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Formation of lubricating layer and flow type during pumping of cement-based materials

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HIGHLIGHTS

- Formation of lubricating layer is a prerequisite of concrete pumpability.
- Lubricating layer thickness amounts to a few millimetres.
- Concrete exhibits either plug flow or shear flow or a combination of both.
- Flow type is defined at low flow rates.
- Pumping pressure estimated using rheological tools is verified on laboratory scale.

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ABSTRACT

The article at hand builds on previously published work (Secrieru et al., 2017) [1] by providing a detailed discussion on the formation of a lubricating layer (LL) and the flow type during pumping of cement-based materials. It is demonstrated that knowledge of the actual thickness of the lubricating layer (LL), its rheological properties, and the flow type is sufficient to predict the pumping behaviour of fresh material. First, the importance of LL formation is highlighted, and the related, previously published experimental investigation methods are briefly presented. Still further, the flow type of mixtures during pumping is assessed. The cementitious materials under investigation exhibited various principal flow types which are already defined at lower flow rates: Plug flow in the case of a flowable, strain-hardening cement-based composite (SHCC), partial bulk shear in mixtures with round and crushed aggregates, and pronounced bulk shear in the cases of a self-compacting concrete (SCC) and a self-compacting mortar (SCM). To predict concrete pumping behaviour an analytical and experimental methodology based on rheological tools is proposed. This combined methodology quantifies the LL thickness and is compared with simulation results using computational fluid dynamics (CFD). Finally, the prediction of pumping behaviour is verified in small-scale pumping measurements.

1. Introduction

The flow pattern of fresh concrete in a pipeline is related to the composition of the concrete and its ability to generate sufficient lubricating material to reduce the friction at the pipe wall-concrete interface. The existence of the lubricating layer (LL) and its high relevance to concrete pumping behaviour have been intensively discussed [2–6]. The LL can be defined as a thin (a few millimetres) and dilute layer at the interface between concrete bulk and pipe wall subject to a pronounced velocity gradient induced by pumping pressure. The movement of concrete without a sufficient LL is immediately marked by a severe increase in pumping pressure and may even result in blockage as an ultimate consequence due to unbalanced concrete properties but also as a result of pumping process design [7]. Hence, overall pumping behaviour depends mainly on the rheological properties and the thickness of the LL but also on the rheological properties of the concrete bulk and to a large extent depends on pumping set-up, type of pump, pipes and hoses: diameter, material (steel/rubber, number of bends and reducers), length, height. The importance of the very formation of a LL is highlighted while other factors such as concrete composition and pipeline geometry either improve or limit its development [4,8,9]. Forming a LL is mostly related to hydrodynamic, the most

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important being flow-induced particle migration (FIPM) [10]. Furthermore, the geometrical wall effect helps in creating a LL by enriching the paste content towards the pipe wall, as the larger aggregates pack nearby the wall [11]. During pumping, shear stresses and deformations concentrate at the pipe wall while the magnitudes of shear rate in the LL can reach over $10^2\ s^{-1}$ [4], see Fig. 1.

Consequently, the particles tend to move away from the wall and towards the centre of the pipe where the material is almost unsheared, resulting in a flow-induced concentration profile, also due to particle collisions at already small Reynolds numbers (Re $\ll 1$) [13]. The process strongly depends on the magnitude of the induced shear stress. Shear stress increases as a function of particle size, and therefore the particle movement is most pronounced on the scale of the coarsest aggregates [14]. Particle migration leaves behind a layer rich in cement paste at the pipe-concrete interface, thus supplying the LL with additional material [2,15]. The composition, rheological behaviour, and thickness of the LL define the interaction between the pumped material and the pipe walls as friction or sliding. From a rheological point of view it has been suggested that the LL behaves similarly to the constitutive mortar of the pumped concrete [4]. This assumption can, however, only be true in part since in terms of paste content and maximum aggregate size the composition of the LL is not identical to that of the constitutive mortar [16]. The reason is that FIPM in fresh concrete at high shear rates alters the composition and rheological properties of the LL [14,17]. For some concretes it seems that the formation of the LL is independent of the flow rate or pumping pressure [2,4]. Still, it remains unclear what happens with the LL during interruptions or changes in flow rates. The following statements have been previously expressed:

- Once the LL is formed, its thickness and rheological properties remain constant, i.e., particle migration has reached equilibrium, and the pressure drop is linear over the pipe length. This holds true only for so-called saturated concrete, in which shear stresses are transferred by hydrodynamic interactions and not via contact friction between particles [2,15];
- LL thickness and pumping pressure at steady-state depend on concrete composition rather than flow rate [4,18]. This conclusion was drawn based on the assumption that both the steady-state equilibrium between particle collisions in the highly sheared LL and the local increase in concrete viscosity in the bulk depend on the concrete composition [4];
- The formation of LL is conditioned by the pipe wall surface material, i.e., steel or rubber, and influences the flow profiles For example, rubber pipes tend to show long and pronounced flow profiles, with reduced velocity at the pipe wall in comparison to steel pipes [19].

