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ScienceDirect

Procedia Engineering 192 (2017) 124 – 129

Procedia Engineering

www.elsevier.com/locate/procedia

TRANSCOM 2017: International scientific conference on sustainable, modern and safe transport

# Influence of the rheological properties of SCC on the formwork pressure

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**Abstract**

Formworks for self-compacting concrete (SCC) are commonly designed under the assumption of full hydrostatic pressure. However, current research shows that SCC's design pressure could be reduced, if the concrete's rheological properties were taken, into account. Knowing the relationship between the properties and the pressure, we can prevent formwork overdesign. This research was based, on the assumption that fresh concrete can be described as a Bingham fluid. This paper presents the correlations between static and dynamic yield stress, and lateral formwork pressure. Measured rheological parameters were compared to standard technical concrete tests. Formwork pressure were determined on the element imitating a column with dimensions of 0.20 x 0.20 m and a height of 1.20 m with two casting speeds 1 and 7 m/h. Three types of cement, 2 superplasticizers, and 2 w/c ratios were used. A correlation between rheological parameters and pressure reduction over time was observed. Based on our results we propose a methodology and testing sequence applicable in practice.



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*Keywords:* SCC; fresh concrete; rheological properties; formwork pressure;

## 1. Introduction

Casting, next to mixing, transporting, placing, and finishing are technological processes, which decide about the durability of concrete. It is almost 30 years since the first self-compacting concrete casting took place. In 1988, when

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Peer-review under responsibility of the scientific committee of TRANSCOM 2017: International scientific conference on sustainable, modern and safe transport
doi:10.1016/j.proeng.2017.06.022

Akashi Kaikyō Bridge construction started using SCC, because of its high flowability, it was assumed that the formwork pressure should be high or even equal, or close to, hydrostatic. It was believed that the concrete would behave as a liquid also when in the form. However, measured lateral formwork pressure during the casting showed results quite opposite to what was presupposed. The pressure was far from hydrostatic [1]. Nevertheless, limited knowledge of the influence of the SCC on formwork pressure causes that designers use the hydrostatic pressure as the safest method to predict the lateral pressure [1-7]. However, current research shows the assumed pressure could be reduced to a range between 18 and 99% of hydrostatic [1, 4, 7, 12, 17-18]. Changes under load are rheological, well described in detail in [1, 8-10, 19]. Studies [1, 8-9, 11, 20] show and it is commonly accepted, that the rheological behavior of fresh concrete may be sufficiently described by the Bingham model's rheological parameters: yield stress and plastic viscosity.

Published models try to describe and help to understand SCC mechanisms during casting, especially, according to lateral pressure. Almost none of listed below takes into account the rheological properties of SCC, especially determined by simple the technical tests:

- Tah's and Price's model [13], based on CIRLA 108, including temperature, formwork shape, casting speed,
- Valhove's et al. model [14], including yield stress, high of fresh concrete, internal friction, formwork shape but exclude casting speed,
- Roussel's and Ovarlez et al. model [15], which includes the high of fresh concrete, formwork shape, casting speed, and yield stress in time which is an experimentally determined by thixotropic ratio $A_{thix}$, connected with concrete reversible stiffness,
- Graubner's and Proske's [16], model which depends on casting speed, internal friction, setting time, material and element size ratio,
- Khayat's and Assad's model [17], characterized by experimentally determined structural ratios $A_1$, $A_2$ and $A_3$ for respectively 0, 100 and 200 min after ending casting. "A" ratios are computed according to "breakdown area" which is connected with the surface between up and down curves due to thixotrophy,
- Beizel's, Beizel's and Muller's [2], model which include casting speed, way of casting, fresh concrete speed, formwork shape, and yield stress in time which is an experimentally determined by thixotropic ratio Cthix, connected with concrete reversible stiffness.

