Engineering Structures 70 (2014) 218–233

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Review article

Numerical simulation of formwork pressure while pumping self-compacting concrete bottom-up

Serge Tichko [a,*], Jens Van De Maele [b], Niels Vanmassenhove [b], Geert De Schutter [a], Jan Vierendeels [c], Ronny Verhoeven [d], Peter Troch [e]

[a] Magnel Laboratory for Concrete Research, Ghent University, Belgium
[b] Ghent University, Sint-Pietersnieuwstraat 25, B-9000 Gent, Belgium
[c] Department of Flow, Heat & Combustion Mechanics, Ghent University, Belgium
[d] Laboratory for Hydraulics, Ghent University, Belgium
[e] Department of Civil Engineering, Ghent University, Belgium

ARTICLE INFO

Article history:
Received 15 April 2013
Revised 3 April 2014
Accepted 4 April 2014
Available online 8 May 2014

Keywords:
CFD
Numerical modelling
Formwork pressure
Self-compacting concrete
Base filling

ABSTRACT

Self-compacting concrete (SCC) enables new casting techniques, filling formworks by pumping bottom-up. However, fundamental questions remain concerning the formwork pressure when following this advanced filling procedure. In order to determine the maximum formwork pressures, a series of formwork filling tests, with SCC being pumped from the base of the formwork, have been performed at the Magnel Laboratory for Concrete Research of the Ghent University. Numerical simulations of these formwork filling tests have also been performed for comparison with the experiments. During the filling process, the formwork pressures were measured close to the base of the formworks, where the maximum pressures were expected to occur. The measured formwork pressures were finally compared with the computed formwork pressures. Both the experiments and the simulations in this study revealed that the formwork pressures during the filling tests were slightly higher than hydrostatic for SCC pumped from the base of the formworks. This was due to the additional occurring hydraulic losses.

Contents

* Corresponding author. Tel.: +32 (0)476 29 26 08; fax: +32 (0)15 71 82 79.
E-mail address: Serge.Tichko@UGent.be (S. Tichko).

http://dx.doi.org/10.1016/j.engstruct.2014.04.008
0141-0296/

Research significance

Most of the available codes and guidelines for determining the formwork pressure have been developed for casting processes with normal vibrated concrete (NVC) [9–13]. Although the DIN 18218 standard [10] gives some design guidelines for use with SCC, these codes and guidelines are generally not suited for casting with SCC when pumped from the base at high casting rates (>7 m/h) [8,15,16]. NVC is traditionally cast from the top of the formwork in several layers, which are individually vibrated in order to remove the entrapped air as much as possible and to ensure good compaction around the steel rebars. As such, the casting rates are rather low. The base filling technique with SCC, which is presented in this article, allows for much faster casting rates with still good compaction. Although the formwork pressures are higher with base filling compared to top filling, the filling times can be noticeably reduced. For the precast industry, this could mean a more cost effective manufacturing process at a higher production rate.

1. Introduction

1.1. Rheological behaviour of self-compacting concrete (SCC)

SCC has been developed in Japan during the 1980s. At that time, the Japanese construction industry encountered many problems due to a lack of skilled and qualified workmen, which slowed down the construction pace and impaired the durability of new concrete structures. During the 1990s, SCC gradually made its entrance into Europe through the Netherlands and the Scandinavian countries, and since then, the amount of SCC being applied in construction is continuously increasing, together with the number of countries where it is being used [1,2].

According to De Schutter [1], SCC can be defined as a concrete which needs to possess sufficient fluidity in order to be able to fill a formwork completely (filling ability) without the aid of other forces than gravity, even when having to flow through narrow gaps (passing ability), but also showing a sufficient resistance to segregation, during flow and in stationary conditions (stability). In order to achieve sufficient fluidity in SCC, without increasing the water content, super-plasticizers must be applied. Only adding super-plasticizers to traditional concrete is not sufficient to create SCC, due to the large amount of coarse aggregates, which can form particle bridges when flowing through a narrow gap, causing blocking. Therefore in order to fulfil the passing ability condition, the amount of coarse aggregates is reduced. On the other hand, extra amounts of fine materials, like limestone filler, fly ash or silica fume are added in order to increase the stability of SCC [1,2].