The statements above imply that the properties of the fully formed LL do not depend on shear rate. This means that the interaction between concrete and LL as two coexisting suspensions is negligible, which seems to be applicable to ordinary concretes exhibiting high yield stress and plug flow. However, the assumption is less consistent with self-compacting concretes, characterised by low yield stress and a very thin LL only [20], and so characterised by the shear flow type [5]. The shear flow condition relates to whether the concrete yield stress is surpassed, resulting in the extension of the shear deformation to parts of the concrete bulk.

The properties of the concrete paste and its volume fraction can give only a superficial estimation of prospective concrete flow [21]. On the other hand, accumulated experimental evidence and findings from numerical simulations show that an *a priori* determination of the actual thickness of the LL and its rheological properties suffice in predicting the pumping behaviour of concrete [16,22]. To date the LL thickness could only partially be measured in a tribometer test [3,9]. The authors are aware of the method proposed in [23], which considers the presence and thickness of lubricating layer. There, the LL thickness is not determined, but, independent of concrete type, generally assumed to be 2 mm. This assumption is supported by the results obtained using an ultrasonic velocity profile, however, in a different study and for different concrete compositions [4]. Since the reach of the ultrasonic waves through very dense concrete is limited, only a part of the region of the assumed LL thickness can be assessed.

Recently, based on simple experimental observation with Sliper and tribometer, it was shown that, depending on concrete composition the layer, thickness can reach values within a range of 1–8 mm [1,6]. In another study [24], numerical modelling with the measured data on site [25] could fit plug-flow with a LL thickness of 0.6–1 mm.

The material forming the LL can be obtained directly by extracting it from the pipeline [26] or indirectly through wet-screening of fresh concrete [4], by employing a high pressure filter press [27] or by collecting it immediately after the completion of a tribometer test [3]. Unfortunately, these approaches are rather time consuming, so that the properties of the extracted LL are measured at a later concrete age. In case of wet-screening, the outcome depends very much on the maximum aggregate chosen "to be present" in the LL and thus the sieve size is being arbitrarily imposed. Lately, measurements with a tribometer have been applied to elucidate changes in the flow resistance occurring at the concrete-pipe wall boundary due to the presence of an LL [1–3,9,28]. The purpose of such experiments is to measure the rheological behaviour of the outermost forming surface layer, i.e. the rheological characteristics of the LL. This layer can, however, partly incorporate bulk material

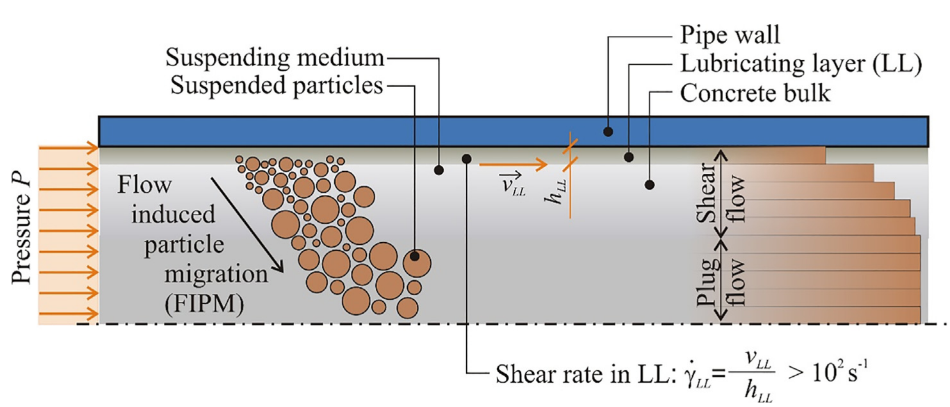

Fig. 1. Schematic representation of lubricating layer formation in a pipeline due to flow-induced particle migration in a pumped concrete [12].