Except models listed above, the only guideline presenting a method to predict the SCC lateral pressure is the German standard DIN 18218:2010-01 [22]. The Standard presents dependences between casting speed, cement setting time, high of fresh concrete, its consistency and weight. The SCC is characterized only by one consistency class, slump flow test above 700 mm. Interestingly, according to DIN 18218, the formwork pressure for the SCC is determined to be less that for vibrated concrete class F6 according do DIN 1045-2 responding to EN 206 (slump flow at the range 630-700 mm). Nonetheless, this standard does not determine the lateral pressure using the rheological properties of concrete.

Knowing the simple dependences between the fresh SCC and formwork pressure can help either the formwork design to be more efficient with a given casting speed or the adoption of appropriate casting speed design knowing formwork strength on-site. This paper shows a comparison of rheological properties of self-compacting concrete identified by rheometer Viskomat XL and technical tests at the same time with measured formwork pressure casted in two different speeds: 1 and 7 m/h.

## 2. Experimental details

### *2.1. Materials and concrete composition*

To obtain a wide range of changeability of rheological properties, the research was conducted with different w/c ratio (0.30, 0.40), commonly produced cement (CEM I 32.5 R, CEM III/A 42.5N-HSR/NA, CEM V (S-V) 32.5R-LH), and superplasticizer (carboxyl ethers PE: SP1, SP2). Tests were carried out at a constant temperature of 20 ºC. The composition of the SCC has been chosen in a manner consistent with the rheological self-compacting mortar, using the composition of the adjustment based on the assumption of equal values of dispersion for concrete. The method of calculation is described in detail in [23]. The compositions of fresh concretes are shown in Tab. 1. A natural sand 0-2 mm and gravel were used as 2-8 mm aggregate.

Table 1. Concrete mix composition.

| Concrete | w/c ratio | Cement | Cement paste, $kg/m^3$ | SP, %C | Sand content, $kg/m^3$ | Aggregates, $kg/m^3$ | Sand ratio % |
|---|---|---|---|---|---|---|---|
| SCC1 | 0.3 | CEM I | 350 | SP1, 3.00 | 884 | 780 | 53.2 |
| SCC2 | | | | SP2, 2.00 | | | |
| SCC6 | | CEM III | | SP1, 1.75 | | | |
| SCC7 | | | | SP2, 1.00 | | | |
| SCC11 | | CEM V | | SP1, 2.50 | | | |
| SCC12 | | | | SP2, 2.00 | | | |
| SCC16 | 0.4 | CEM I | 350 | SP1, 1.00 | | | |
| SCC17 | | | | SP2, 0.75 | | | |
| SCC21 | | CEM III | | SP1, 0.75 | | | |
| SCC22 | | | | SP2, 0.50 | | | |
| SCC26 | | CEM V | | SP1, 1.50 | | | |
| SCC27 | | | | SP2, 0.75 | | | |

### *2.2. Rheology of fresh concrete – testing procedures*

The rheological parameters were determined using rotational rheometer Viskomat XL by regression analysis according to relation (1) corresponding to a Bingham model:

$$T = g + h \cdot N \tag{1}$$

where $g$ [Nm] and $h$ [Nms] are rheological constants corresponding to Bingham yield stress and plastic viscosity respectively [8-9, 11, 20-21]. After determining the measurement constants of the rheometers the values $g$ and $h$ may be represented in physical units. For the purpose of this study, both $g$ and $h$, are named as respectively yield stress and plastic viscosity.

The rotational speed for Viskomat XL and the time of measurement are shown in Fig. 3 (left). The proposed procedure allows to measure: the 1st and 2nd static yield stress ($g_{stat}$), the nature of the hysteresis loop, the dynamic yield stress ($g$) and plastic viscosity ($h$) during one measurement (Fig. 3 right).

In parallel to the rheometric tests, the technical tests were performed according to EN 12350-2, EN 12350-8 for fresh concrete using the Abrams cone (slump-flow test). The diameter of concrete slump flow and propagation time $T_{500}$ to a diameter of 500 mm with an accuracy of 0.1 s, were determined. Spreading was carried out using a device for vertical lifting of the cone at a constant speed. Tests were determined after mixing (0'), after 20, 40 minutes of resting (20', 40'), in the 80 minute, after one minute re-mixing (80') and after 20 min of resting (100') (Fig. 3).

