Construction and Building Materials 88 (2015) 188–195

Contents lists available at ScienceDirect

Construction and Building Materials

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

Influence of temperature and concrete reinforcement on vertical formwork design

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HIGHLIGHTS

- 12 columns of self-compacting concrete were constructed.
- The influence of reinforcement and temperature on lateral pressure was studied.
- The maturity functions are a suitable methodology for determining striking times.
- A column and a group of specimens were tested to validate proposed methodology.

ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form 6 March 2015
Accepted 10 April 2015
Available online 29 April 2015

Keywords:
Self-compacting concrete
Lateral pressure
Striking method
Reinforcement
Temperature

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 pressure stabilization time is important for determining formwork removal time.

This work describes an experimental study of columns made with self-compacting concrete (SCC) to determine the variation in the maximum lateral pressure and the pressure stabilization time with the following variables: concrete temperature and the presence of different reinforcement densities.

Maturity functions and their relationship to the resistance acquired by the concrete over time were studied in order to determine the minimum times for formwork removal.

The results show that SCC temperatures have an inverse relationship with the lateral pressure of fresh concrete, and the influence of reinforcement on the maximum lateral pressure depends on the number of steel bars and their arrangement; moreover, the lateral pressure of fresh concrete has no influence on the pressure stabilization time. Finally, a formwork removal method based on the maturity index was proposed.

1. Introduction

Self-consolidating concrete (SCC) is a high-performance concrete characterized by its ability to flow under its own weight and achieve good consolidation without mechanical vibration due to special mixture proportions, where the use of specific superplasticizers is required [1]. SCC is also characterized by its ability to facilitate the casting of the formwork in densely reinforced sections and areas with restricted access, without any segregation, blocking of coarse aggregate, or bleeding or grout exudation.

The design of vertical formwork is governed by the lateral pressure exerted by fresh concrete. While maximum lateral pressure is the key parameter in formwork design, the pressure stabilization time (PST) is important in determining formwork removal time. As Harrison [2] states, formwork represents a significant amount of capital that is locked in for the period between filling the formwork and striking the formwork. Therefore, the sooner striking process occurs, the lower the cost of the concrete structure; it should also be kept in mind that formwork systems for concrete walls or columns account for up to 60% of a concrete structure's cost [3].

PST is the time needed for concrete to support its own weight. However, as Harrison established [4], vertical formwork can be removed not only when the concrete is able to withstand its own weight, but also when it is capable of withstanding all the stresses caused by the striking process.

The most conservative way of calculating the maximum lateral pressure is to consider a hydrostatic distribution that takes into account concrete density, but several authors present different

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http://dx.doi.org/10.1016/j.conbuildmat.2015.04.017
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experimental data which shows that the maximum lateral pressure is lower than the hydrostatic pressure [5–7]. Assaad et al. [8] established that the lateral pressure exerted by SCC on vertical formworks is directly related to thixotropy, so when an increase in the thixotropic behavior occurs, the initial lateral pressure after formwork placement decreases and the rate of pressure decay increases. Despite the strong influence of thixotropy, there are several factors that also affect lateral pressure and its development over time.

1.1. Influence of reinforcement

There are few works in the literature that have studied the influence of reinforcement on maximum lateral pressure, and no studies have been found in the literature that address the influence of reinforcement on PST.

Rodin [9] establishes that the presence of reinforcing bars may have an influence on maximum lateral pressure in that the bars generate friction with fresh concrete, and this friction can reduce maximum lateral pressure. According to Santilli [10], the formwork's roughness has a great influence on the friction force between concrete and formwork, which is an important parameter for determining the envelope of the lateral pressure. Perrot et al. [11], despite not specifically studying the influence of reinforcement on PST, state that the effect of reinforcement on the initial rate of pressure decay in formwork is not negligible. They establish that a column without reinforcement presents a pressure drop of 5 kPa, while the same mixture with a 25 mm reinforcement bar in the center presents a pressure drop of 8 kPa.

1.2. Influence of temperature

Similar to the study of the influence of reinforcement on the maximum lateral pressure and its variation over time, there are not many studies in the literature on the influence of temperature on the value of the maximum lateral pressure exerted by SCC on vertical formwork and PST. This is not the case, however, for traditional vibrated concrete, where we have studies such as those by Roby [12], Gardner [13], and Alexandridis and Gardner [14]. Roby [12] shows that the pressure exerted by concrete on the walls of vertical formworks at high temperatures is smaller than the pressure exerted at a lower temperature; this was also verified by Gardner [15] at temperatures between 2 and 27 °C.

