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Analysis of casting rate for the validation of models developed to predict the maximum lateral pressure exerted by self-compacting concrete on vertical formwork

S. Teixeira [a], A. Santilli [b,*], I. Puente [c]

[a] University of Navarra, Institute of Civil Engineering, TECNUN, Paseo Manuel Lardizábal 13, 20018 San Sebastian, Spain
[b] Universidad de Montevideo, Facultad de Ingeniería, Prudencio de Pena 2544, Montevideo, Uruguay
[c] University of Navarra, Institute of Civil Engineering, TECNUN, Paseo Manuel Lardizábal 13, 20018 San Sebastian, Spain

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ABSTRACT

The design of vertical formwork is governed by the lateral pressure exerted by fresh concrete; while maximum lateral pressure is the key parameter for formwork design, the rate of pressure decay and the time needed for pressure stabilization are important for determining formwork removal time.

An analysis of different models for predicting the lateral pressure generated by SCC on vertical formwork was carried out, raising the issue of a fundamental parameter like the casting rate. The work also compiles experimental data published over 15 years. A total of 137 experimental data points were collected, 131 for SCC poured from the surface of the formwork and the remaining 6 for SCC pumped from the bottom of the formwork.

Experimental data obtained from different authors were utilized in order to compare the adequacy of the different models in three zones: experimental data with casting rates under 3 m/h, experimental data with casting rates between 3 and 10 m/h, and experimental data with casting rates over 10 m/h. The results were established by not only taking into account the three different zones, but also the formwork safety .

1. Introduction

The use of Self-Compacting Concrete (*SCC*) has grown in recent years due to the interest in reducing or eliminating vibrations during placement, and also to facilitate the casting of densely reinforced sections and areas of restricted access. Despite the fact that *SCC* has been well established in the precast concrete industry, current efforts emphasize on site casting. The lateral pressure developed by the fresh concrete controls the design of formwork systems for vertically cast elements.

Several factors affect the value of maximum lateral pressure. The literature classifies those factors into three categories: formwork characteristics, concrete characteristics and placing method. Several researchers have studied these variables [1-6]. Each category contains a large number of factors, which explain the complexity of the problem. Therefore, different models [7–9] are frequently used for predicting fresh concrete lateral pressure.

Despite the many factors that influence concrete lateral pressure, according to models proposed by different researchers [7–9], the casting rate of *SCC* into the formwork appears either implicitly or explicitly in all of them. Due to the fact that *SCC* can be placed continuously as the need for vibration between successive layers can be eliminated, it is tempting to cast as quickly as possible. While this brings an increase in productivity, the lateral pressure exerted by *SCC* on formwork will be greater [10]. Thus, new formwork design criteria and possibly new design models have to be developed for use with *SCC*.

Gardner [11] states that the lateral pressure results are higher for a given formwork height where concrete is cast rapidly as it takes less time to increase its shear strength and wall friction compared to another concrete cast at a lower rate. This was affirmed by Kwon et al. [12], who determined that if the same mixture is used for casting, the maximum pressure depends on the casting rate. Khayat et al. [13] concluded that the development of maximum lateral pressure exerted by the *SCC* was slightly affected by the increase in the casting rate from 10 to 25 m/h for a column of 200 mm in diameter. Assaad and Khayat [14] showed that a decrease in the casting rate from 25 to 5 m/h can reduce the maximum lateral pressure by 15% and the interruption of the casting process for 10 or 20 min between subsequent lifts can lead to considerable reduction in formwork pressure. Therefore, as

* Corresponding autor.
E-mail addresses: steixeira1@um.edu.uy (S. Teixeira), asantilli@um.edu.uy (A. Santilli), ipuente@tecnun.es (I. Puente).

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concluded by Graubner et al. [15] in their experimental work, the most important parameter controlling the pressure of fresh concrete on construction sites is the casting rate.

The literature shows that the influence of the casting rate on maximum lateral pressure is not linear. Santilli et al. [16] studied the influence of the casting rate on different experimental models for vibrated concrete. The authors concluded that while a linear relationship is shown at low casting rates, this relationship becomes weak at higher casting rates.

Santilli et al. [16] considered three zones in studying the influence of the casting rate on the maximum lateral pressure: the first zone is the one with casting rates under 3 m/h, the second zone is the one where casting rates range from 3 to 10 m/h, and the last zone is for high casting rates over 10 m/h.

