Journal of Building Engineering 12 (2017) 77–86

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Statistical model for predicting the maximum lateral pressure exerted by self-consolidating concrete on vertical formwork

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ARTICLE INFO

Keywords:
Lateral pressure
Self-consolidating concrete
Formwork design
Experimental model

ABSTRACT

In order to design vertical formwork on a construction site, it is necessary to have a model that predicts the lateral pressure exerted by self-consolidating concrete *(SCC)* and does not require the determination of rheological or tribological parameters through a laboratory test or with a specific device.

Due to the mix design, this type of concrete does not require any vibration method and can be filled continuously without presenting segregation. Therefore, high placement rates (over 10 m/h) are common practice today.

The aim of this work is to develop a statistical model that predicts the maximum lateral pressure exerted by *SCC* on vertical formwork. However, considering the conditions of placement, for this type of concrete on real constructions, another principal objective of the model is to obtain an accurate prediction of the maximum lateral pressure when *SCC* is poured at placement rates of over 10 m/h.

The model takes into account seven of the variables that affect the lateral pressure of fresh concrete: placement rate, slump flow, height of the concrete piece, concrete temperature, cement type, minimum dimension and size of the cross section. 131 experimental data were collected from the literature and were considered for the formulation of the model.

In addition, a survey was conducted with 105 construction managers from different companies in over 20 countries.

The results show that the model presents a very good approximation to the experimental data, especially for high placement rates.

1. Introduction

The use of *SCC* has grown in recent years due to the interest in reducing or eliminating vibration during placement in order to facilitate the casting of densely reinforced sections and formwork areas with restricted access or for architecturally exposed elements with a lower tolerance for consolidation deficiencies. Since this type of concrete does not require any vibration method, high rates of placement are observed in construction sites, relative to traditional concrete, which can result in higher lateral pressure exerted against the formwork [1].

The lateral pressure exerted by fresh concrete must be known to correctly dimension formwork panels. The simplest but most conservative solution is to consider a hydrostatic distribution, along with concrete density. Although this simplification solves the problem of safety, it ignores the economic factor, since the formwork fabrication cost is proportional to the lateral pressure considered for dimensioning [2]. An overestimation of the lateral pressure results in an increase in the cost of the formwork, which can be up to 60% of the cost of the concrete structure [3]. At the same time, the economic factor is always limited by vital safety considerations. An underestimation of pressure may cause deformed structural elements or, in the worst case, the failure of the formwork.

Moreover, according to several authors, such as Assaad and Khayat [4], Khayat et al. [5], and Billberg et al. [6], the casting rate is a determining factor in the maximum lateral pressure exerted by the self-consolidating concrete on vertical formwork. It is noteworthy that casting rate differences are higher in the case of *SCC* columns, where the cross-sectional area is small. However, in the case of walls, where the cross-sectional area is significantly higher, the casting rate usually does not reach values that are as high as those of columns.

In addition, considering hydrostatic pressure in cases with low casting rates generates an overestimation of the value of maximum lateral pressure. Because of this, several models with a very good approximation in predicting the maximum lateral pressure have been

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http://dx.doi.org/10.1016/j.jobe.2017.05.004
Received 28 October 2016; Received in revised form 3 May 2017; Accepted 4 May 2017
Available online 05 May 2017
2352-7102/

developed for low casting rates, based on the determination of rheological or tribological parameters. Among these models we can find Vanhove et al. [7], Ovarlez and Roussel [8], and Khayat and Omran [9].

However, in cases with high casting rates, an increase in the value of maximum lateral pressure can be observed, although they are lower than the hydrostatic values. The previously cited models usually adopt the value of the hydrostatic pressure under these conditions. Therefore, in cases of high casting rates, the maximum lateral pressure are closer to the hydrostatic values in comparison of cases of low casting rates.

This work compiles the experimental data published over the last ten years, with the objective of determining a statistical model for predicting the maximum lateral pressure exerted by *SCC* on vertical formwork. This article also seeks to develop a model that is appropriate for use on construction sites. The model does not require special devices, or tests that requires long periods of rest.

In addition, a survey was conducted with 105 construction managers from different companies in over 20 countries to determine whether it was considered practical to determine the rheological parameter on the construction site.

2. Experimental models

While many authors have studied the maximum lateral pressure exerted on vertical formwork, this work considers only the models developed for *SCC*.

The hydrostatic model is the most conservative as it considers *SCC* to be a fluid, establishing that the lateral pressure on the formwork follows a hydrostatic distribution, with concrete density.

Vanhove et al. [7] determined the lateral pressure of concrete on formwork based on an analogy with Janssen´s theory [10]. The authors assumed that the lateral pressure is proportional to the vertical pressure, where the proportionality factor (K) is constant along the entire height and depends on the internal friction angle of the material (φ). As a result, they proposed Eq. (1) to determine the lateral pressure of fresh concrete.

$$P(h) = \frac{\rho g A - \alpha\tau_0(2e+2L)}{\alpha(2e+2L)\mu K}\left(1-e^{-\frac{\alpha(2e+2L)\mu K h}{A}}\right) \tag{1}$$

Where: P_{max} is the maximum lateral pressure (kPa); ρ is the density of the material (kg/m^3); g is the gravity constant (m/s^2); A is the area of formwork pressure (m^2); τ_0 is the friction stress (Pa); e is the formwork thickness (m); L is the formwork width (m); K is a reduction coefficient which depends on the internal friction angle; H is the formwork height (m); α is a coefficient that considers the physical phenomenon of the problem and controls the imperfections.