Several material models are available for describing the rheological behaviour of fresh concrete, such as the Bingham model [3], the modified Bingham model [2] or the Herschel-Bulkley model [4]. In all these material models a (dynamic) yield stress is defined, which is the minimum value of the applied shear stress needed to maintain flow. For the present study the Herschel-Bulkley model has been selected, because this model is able to capture the fresh behaviour of a wide variety of SCC mixes. The Herschel-Bulkley model is formulated mathematically in

$$\tau_{HB} = \tau_{0,HB} + K_{HB}(\dot{\gamma})^{n_{HB}} \tag{1}$$

where: the index HB stands for Herschel-Bulkley, τ_{HB} the shear stress in the material [Pa], $\dot{\gamma}$ the shear rate in the material [1/s], $\tau_{0,HB}$ the yield stress [Pa], K_{HB} the consistency factor[Pa s^n] and n_{HB} the consistency index [–].

The Bingham model can be considered as a special case of the Herschel-Bulkley model, for which the consistency index n_{HB} equals one. Using the Herschel-Bulkley model to describe the steady state behaviour of SCC is not so straightforward though. The consistency factor K_{HB} has no physical meaning. The dimension of K_{HB} is Pa s^n, meaning that the consistency factor is also dependent on the consistency index n_{HB}. Only when n_{HB} equals one (Bingham), the consistency factor K_{HB} can be regarded as the plastic viscosity μ_p of the concrete. Furthermore, the apparent viscosity, defined as the ratio between the instantaneous shear stress and shear rate, is becoming infinite when the shear rate approaches zero. This singularity will have to be handled properly in numerical simulations, as will be explained in Section 3.2.

Depending on the mix design, SCC in the fresh state can show thixotropic behaviour and shear thickening to various degrees. Thixotropy can be defined as a reversible build-up and breakdown of internal structure, due to flocculation or coagulation of cement particles for which the influence of inter-particle forces is still significant. Shear thickening is an increase in apparent viscosity with increasing shear rate, when no yield stress is present. When the fluid has a yield stress, the apparent viscosity will first decrease when the shear rate increases, and from a certain shear rate value on, the apparent viscosity will increase again when the shear rate further increases (see Fig. 1). The effect of shear thickening

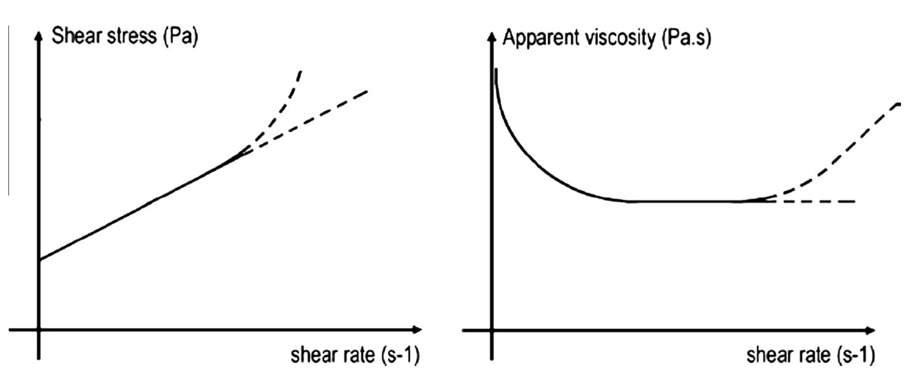

Fig. 1. Typical shear stress vs. shear rate curve (left) or apparent viscosity vs. shear rate curve (right) for cementitious materials [5].