Construction and Building Materials 111 (2016) 450–460

Contents lists available at ScienceDirect

Construction and Building Materials

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

An experimental study on the lateral pressure of fresh concrete in formwork

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HIGHLIGHTS

- Four specifications to calculate lateral pressure are compared to obtain differences.
- The effects of factors on lateral pressure are tested and analyzed in experiments.
- A modification to the lateral pressure formula denoted in GB50666-2011 was proposed.

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 19 December 2015
Accepted 17 February 2016
Available online 21 March 2016

Keywords:
Concrete
Formwork
Lateral pressure
Concrete slump
Vibration
Casting speed

ABSTRACT

Most of the accidents related to concrete formwork are triggered by improper construction operations and the unsound lateral pressure estimations detailed in concrete formwork specifications. In this study a series of experiments was conducted to reveal the effect of different factors on lateral pressure. The results show that concrete slump, casting speed, and vibration mode can greatly influence the pressure; and the data obtained in the experiments differ greatly from the values yielded by different specifications. A modification is proposed to the GB50666 specification in order to improve the accuracy and reliability of pressure estimations.

1. Introduction

Formwork is very critical to a building constructed by cast-in-place reinforced concrete and it comprises a high proportion of the total cost of concrete engineering. Extensive research has been conducted on the lateral pressure of concrete formwork recently. However, the components and mechanics of the lateral pressure in fresh concrete formwork have not been thoroughly understood. This can potentially cause design complications, poor construction quality, and accidents. Therefore, it is necessary to investigate the factors affecting the lateral pressure of fresh-concrete vertical formwork. Gardner and Quereshi [1] argued that the use of vibration to fluidize concrete can destroy the shear strength and eliminate the friction in formwork. Once concrete is completely fluidized, it behaves as a fluid because the lateral pressure is equal to the hydrostatic pressure produced by a fluid with the density of concrete. Gardner [2] stated that, as depth and time increase, concrete develops internal shear strength and friction, causing the pressure to increase with depth at a lower rate than hydrostatic pressure. He also demonstrated that, for depths greater than 2 m, the magnitude of lateral pressure decreases near the base of a form. Santilli et al. [3,4] and Puente et al. [5] determined that, for low placement rates, a very low correlation coefficient exists between the concrete yield stress resulting from the slump cone and the maximum pressure reductions resulting from the hydrostatic cone. This relationship is even stronger for high placement rates. Arslan [6] and Arslan et al. [7] studied the influence of surface materials on lateral pressure and concluded that lateral pressure in concrete can be decreased by almost 40% by implementing a drainer system or a liner on the surfaces of formwork. Hurd [8] provided detailed suggestions concerning formwork design calculations. His work shows that lateral pressure overestimations increase the costs of formwork, which comprise about 60% of the costs of concrete structures [9]. This finding is confirmed by Kopczynski [10]. Studies concerning the lateral pressure of self-compacting concrete (SCC) formwork [11–14] have indicated that the pressure envelopes of SCC are similar to hydrostatic pressure. However, Omran et al. [15] reached a different conclusion—that the lateral pressure of SCC is obviously

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.067
0950-0618/

less than the hydrostatic pressure produced by a fluid with the density of concrete.

The design standards of concrete formwork in different countries are based on industry standards [16–19] that are constrained by the economics of concrete construction and the requirements of concrete engineering quality and construction safety. Although formwork has been designed with more and more concern for safety recently, a number of accidents caused by the collapse of concrete formwork still occur. In order to provide a better reference for concrete formwork design, a series of experiments was conducted in this study to reveal the effects of critical factors on the lateral pressure values by comparing four standards: the ACI Committee 347 [16], CIRIA Report 108 [17], GB50666-2011 (China) [18] and TZ210-2005 (China) [19]. The critical factors include the concrete slump, rate of placement, initial setting time, environmental temperature, and vibration mode. On the basis of the experimental results, we propose some modifications to the GB50666 specification in order to improve the accuracy and reliability of pressure estimation through a regression analysis.

2. Comparison of the estimated formwork lateral pressure values using different specifications

In this section, four specifications are selected as the standards to calculate pressure values using Eqs. (1)–(7). We analyze the effects of the rate of placement, concrete slump, initial setting time and environmental temperature on the lateral pressure values estimated using different specifications.

(1) GB50666-2011 ⟨⟨Code for the construction of concrete structures⟩⟩ [18].

