with a placing time of 25 minutes (v = 12.5 m/h), a pressure reduction of about 23 percentages was measured.

In the test series II, with a defined velocity of 25 m/h - in correlation with decreasing the slump flow value - a reduction of the pressure was determined. With a slump flow sm = 71 cm, a reduction of the maximum pressures of about 40 percentages - in comparison with the hydrostatic value - was observed (column II/2b, M1) (figure 4). Reducing the slump flow, the influence of velocity on the pressure increases significant.

Fig. 4: Formwork pressure when varying the slump flow value (test series II, point of measurement M1)
2.5 Proposal for the calculation

Based on the test result, a proposal for the calculation, founded on the regulations of the DIN 18 218 [4], was developed. The proposal is well manageable for the practical application and takes into account the pouring velocity as well as the setting behaviour of the fresh concrete. The advantageous influences of the silo effect and the reinforcement are not included.

The idea of the calculation model is that at the end of solidification not the pressure itself but the ratio of horizontal to vertical pressure \( \lambda = 0 \).

\( \lambda(t) \) - Describes a function depending on time:

\[
\lambda(t) = \lambda_0 \cdot \left(1 - \frac{t}{t_E}\right),
\]

\( \lambda_0 \) - Ratio of the horizontal to the vertical pressure at the beginning of placing;

for SCC \( \lambda_0 \approx 1,0 \)

The integration of the increment of pressure over the height leads to the maximum pressure \( p_{\text{max}} \), with the corresponding parameters:

\[
p_{\text{max}} = \frac{\gamma_b \cdot v \cdot \dot{\lambda}_0 \cdot t_E}{2}
\]

\( t_E \) - end of solidification,

\( \gamma_b \) - specific gravity

\( v \) - rising velocity

Equation 1 assumes, that a continuous setting - from the begin of casting to the end of solidification - occurs. The same value for \( p_{\text{max}} \) is described through a function \( \lambda(t) \), whose integral over the time, to the time \( t_E \), corresponds to the linear equation. SCC normally warrants this last condition.
Also during the placing of SCC dynamic loads can occur, for example by the free falling concrete. The implementation of an additional safety margin (like in DIN 18 218) is therefore reasonable. Also the time dependent pressure-ratio $\lambda$ is not exactly known. Therefore a pressure distribution over the height with a hydrostatic behaviour up to the maximum pressure, followed by a constant value up to the end of the solidification is recommended (figure 5). A prediction about an absolute upper limit for the formwork-pressure, like denoted in several standards for normal concrete, is not possible at the moment.

If SCC with a low yield value (wide slump flow value) is used, a higher pressure should be taken into account in comparison to a normal concrete (flowability according to DIN 18 218) (figure 6).

Hydrostatic behaviour plus the additive to break the friction between concrete and formwork should be calculated, when the concrete is pumped inside from below.

Fig. 5: Proposal to spread the formwork pressure of SCC
Fig. 6: Formwork pressure of SCC depending on rising velocity in comparison to normal compacted concrete according to DIN 18 218 [4]

conditions:
specific gravity $\gamma = 25$ kN/m³, temperature of the concrete $T = +15^\circ$C
SCC-without vibration, concrete vibrator for normal concrete
3. ABILITY TO DEAERATE

3.1 Tests

In combination with the research work concerning the formwork pressure [5], studies to the deaerating-ability of SCC during the fabrication of precast products were done.

Evaluated were different properties of the fresh and hardened concrete (for example air pore content and compressive strength) on extra-fabricated elements as well as on the columns (drilling core). The drilling cores (Ø/h - 10/10 cm) were extracted at the distance of 400 cm (D1), 200 cm (D2) and 50 cm (D3) related to the top of the column. The studies, regarding the behaviour of deaeration in the formwork, were supported by in the formwork integrated windows [5].