### *2.3. SCC formwork pressure – testing procedure*

Measurement of the SCC formwork pressure were conducted on the element imitating a column with dimensions of 0.20 x 0.20 m and a height of 1.20 m [24]. Casting speeds were constant at 1 and 7 m/h. Formwork pressure were measured by pressure sensors with diameter of 87 mm. The pressure sensors were placed at the bottom of the column, at the heights of 0.135 m, 0.375 m and 0.75 m (from the bottom of the formwork). Presented results illustrate the lowest sensor measurement (0.135 m from the bottom).

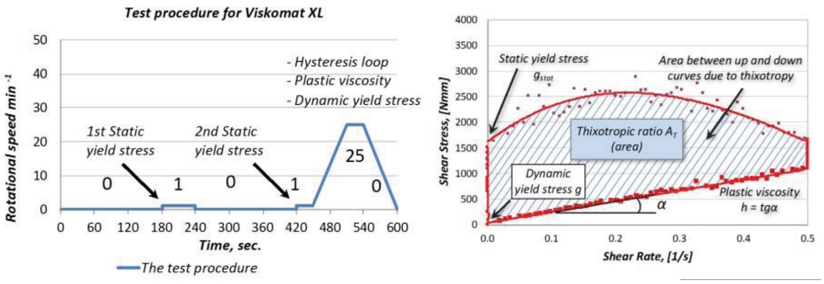


Fig. 2. The rheological test procedure for Viskomat XL (left) and graphical determination of hysteresis loop, initial static and dynamic yield stress, and plastic viscosity - measurement between 420-600 s (right).

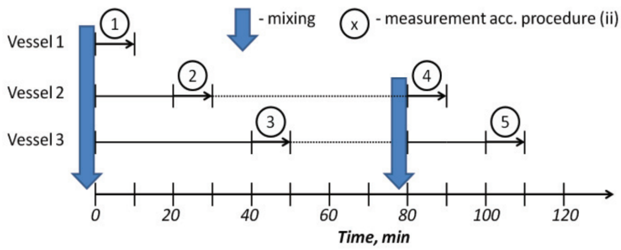


Fig. 3. Measuring sequence.

## 3. Experimental results and discussion

The obtained correlations of the SCC characteristics, measured by the slump flow test and rheometer Viskomat XL (yield stress g and plastic viscosity h) are presented in Fig 4. Results prove very high correlation between laboratory and technical tests, which may be used equivalently to assess the self-compacting concrete rheological properties.

Fig. 5 presents the correlation between the yield stress and slump flow test ratio (yield stress/slump flow) after mixing and lateral formwork pressure. The higher slump flow, the lower yield stress, which causes the higher lateral formwork pressure. Two mixes were omitted because of mix segregation. For presented mixes, the linear correlations between slump flow, yield stress and formwork pressure were found.

After casting, the formwork pressure reduction was observed (Fig. 6). For concrete mixes, the correlations between the lateral pressure reduction 20 min after casting and subtraction static and dynamic yield stress obtained 20 min after casting, were found. The lateral pressure reduction is directly proportional to difference between static and dynamic yield stress in time. However, the main factor is increasing the static yield stress, which is responsible either for reversible or irreversible concrete stiffening.

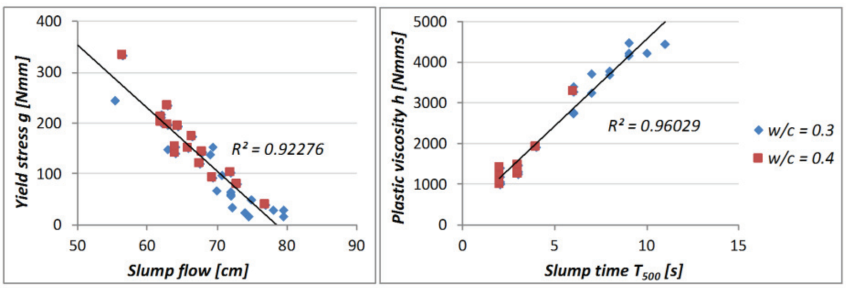


Fig. 4. Slump flow vs. yield value g (left) and flow time $T_{500}$ vs. plastic viscosity h (right) determined by rheometer Viskomat XL in 0‘, 40’, 80’ and 100’ minute, after mixing.