According to Appendix A.0.4 of the GB50666-2011 specification, when the concrete has a slump of no more than 180 mm and a normal internal vibration with a placement rate of less than 10 m/h, the smaller of the values yielded by Eqs. (1) and (2) should be selected as the lateral pressure value.

$$F = 0.28 D_c t_0 \beta R^{\frac{1}{2}} \tag{1}$$

$$F = D_c h \tag{2}$$

For concrete with a slump greater than 180 mm and a rate of placement greater than 10 m/h, the lateral pressure of the formwork can be calculated using Eq. (2). In Eqs. (1) and (2), D_c represents the weight density of the concrete (kN/m^3); and t_0 indicates the initial setting time of the concrete—if there are no measured data, the initial setting time can be calculated from $t_0 = 200/(T + 15)$, where T is the environmental temperature in °C. The parameter β is the correction factor for the concrete slump (λ): $\beta = 0.85$ when $50\text{ mm} < \lambda \leqslant 90\text{ mm}$, $\beta = 0.9$ when $90\text{ mm} < \lambda \leqslant 130\text{ mm}$, and $\beta = 1.0$ when $130\text{ mm} < \lambda \leqslant 180\text{ mm}$; R represents the rate of placement (m/h), and h represents the depth of the concrete from the top of the placement to the point of consideration in the formwork.

(2) TZ210-2005 Technical guide for construction of railway concrete engineering [19].

For new-site large-volume concrete and common concrete projects, the formwork lateral pressure can be calculated using Eq. (3), where R represents the placement rate (m/h).

$$F = \frac{72R}{R + 1.6} \geqslant 19 \tag{3}$$

TZ210 primarily considers the influence of the rate of placement while neglecting the effects of the initial setting time of the concrete and the concrete's temperature. Furthermore, the concrete slump-correction is not considered in TZ210.

(3) ACI Committee 347R-04, Guide to formwork for concrete [16].

For concrete with a slump of no more than 175 mm, and placed using normal internal vibration to a depth of no more than 1.2 m, the formwork lateral pressure can be calculated by using Eq. (4).

$$P_{\max} = C_w C_c \left[7.2 + \frac{785R}{T + 18.7} \right] \tag{4}$$

Eq. (4) can also be applied to calculate the pressure value of columns ranging from 30 C_w (kPa) to $\rho g h$ and for walls with a rate of placement less than 2.1 m/h and a placement height less than 4.2 m.

For walls with a placement rate that is less than 2.1 m/h and a placement height that is greater than 4.2 m, or all walls with a placement rate that ranges from 2.1 to 4.5 m/h, the pressure value can be calculated by using Eq. (5).

$$P_{\max} = C_w C_c \left[7.2 + \frac{1156}{T + 18.7} + \frac{224R}{T + 18.7} \right] \tag{5}$$

The minimum is 30 C_w (kPa) and the maximum is $\rho g h$; $P_{\max}$ represents the maximum lateral pressure (kPa); R is the rate of placement (m/h); T is the temperature (°C) of the concrete during placement; C_w, C_c, and D_c indicate the unit weight coefficient, the chemistry coefficient, and the weight density of the concrete (kN/m^3), respectively.

(4) CIRIA Report No. 108 [17].

The maximum concrete pressure of a formwork is less than $D_c h$ and can be calculated by using Eq. (6).

$$P_{\max} = D_c \left[C_1 \sqrt{R} + C_2 K \sqrt{H - C_1 \sqrt{R}} \right] \tag{6}$$

In Eq. (6), if $C_1 \sqrt{R} > H$ then the fluid pressure ($D_c h$) equals the design pressure. The coefficient C_1 depends on the size and shape of the formwork; for walls, C_1 is set at 1, and for columns C_1 is set at 1.5. The coefficient C_2 depends on the constituent materials of the concrete; for ordinary Portland concrete (OPC) without a retardant, C_2 is set at 0.3 and it is set at 0.45 for OPC with a retardant. H represents the height of the vertical formwork (in meters), and K is the temperature coefficient yielded by Eq. (7).

$$K = \left(\frac{36}{T + 16} \right)^2 \tag{7}$$

In order to compare these pressure values calculated according to the four specifications, a real project was used to analyze the effects of the environmental temperature, concrete slump, initial setting time, and pouring speed on the lateral pressure values of concrete formwork. The concrete, which is mixed in a mixing plant, has a strength grade of C40 with a retardant. The weight density value of the concrete equals $D_c = 25\ \text{kN/m}^3$ and $H = h = 9$ m. The detailed results of the analysis are described in the following sections.

2.1. Placement rate

The effects of different rates of placement (R) on the lateral pressure of formwork were analyzed under the conditions of an initial setting time of six hours, a 120 mm concrete slump, and a temperature of 20 °C. The correction factor of the concrete slump (β) is equal to 0.9 according to GB50666, and the unit weight coefficient (C_w) according to ACI347 is equal to 1.1. The chemistry coefficient (C_c) according to ACI347 is equal to 1.2. The coefficient