3.2 Results

It was observed, that the deaeration or respective the compaction is influenced by:

- the rising velocity,
- the rheological behaviour of the fresh concrete in time of pouring (evaluated for example by the slump flow value (sm) and the time of spreading (t500)),
- the technique of filling / height of free fall,
- the length of flowing in the formwork,
- the pressure conditions in the mould.

The last parameter rather has an effect on the reduction of the entrapped air pores due to compression.

Merely as a parameter of conditional importance the velocity of rising was evaluated. In the test series I (sufficiently high slump flow) with an increase of velocity, no significant increase of air pore content in the hardened concrete could be determined (table 4).

Only if extremely high velocities of beyond 80 m/h were choose, large bubble holes on the surface with diameters up to 1,5 cm were visible.
Tab. 4: Open porosity in the drilling core, determined with the vacuum-water-adsorption test in Vol. %

<table>
<thead>
<tr>
<th>Element Nr.:</th>
<th>Velocity of pouring (concrete level in the formwork) [m/h]</th>
<th>Slump flow value (sm – without J-ring) at the begin of pouring [cm]</th>
<th>D1 (bottom)</th>
<th>D2 (middle)</th>
<th>D3 (top)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>12.5</td>
<td>73.5</td>
<td>14.00</td>
<td>14.19</td>
<td>13.42</td>
</tr>
<tr>
<td>2a</td>
<td>25.0</td>
<td>75.5</td>
<td>13.94</td>
<td>13.45</td>
<td>14.73</td>
</tr>
<tr>
<td>3a</td>
<td>40.0</td>
<td>75.0</td>
<td>13.41</td>
<td>13.90</td>
<td>14.00</td>
</tr>
<tr>
<td>4a</td>
<td>80.0</td>
<td>73.5</td>
<td>14.37</td>
<td>15.46</td>
<td>15.58</td>
</tr>
<tr>
<td>5a</td>
<td>160.0</td>
<td>74.0</td>
<td>14.03</td>
<td>14.63</td>
<td>15.42</td>
</tr>
</tbody>
</table>

The rheological qualities of the fresh concrete can be assumed as the most significant factor for the deaeration. The reduction of the slump flow diameter (increase of the yield stress) in connection with a longer spreading time $t_{500}$ (decrease of the viscosity) increased the air pore content significant and reduced the compressive strength as well (Tab. 4). Furthermore the quality of the concrete surface got insufficient.
Tab. 7: 56 days-compression strength ($f_c$) of the cubes and drilling cores in correlation to the slump flow value ($sm$); element 2a (reference), 2b and 2c, $v = 25$ m/h

The variation of the reinforcement construction as well as the reinforcement content in the test series III didn’t influence the deaeration. This statement is mainly valid for a low reinforcement content.

Sufficient deaeration on the investigated elements was guaranteed, complying following practical regulations.

- A minimum slump flow value without the circular blocking obstacle (J-Ring) in the time of placing of $sm = 74$ cm is to guarantee; also the time of spreading $t_{500}$ shouldn’t be higher than 3 seconds.
- The concrete is not allowed to flow against the vertical wall, but placed central, to avoid segregation due to the contact of the concrete with reinforcement. If narrow moulds are used, the free height of fall should be as low as possible (at most 2 m).
- The velocity of rising shouldn’t be higher than 50 m/h.
If the form has large cross-sections, the deaeration is supported by a long flow-distance (for example walls). In this case it is possible to derivate from the proposed values concerning the slump flow and the time $t_{500}$.

The recommended velocity of placing should be reduced further in areas with high reinforcement concentration to guarantee the completely form filling and the cover of reinforcement.

4. Conclusion

Concerning the pressure on formwork, approximately hydrostatic conditions in the formwork were observed, if the fresh concrete had a high slump flow value. At the same velocity, a lower slump flow reduced the pressure on formwork significantly. A developed calculation model allows an estimation of the exerting pressure. Respecting the deaeration of SCC, it was observed that the velocity of pouring has a low influence on the air pore content, but the rheological properties (described e.g. by the slump flow test) affect significant.
5. Literature


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