μ is the friction coefficient, whose value is determined by a tribometer. The tribometer considers the movement between concrete and formwork, thus being able to determine the static and dynamic friction coefficient.

The principle behind the tribometer is based on slipping a metal plate at a given velocity between two samples of concrete which are being subjected to a known pressure. The plate slides horizontally in order to reduce the gravity force. The concrete is placed in two sample holders of 120 mm in diameter that have a gasket system to prevent any possible water filtration through the union. The samples also have a mobile bottom to transmit the pressure delivered by the pneumatic jack to the material. A schematic representation of the sample holder and the metal plate can be seen in Fig. 1a.

Vanhove et al. [7] calculated the friction coefficient (μ) as the ratio between friction force (F) and normal force delivered by the pneumatic jack (N), as shown in Fig. 1b. The resulting friction force (2 F) can be measured since the velocity of the interchangeable plate (V) is a known parameter, while the normal force (N) is determined with the pressure exerted by the pneumatic jack and the area of the mobile bottom of the sample. The resulting friction force is 2 F, since it is believed that the two samples have similar friction.

As can be seen from the above, the test, despite its great precision, has a certain complexity that makes its use on construction sites very difficult.

Ovarlez and Roussel [8] proposed a theoretical model that characterizes *SCC* by its yield stress (τ_0) as a function of resting time. They assume that for stresses with values below τ_0, *SCC* behaves like an elastic material, and the friction against the formwork walls can take a value between 0 and τ_0. The lateral pressure may be determined from Eq. (2) for a rectangular formwork and from Eq. (3) for a circular one.

$$P_H = K\left(\rho g H - \frac{(H-e)^2 A_{thix}}{eR}\right) \tag{2}$$

$$P_H = K\left(\rho g H - \frac{(H-e)^2 A_{thix}}{rR}\right) \tag{3}$$

Where: P_H is the lateral pressure during casting at a depth H (kPa); ρ is the density of the material (kg/m^3); g is the gravity constant (m/s^2); H is the formwork height (m); e is the formwork width (m); r is the formwork radius (m); R is the rate of placement (m/h); K is the ratio between lateral and vertical pressure; A_{thix} is a flocculation coefficient (Pa/s), which is determined experimentally according to the yield stress taken by the rheometer at different times.

Ovarlez and Roussel [8] performed experimental tests on the evolution of yield stress with a concrete rheometer called BTRHEOM [11], which allows the quantitative determination of the yield stress. The main feature of this rheometer is that it quantifies the yield stress and viscosity of concrete mixtures. Ovarlez and Roussel [8] assume a yield stress increasing linearly over time, as shown in Eq. (4).

$$\tau_0(t) = A_{thix}t \tag{4}$$

Where τ_0 is the yield stress.

Unlike rheometers with concentric cylinders, this instrument is a parallel plate rheometer. As shown in Fig. 1c the concrete sample is placed between a fixed and a rotating plate, which has a known angular velocity W. The yield stress in this type of rheometer is imposed by geometry. The shear stress can be calculated through the relation between the moment and the angular velocity. Fig. 1c. shows the shear distribution in BTRHEOM and its schematic representation.

Khayat and Omran [9] determined the maximum value of the lateral pressure using a statistical model based on experimental data obtained from a PVC column of 200 mm in diameter and 0.7 m high. In the tests, the column was filled with 0.5 m of concrete, and by injecting pressurized air, they simulated different column heights up to 13 m.

Khayat and Omran [9] expressed P_{max} as a function of concrete height, casting rate, concrete temperature and the aggregates' structural build up. The latter is expressed in terms of static yield stress after 15 min of rest. They described two possible empirical methods for determining the yield stress values of *SCC* at rest: the portable vane method [12] and the inclined plane method [13]. The procedures for performing these tests are described in [12,13], respectively. If the first method is employed, P_{max} is determined by Eq. (5). The model also considers the influence of the maximum size aggregate (*MSA*) and the effect of waiting time (*WT*) between successive lifts.

$$P_{max} = \frac{\gamma H}{100}[98 - 3.82H + 0.63R - 0.63T + 0.011D_{min} - 0.021PV_{\tau_{0rest15mins}}]f_{MSA}f_{WT} \tag{5}$$

Where: P_{max} is the maximum lateral pressure against the formwork (kPa): γ is the specific weight of concrete (kN/m^3); H is the concrete height (m); R is the casting rate (m/h); T is the concrete temperature (°C); D_{min} is the minimum formwork dimension (mm); f_{MSA} is a correction factor for MSA other than 14 mm; f_{WT} is a correction factor that reflects the effect of the waiting time between successive lifts; $PV_{\tau 0rest15mins}$ is the static yield stress measured by the portable vane