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Prediction of pumping pressure by means of new tribometer for highly-workable concrete

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ABSTRACT

Predicting pressure during pumping has received special attention in recent years. For conventional vibrated concrete (CVC), Kaplan et al. developed a tribometer to characterize the properties of the lubrication layer that is formed when concrete flows in a pipeline, to predict pressure. As this approach is limited to CVC, a new tribometer and data treatment procedure were recently developed by the authors, extending this approach for highly-workable concrete.

This paper describes full-scale pumping tests undertaken to validate the tribological properties of the lubricating layer, determined using the novel tribometer. The program involved pumping 25 concretes, including 18 self-consolidating mixtures in a 30 m long loop. The paper describes the pump, circuit, pressure and flow rate measurements, and the employed rheometer and tribometer, which are needed to predict pumping pressure. The results show that the model developed by Kaplan et al. accurately predicts pressure losses, confirming that the developed tribometer delivers accurate results for highly-workable concrete. Furthermore, it is shown that the assumption employed for CVC where the concrete flows as a plug surrounded by the lubrication layer is not always true, as the occurrence of plug flow depends on pumping characteristics, pipe diameter and concrete rheological and tribological properties.

1. Introduction

Understanding factors affecting pumping of concrete has been a challenge for decades, and many attempts have been made to estimate pressure loss during pumping or the total pressure required to pump concrete over a certain distance [1–10]. A number of practical guidelines have been developed to predict pumping pressure as a function of the discharge rate of the concrete, pipeline diameter, concrete consistency and equivalent length of the circuit [11–13], including quantifying the effect of bends and reducers. Other experiential guidelines that offer recommendations regarding the minimum paste volume and sand-to-total aggregate ratio are proposed to reduce problems occurring during pumping of concrete [11–14].

In the early 2000's, Kaplan et al. [6,15] developed a fundamental model describing the pressure loss in straight pipes during pumping. The model predicts the needed pumping pressure as a function of the geometry of the pipeline (length and radius of the pipes), anticipated flow rate, rheological properties of the concrete and properties of the lubrication layer (also called boundary layer). The lubrication layer is formed by the migration of coarse aggregates towards the center of the pipe: i.e. the zone of the lowest shear rate, leaving a more fluid cement-paste or micromortar layer near the wall [2,3].

Eq. (1) expresses the shear stress at the wall. Eqs. (2) and (3) describe the theoretical model of Kaplan et al. for the case of the bulk concrete not undergoing any shearing, and the case where both the lubricating layer and the concrete undergoing some shearing, respectively. During the flow of concrete in a pipe, if the wall shear stress (τ_w) is smaller than the concrete yield stress (τ_0), the bulk concrete is not sheared, and Eq. (2) applies. In the other case ($\tau_w > \tau_0$), Eq. (3) delivers a theoretical prediction of the pressure loss.

$$\tau_w = \frac{\Delta p_{tot}}{L} \cdot \frac{R}{2} = \Delta p \cdot \frac{R}{2} \tag{1}$$

$$\Delta p_{tot} = \frac{2L}{R}\left(\frac{Q}{3600\pi R^2 k_r}\eta_{LL} + \tau_{0,LL}\right) \tag{2}$$

$$\Delta p_{tot} = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi R^2 k_r} - \frac{R}{4\mu_p}\tau_{0,LL} + \frac{R}{3\mu_p}\tau_0}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{0,LL}\right) \tag{3}$$

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where τ_w is the wall shear stress (Pa), Δp_{tot} is the pressure loss over the entire pipeline length (Pa), Δp is the pressure loss per unit of length of the pipeline (Pa/m) = $\Delta p_{tot}/L$, L is the length of the pipeline (m), R is the radius of the pipeline (m), Q is the flow rate of concrete (m^3/h), k_r is the filling coefficient of pumping cylinders (−), η_{LL} is the viscous constant of the lubrication layer (Pa s/m), which is the viscosity of lubrication layer divided by its thickness; this is done since the thickness is unknown, $\tau_{0,LL}$ is the yield stress of the lubrication layer (Pa), τ_0 is the yield stress of the bulk concrete (Pa), and μ_p = plastic viscosity of the bulk concrete (Pa s).

As can be seen in Eqs. (2) and (3), the input of the lubrication layer and bulk concrete rheological properties are required. The rheological properties of concrete can be measured using commercially available devices, but the characterization of the lubrication layer requires the use of a tribometer.