In the case of SCC, some authors use different models that are affected by the temperature of concrete to predict the value of the maximum pressure exerted by SCC on vertical formwork. The German guidelines DIN 18218-10 [16], based on the research of Proske [17], developed a model for determining the maximum pressure at 15 °C, where there is a correction coefficient for every degree of difference from 15°. The model proposed by ACI Committee 347 [18] presents casting rate and concrete temperature as the most important parameters. On the other hand, CIRIA Report 108 [19] proposed an envelope for lateral pressure in formworks, where the value of the maximum lateral pressure depends on concrete temperature, among others parameters.

Moreover, Assaad and Khayat [20] state that the variation of fresh concrete temperature has a limited effect on the maximum lateral pressure developed by SCC at the time of casting, while the rate of pressure drop with time increases with concrete temperature since it promotes faster cohesion.

Assaad and Khayat [21] established that the time necessary for pressure cancelation can be correlated to the setting time determined by the Standard Penetration Method [21]. While Meddah and Tagnit-Hamou [22] propose a methodology for determining the time at which the internal stress of concrete starts to develop based on direct measurement related to shrinkage strain development, the determination of setting time can be considered to be a indirect measurement. Santilli et al. [23] affirm that PST can be correlated with setting times, but they state that in order to study the striking methods, maturity functions seem to be a better predictor.

1.2.1. Maturity functions

The maturity functions method has its origin in studies carried out by Nurse [24] and Saul [25] on methods of accelerated curing. These studies were later standardized by ASTM C-1074 [26]. The method consists of determining maturation graphics to estimate the development of compressive resistance and other mechanical properties of concrete under different temperature conditions. ASTM C-1074 standard [26] recommends that the maturation coefficient be calculated using Eq. (1).

$$M = \sum_{0}^{t} (T - T_0) \times \Delta_t \tag{1}$$

where:

M is the maturity value at age t (°C h).

T is the average curing temperature of concrete during interval Δ_t (°C).

T_0 is the datum temperature (Masana [27] recommended a T_0 of −10 °C).

t is time (h).

Δ_t is the period of time at temperature T (h).

The ASTM C-1074 [26] standard establishes a relationship between maturity and in-situ resistance. This standard states that for a given dosage, the resistance–maturity curve of concrete is unique. In the present paper, the linear behavior of the resistance–maturity curve at early ages (less than one day) is considered, as shown in Fig. 1.

Standards such as DIN 1045 [28] and ACI 347-04 [29] state that the ability of concrete to self-support is not a sufficient condition for demoulding. They establish that the development of compressive strength is a key factor in determining the minimum time until formwork can be removed.

In the literature, standards and authors present noticeable differences in the strengths that are proposed as the minimum for formwork removal. For example, Harrison [2] states that for striking, concrete must achieve a minimum strength of 5 N/mm^2 in cubic specimens; Masana [27] establishes a strength of 2 N/mm^2 and Calavera [30] says that the minimum strength is 8 N/mm^2 in cubic specimens.

As mentioned above, there are not many in-depth studies on the influence of concrete temperature and the presence of reinforcement on the maximum lateral pressure and PST. Therefore, one of the objectives of this paper is to determine the influence of concrete temperature and the presence of reinforcement on the maximum lateral pressure and PST. Another aim is to study the maturity coefficients in order to propose the minimum times needed for safe striking.

2. Experimental program

2.1. Experimental methodology

Two different studies were performed. The first study looked at the influence of reinforcement on the maximum lateral pressure exerted by SCC on the formwork and the PST. The second study investigated the effect of temperature on the same parameters as the first study, which are: the maximum lateral pressure and the PST. In both cases, SCC with the same composition and the same formwork were used, only the density of reinforcement and the temperature were changed.

For the first study, 8 columns were built, two without any reinforcement, two with the maximum reinforcement density allowed by EHE-08 [31], two with the minimum reinforcement allowed by EHE-08 [31], which states that the steel area has to be greater than 4% of the concrete area, and the remaining two were built with an average reinforcement density that falls between the maximum and