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Development of a tribometer to characterize lubrication layer properties of self-consolidating concrete

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ABSTRACT

The last decade, significant advances have been made in investigating, understanding and predicting the flow characteristics during pumping of concrete. Kaplan developed theoretical equations based on the rheological and tribological properties of concrete to predict pumping pressures. Several tribometers were developed to characterize the flow properties of concrete along a smooth wall, but none of them allows the use of highly-workable concretes. The main reason is that for the calculation of the yield stress and viscous constant of the lubrication layer, the concrete is not allowed to be sheared.

In this paper, a new design for the concrete tribometer is presented, along with a calculation procedure to eliminate the contribution of concrete shearing from the rotational velocity. In this way, the viscous constant can be calculated in the same way as for the previously developed tribometers. The analysis of the data reveals that the total flow resistance in the tribometer (I_{trib}) is well related to the plastic viscosity for SCC and to the yield stress for the other concretes, which is in line with practical results on the influence of rheology on pumping pressure. The viscous constant of the lubrication layer appears related to the plastic viscosity of SCC, but the paper shows that many mix design parameters influence this relationship.

1. Introduction

In the past, many attempts have been made to estimate the pressure during pumping of concrete [1–10]. Based on practical experience, several guidelines were developed to predict pressure as a function of the discharge rate, length of the circuit, concrete consistency, etc. [11–13]. Several practical guidelines for quantifying the effect of bends and reducers, for minimum paste volume and minimum sand-to-total aggregate ratio were proposed to reduce problems occurring during pumping of concrete [11–14].

Kaplan [6,15] developed a fundamental model describing the pressure loss during pumping in straight pipes, based on the rheological properties of the concrete and the properties of the lubrication layer (also called boundary layer). During pumping of concrete, aggregates tend to move to the center of the pipe, while a more fluid layer, rich with cement paste, is formed near the wall; this layer is called the lubrication layer. In the work of Kaplan [6], the rheological properties of the concrete are described by the Bingham model, identifying a yield stress (Pa) and a plastic viscosity (Pa s) [16]. These properties can be measured with different commercially available rheometers. The properties of the lubrication layer need to be measured with a so-called tribometer, which is a device, similar to a rheometer, which allows the formation of the lubrication layer near one of the rotating parts. Indeed, in contrast to a concrete rheometer, where horizontal segregation is prevented (or at least minimized) by the presence of protruding ribs or a vane, a tribometer contains a smooth wall allowing the creation of the more fluid cement-paste layer.

During pumping, conventional vibrated concrete (CVC) is known to move as a plug in pipes, surrounded by the lubrication layer [2–6]. This layer takes all the shearing and allows the concrete to be pumped. For highly-workable concrete (HWC – slump flow in the range of 400–600 mm) and self-consolidating concrete (SCC – slump flow larger than 600 mm), the relatively low yield stress [17,18] of the material causes also a part of the concrete to be sheared during pumping, in addition to the shearing of the lubrication layer. This is taken into account in the model of Kaplan [6], which contains an equation for both flow conditions. On the other hand, the characterization of the lubrication layer in a tribometer requires, up to now, that the concrete in the tribometer is not sheared, and that the entire velocity difference occurs in the lubrication layer. As a result, the lubrication layer properties of highly-workable concrete are more difficult to be quantified.

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List of symbols

H	height (m)
I_{trib}	total flow resistance in tribometer (Nms) = slope T–N line
N	rotational velocity (rps)
R	radius of cylinder (m)
T	torque (N m)
V	linear velocity (m/s) = $2\pi NR$
$\dot{\gamma}$	shear rate (s^{-1})
η	viscous constant (Pa s/m)
μ_p	plastic viscosity (Pa s)
τ	shear stress (Pa)
τ_0	yield stress (Pa)

Indices

cone	cone of the developed tribometer
i	inner, mostly reflecting the inner cylinder
LL	lubrication layer
o	outer, mostly reflecting the outer cylinder
p	plug, boundary between sheared and unsheared zone

This paper describes the development of a new tribometer for HWC. It discusses how the lubrication layer properties are obtained and provides a short description of the currently available tribometers. These tribometers are judged not suitable for HWC, mainly because the low yield stress of HWC and SCC causes the bulk concrete to be sheared, which is in contrast to the basic assumption for tribology. As a consequence, complex 3-D flows, or large variations in shear rates inside the tribometer make these apparatuses less reliable for HWC and SCC. The newly developed tribometer and data treatment procedure accounts for the shearing in the bulk concrete and delivers an approximate correction for the secondary flow effects. Finally, the results of a series of tests are discussed by comparing the flow behavior in the tribometer (total flow resistance and the viscous constant of the lubrication layer) to the rheological properties and mix designs of the tested concretes.