In summary, this type of concrete can be cast more rapidly than traditional concrete and the effect of the casting rate on the lateral pressure is different. As the literature shows, experimental data with low casting rates are mostly carried out in laboratories and experimental data with high casting rates are carried out on construction sites since this type of concrete does not require any compaction method. Therefore, this work presents a determination of *SCC* lateral pressure from an experimental model into three zones according to the variable effect of the casting rate, and then compares those models with experimental data obtained from the literature.

Nowadays, there is no universally accepted model for predicting fresh concrete lateral pressure for *SCC*. For that reason, this work describes the models formulated in the literature to predict maximum lateral pressure for *SCC* and compiles the experimental data published over the last 15 years with the objective of unifying all the experimental data on lateral pressure presented in the literature and validating the models.

2. Models developed to predict the maximum lateral pressure

The models developed to predict the maximum lateral pressure exerted by *SCC* on vertical formworks were compiled from the literature. These models, described below, will be validated and compared to each other according to the experimental data published over the last 15 years.

2.1. Hydrostatic pressure

The literature shows that the hydrostatic model is the most conservative as it considers *SCC* like a fluid, establishing that the lateral pressure on the formwork has a hydrostatic distribution, with concrete density.

2.2. ACI Committee 347

The ACI Committee 347 [17] suggested an hydrostatic distribution in case of Self-Consolidating concrete until the effect on formwork pressure is understood by measurement.

2.3. Vanhove et al.

In 2004, Vanhove et al. [7], based on an analogy with Janssen's theory [18], determined the lateral pressure of concrete on formwork. The authors considered the concrete to be a continuous material and assumed that the horizontal pressure is proportional to the vertical one, where the proportionality factor (K) is constant throughout the entire height and depends on the material's internal friction angle (ϕ). Another consideration in the model is that the friction between concrete and formwork is governed by Coulomb's law. The authors considered the friction coefficient (μ) to be constant. As a result, the authors proposed Eq. (1) to determine fresh concrete lateral pressure.

$$P\ max=\frac{\rho gA-\alpha\tau_0(2e+2L)}{\alpha(2e+2L)\mu K_1}\left(1-e^{-\frac{\alpha(2e+2L)\mu K_1 H}{A}}\right) \tag{1}$$

where:

ρ is the density of the material.

g is gravity.

A is the area of the formwork pressure.

τ_0 is the yield shear stress. An equation given by the authors [7] has to be used to determine this parameter.

e is the formwork thickness.

L is the formwork width.

K_1 is a reduction factor of the hydrostatic pressure.

H is the formwork height.

μ is the friction coefficient.

α is a coefficient that considers the physical phenomenon of the problem and that controls the imperfections. From experimental measurements, the authors determined a value of $\alpha=0.15$ when the formwork is filled from the top and a value of $\alpha=0.34$ for concrete pumped from the bottom of the formwork.

2.4. Lange et al.

Lange et al. [19] characterize the concrete behaviour at rest by the characteristic pressure decay after casting. The authors developed the expression detailed in Eq. (2) for predicting the lateral pressure, in the case of a continuous casting.

$$P_h=\gamma Rt\frac{C_0}{\left(at^2+1\right)^{\alpha}} \tag{2}$$

where.

$C(t)$ is the characteristic pressure decay as a function of time.

C_0 is the initial pressure, and the time-dependent variables, a and a are used to fit the function to the pressure decay.

α and a time-dependent variables used to fit the function to the pressure decay.

2.5. Ovarlez and Roussel

In 2006, Ovarlez and Roussel [8] proposed a theoretical model that characterizes *SCC* by its yield stress (τ_0) as a function of resting time. As a simplification, they consider Tresca's plasticity criterion, meaning that τ_0 is the maximum sustainable shear stress for an internal plane. Furthermore, the authors assumed 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. (3) for rectangular formwork and from Eq. (4) for circular formwork.

$$P_{max}=K_2\left(\rho gH-\frac{(H-e)^2A_{thix}}{LR}\right) \tag{3}$$

$$P_{max}=K_2\left(\rho gH-\frac{(H-e)^2A_{thix}}{rR}\right) \tag{4}$$

where:

r is the formwork radius.

K_2 is the ratio of lateral to vertical pressure.

A_{thix} is a flocculation coefficient.

Perrot et al. [20] develop a model described in Eq. (5) based on the model proposed by Ovarlez and Roussel [8] for predicting the maximum lateral pressure in case of reinforcement elements.