A concrete tribometer is comparable to a concentric cylinder concrete rheometer, but the formation of the lubrication layer near the inner cylinder is not prevented in a tribometer. In concrete rheometers, the inner and outer cylinders are often equipped with protruding ribs or blades to prevent the formation of the lubrication layer. Concrete tribometers, on the other hand, have a smooth wall at the inner cylinder, allowing the lubrication layer to be formed against that surface. A number tribometers were developed over the last decade by Kaplan [6], Chapdelaine [7,8] and Ngo [16], and their respective coworkers. These tribometers have been developed for conventional vibrated concrete (CVC) as the bulk concrete must be entirely stationary inside the tribometer (i.e., the bulk concrete away from the lubricating layer is not sheared). This condition is not fulfilled when employing highly-workable concrete (HWC), including self-consolidating concrete (SCC) due to the relatively low yield stress of the material. Part of the bulk concrete can indeed undergo shearing during flow in addition to the lubricating layer. In response, the authors have recently developed a new concrete tribometer, combined with an adapted measurement and data interpretation procedure, enabling the characterization of the lubrication layer for HWC. Further details on the development and operating procedures of this tribometer can be found in [17].

The theoretical model developed by Kaplan et al. has not been validated for HWC and SCC, seen the bulk HWC and SCC are likely to be sheared in the tribometer. The proposed testing and calculation procedures of the lubrication layer properties of HWC, including SCC [17] also needs verification.

This paper describes the validation of this newly developed tribometer that was used in a comprehensive full-scale pumping test study, carried out at the Université de Sherbrooke in Canada in 2012 to evaluate the pumping characteristics of mostly high strength HWC and SCC mixtures. In total, 25 concrete mixtures of different compositions were pumped using a 30 m long instrumented loop circuit. Pumping pressure, flow rate, rheological and tribological properties and workability characteristics were determined at various time intervals. A detailed description of the pumping circuit, instrumentation and calibration procedures, and rheological and tribological measurements is given in this paper. The rheological and tribological properties are then combined with the flow rate to validate the applicability of Kaplan's et al. models (Eqs. (2) and (3)) for HWC. The predicted pressure data are compared to the experimental pressure measurements.

2. Pumping circuit

2.1. Pump

The concrete pump used in this research project was a truck-mounted piston pump, Schwing BPL 900. The pump had a maximal discharge rate of 90 m^3/h (±25 l/s) and a maximum pressure that could be exerted on the concrete of 6000 kPa (60 bar). It is important to note that the maximum discharge rate and maximum pressure could not be reached at the same time. Furthermore, the maximum pressure was not applied to avoid any risk of accident during the pumping campaign in the closed circuit loop testing. The pump employed had two cylinders of 200 mm in diameter and a 2 m stroke length. As a result, theoretically, a total of 62.8 l of concrete could be pumped inside the pipes with every stroke. The pistons inside the pumping cylinders alternately pushed the concrete inside the circuit and pulled the concrete from the concrete reservoir, which had an approximate capacity of 0.75 m^3. A powerful valve inside the concrete reservoir switched the connection between the pumping cylinders and the circuit when the pushing cylinder was emptied. This change could be clearly heard on-site, and it was accompanied with a pressure drop in the circuit, which was captured by the pressure sensors and strain gauges (see further). The discharge rate of the pump could be manually varied by the operator. Stepwise variations in the flow rate were imposed for every concrete, but the range of flow rates depended on the pressure the concrete generated.

2.2. Pipes

The placing boom of the concrete pump was not used. Instead, the 30 m loop circuit was directly attached to the concrete pump, as can be seen in Fig. 1. The main components of the circuit were two straight horizontal sections each measuring 11 m in length with two different diameters: 100 and 125 mm (4" and 5"), as indicated in Fig. 2. A combination of reducers was installed at the beginning of the circuit to fit the 100 mm pipe sections to the 200 mm diameter pipe exiting the pump. At the end of the first 11 m straight section, the circuit had a 180° bend, composed of one 90° bend with 100 mm in diameter, a 1 m straight pipe enlarging the diameter to 125 mm and another 90° bend (Figs. 2 and 3). The second horizontal straight section was connected to this elbow. At the end of the 11 m straight section with 125 mm diameter pipes, the loop was completed by vertical and horizontal parts (all using 125 mm pipes) (Fig. 1). This approximate 1.5 m increase in height allowed the discharge of the pumped concrete back inside the reservoir of the pump. This last segment of the pumping circuit could be slightly turned away from the reservoir to enable sampling and calibration of the flow rate. In the remaining part of this paper, the 100 mm diameter pipes are referred to as "small" pipes, while the 125 mm pipes are referred to as "large" pipes.

Fig. 1. Pump, beginning and end of the pumping circuit. Concrete flows from the pump in the pipes (bottom right) towards the left (in background). The final stretch of the circuit is elevated to allow the concrete to be pumped back into the reservoir, or take a sample.