2. Quantification of lubrication layer properties

The properties of the lubrication layer are quantified in a similar way as the rheological properties of cementitious materials. The configuration of a tribometer is based on the principle of coaxial cylinders, where one cylinder rotates relatively to the other. At various rotational velocities, the resulting torque is measured. For rheology, the data points, expressed as torque as a function of rotational velocity, can be transformed into shear stress–shear rate data, using the Reiner–Riwlin equation [19,20]. If in a rheometer, only a part of the material is sheared due to the presence of a plug, the shear stress–shear rate data must be calculated iteratively, as the plug radius would depend on the yield stress of the material.

In contrast to rheology, the determination of the properties of the lubrication layer does not involve a homogeneous material. Theoretically, the material in the tribometer could be divided into two zones: The cement-paste (or micromortar) constituting the lubrication layer, and the bulk concrete. For CVC (and any other concrete type with a rather high yield stress), all shearing is concentrated in the lubrication layer [6,8]. The torque can easily be transformed into a shear stress (in Pa) at the inner cylinder, as this is the place where the lubrication layer forms (Eq. (1)).

$$\tau_i = \frac{T}{2\pi R_i^2 h} \tag{1}$$

The yield stress of the lubrication layer can be obtained by the extrapolation of the obtained τ–V curve to zero velocity. The calculation of the viscosity (in Pa s) is not evident, as it would require the determination of the thickness of the lubrication layer to calculate the shear rate. Until now, no precise method has been described to measure the thickness of this layer inside a tribometer. Consequently, a new parameter has been defined by Kaplan [6]: The viscous constant (in Pa s/m), which is simply the slope of the line in a shear stress–linear velocity diagram. As a result, the properties of the lubrication layer are described by Eq. (2) [6,8]:

$$\tau_{LL} = \tau_{0,LL} + \eta_{LL} V \tag{2}$$

The linear velocity can be easily determined as the product of the inner cylinder radius and the angular velocity, or as $2\pi R_i N$, with N being the rotational velocity (in rps).

It should be noted that for the derivation of Eq. (2), a constant shear rate in the lubrication layer is assumed [6,8]. This is justified by the small thickness of the lubrication layer, reflecting the case of a narrow gap coaxial cylinders rheometer [21].

3. Description of available tribometers

In this section, the three different tribometers that can be used with the pressure prediction model of Kaplan are briefly described. The restrictions on using these tribometers to determine the tribological characteristics of HWC are commented. An overview of the different tribometers and their restrictions is given in Fig. 1.

Kaplan [6] modified the BTRheom [22] to obtain a concentric cylinders tribometer (Fig. 1: top). The main problem with the modified BTRheom is the sealing between the stationary bottom plate and the rotating inner cylinder. This sealing is provided by a rubber strap, which causes an additional torque during measurement. An idle measurement before loading the concrete in the tribometer provides a correction factor, but with intense application, cement paste and sand particles get attached to the seal, thus progressively increasing its resistance during flow. Although the rubber seal is a disadvantage, this kind of tribometer has been successfully used for CVC.

In order to overcome the problem with the rubber seal in the Kaplan tribometer, Chapdelaine [8] developed a new type of tribometer, based on the Tattersall Mk-III rheometer [16] (Fig. 1: middle). The rotating device is an open cylinder, while the concrete bucket is equipped with ribs at the outer wall and a small vane is installed in the center. The main advantage of this tribometer, is that it does not require the installation of a rubber seal.

In his research, Ngo [23] developed a portable variation of the modified BTRheom. It consists of a closed cylinder which is rotated in a bucket of concrete, maintaining a clear spacing between the bottom of cylinder and the bottom of the bucket (Fig. 1: bottom). By inducing the spacing, the necessity of a seal is avoided. To eliminate the influence of the bottom part of the inner cylinder, the determination of the lubrication layer properties is done in two steps. In the first step, the bucket is filled with concrete in a way that the bottom of the inner cylinder touches the upper concrete surface, and a first sweep of the velocity curve is performed. In the second step, the concrete bucket is entirely filled, and the same velocities are applied to the inner cylinder. The properties of the lubrication layer of CVC can thus easily be determined when subtracting step 1 from step 2.

The main difficulties that arise if these tribometers would be used for HWC, including SCC, is the shearing of the bulk concrete, as HWC and SCC have relatively low yield stresses that are likely to