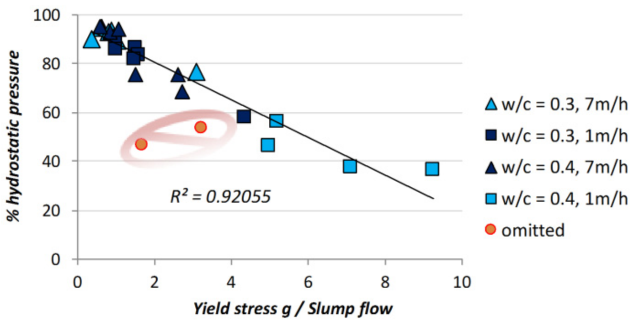


Fig. 5. Yield stress / Slump flow ratio after mixing (0') vs. lateral formwork pressure just after casting, depending on w/c ratio and casting speed. Omitted mixes were unstable.

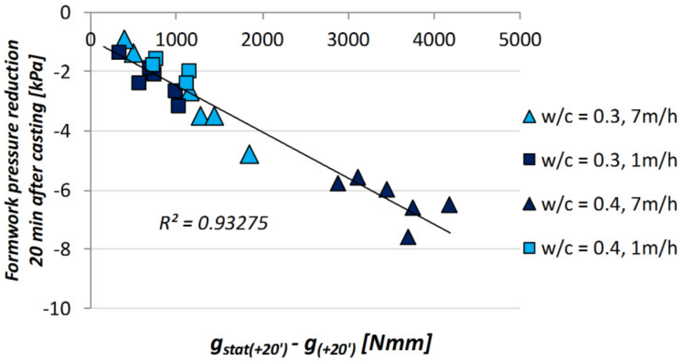


Fig. 6. Lateral formwork pressure reduction 20 min after casting according to static and dynamic yield stress change.

## 4. Summary

There is a good correlation between the lateral formwork pressure, and its reduction and rheological properties of the SCC. Increasing slump flow, which is characterized by the low dynamic yield stress, causes the higher lateral formwork pressure. For w/c = 0.3 there were not significant differences between the formwork pressure and casting speed, except for CEM I and PE1, which has the lowest slump flow after mixing. For w/c = 0.4 casting speed had influence on lateral pressure. Slow casting caused lower pressure, because of loss of workability in time. That feature was observed especially 20 min after fast casting, where pressure reduction was at the highest level. The largest pressure reduction after the rapid casting was for CEM I with PE2 and CEM III, with PE and PE2, which were characterized by very fast, reversible thixotropic stiffening. As a result, it can be concluded that rheological properties of the SCC, especially static and dynamic yield stress in time decides on formwork pressure. The next step in research is to expand the research to other chemical admixtures and to find the correlation between the static yield stress, obtained by rheometer and technical tests; in addition to develop the correlations between the rheological properties of the SCC and lateral formwork pressure and to verify them on a wall-like element.

## Acknowledgements

This paper was elaborated with the financial support of the Project No. 842/B/T02/2011/40 "The influence of time and technological factors on rheological properties of self-compacting concrete in terms of the pressure on the formwork" financed by the from the National Science Centre in Cracow, Poland, project “Innovative cementitious materials and concretes made with high – calcium fly ashes” co-financed by the EU from the European Regional

Development Fund and the project "DoktoRIS - Scholarship program for innovative Silesia" co-financed by the European Union under the European Social Fund. Research has been done in collaboration with HARSCO Infrastructure Poland (HUNNEBECK Poland). This work was developed while Michał Drewniok was at Silesian University of Technology, Faculty of Civil Engineering, Poland.

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