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Virtual Sliding Pipe Rheometer for estimating pumpability of concrete

Venkatesh Naidu Nerella, Viktor Mechtcherine *

Technische Universität Dresden, Institute of Construction Materials, Dresden, Germany

HIGHLIGHTS

- A single-phase CFD model was developed for simulating pumpability tests with Sliper.
- Models without a lubricating layer (LL) are not generally applicable to concrete.
- The lubricating layer was implemented in the pipe flow CFD model.
- Influences of rheological parameters and thickness of LL were demonstrated.
- Particle-concentration-based models were suggested to estimate LL properties.

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ABSTRACT

Predicting the pumping pressure needed to ensure a consistent flow rate of concrete is crucial to the success of current construction processes and newly introduced, but fast-growing 3D-concrete printing techniques. The Sliding Pipe Rheometer (Sliper) has recently proved to be a reliable experimental tool in predicting pumping pressure. Building on the experimental results of an earlier investigation by means of Sliper, a single-fluid numerical model for simulating Sliper tests (virtual Sliper) was developed using Computational Fluid Dynamics (CFD). Various observations as well as numerical limitations of the model and their physical origins were analysed. It was demonstrated that lubricating layer has vital influence on concrete pumping and that single phase numerical models, not considering the lubricating layer are only applicable to some specific concrete compositions. Hence, the initial single-phase model was improved by implementing a separate lubricating layer; its properties were calculated using Chateau-Ovarlez-Trung and Krieger-Dougherty models. Experimental and numerical comparative analyses confirm the validity of the above-mentioned approach in calculating lubricating layer properties. Parameter sensitivity analysis showed that the plastic viscosity and thickness of the lubricating exert the dominant influences on pumping pressure. The virtual pumpability testing tool as developed should enable a more purposeful material design of pumpable concrete and pre-estimation of pumping processes.

1. Introduction

Concrete pumping has emerged as one of the most important processing technologies in the construction industry. It often makes possible the reduction of construction costs and considerably speeds up the construction process. Concrete pumping is also crucial to many advancements in construction-related processes such as Digital Construction (DC), often called 3D-printing with concrete. In the case of onsite DC techniques, concrete must be transported or pumped over longer distances, periodically stopping after having pumped each layer, but without any blockages or circuit breakdowns over longer time durations (see Fig. 1).

1.1. Testing pumpability of concrete

Concrete pumping occurs by pushing concrete using high pressure into pipelines made of either flexible, abrasive resistant material or steel. In other words, the force of the applied pressure causes the concrete material to deform in the direction of the force applied and so to transmit the force further. The pressure required to pump concrete depends on its composition as well as on the pumping specifications such as distance, height to pump, pipe diameter, and discharge rate. Any changes in the composition of concrete such as water-to-binder ratio, aggregate size distributions (grading), and admixtures can exert a pronounced influence on its

* Corresponding author.
E-mail address: mechtcherine@tu-dresden.de (V. Mechtcherine).

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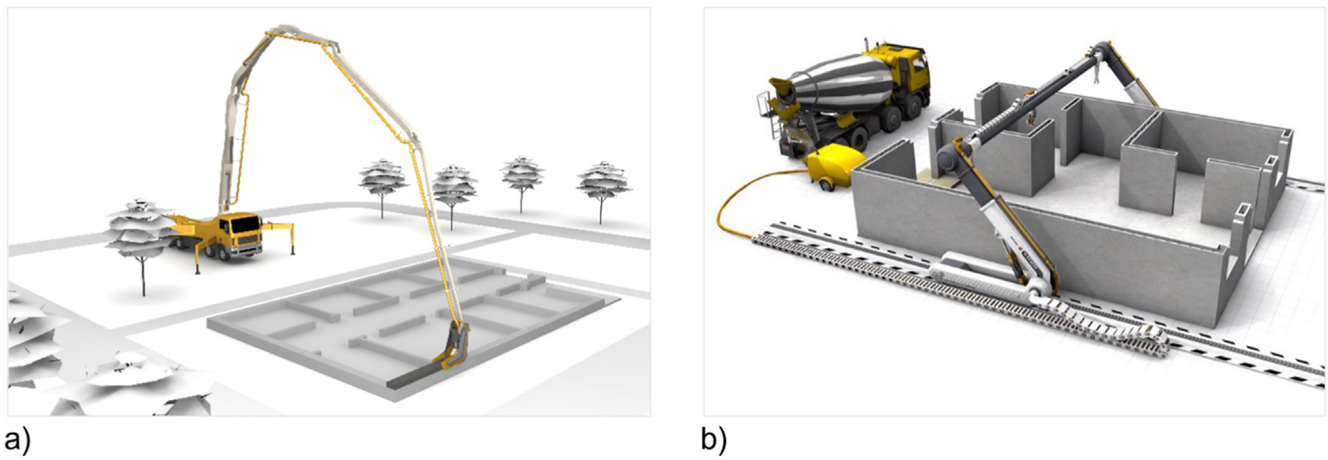

Fig. 1. Examples of concrete printing technologies: a) a CONPrint3D: concrete boom pump is depicted pumping and precision-placing fresh concrete (source: TU Dresden), b) Contour Crafting: a concrete pump is depicted pumping concrete to a rail-mounted robotic printhead (source: University of Southern California).

rheological properties, indeed its behaviour during pumping. Hence, predicting the discharge pressure needed to pump a particular concrete mixture over a given distance or height at a specific rate is not trivial. Much research has been conducted on this topic, especially during the last two decades, which has led in turn to different prediction models and test approaches [1–7]. Conventionally, this crucial task has been accomplished using methods based on empirical test methods [6] or experience [8]. However, such empirical approaches have proven unreliable because of differences in laboratory testing conditions and the corresponding actual situation during pumping [4,6,9]. Not so in the case of the Sliding Pipe Rheometer (Sliper, see Fig. 2) which is a relatively new device developed to overcome the conventional problems in testing the pumpability of concrete and estimating discharge pressures for various concrete types [4].

As the first part of this research, extensive laboratory investigations [6] were conducted using Sliper. Using the rheological parameters *a* and *b* obtained from Sliper experiments and the specifications of pumping circuit, one can estimate the discharge pressure *P* required for a pumping circuit under field conditions using Eq. (1) (considering plug/slip flow with no deformation in the plug [10,11]):

$$P = \frac{4L}{D} a + \frac{16 \cdot L \cdot Q}{\pi \cdot D^3} b + \rho \cdot g \cdot H \tag{1}$$

where L is the length, D is the diameter of the pipeline, ρ is the density of concrete, H is the pumping height, and Q is the desired flow rate.

Assuming a linear relationship between P and Q, see [4,10] and Fig. 2c, according to Eq. (2),

$$P = A + B \cdot Q + P_H \tag{2}$$

where P_H = pressure induced by deadweight of concrete in the Sliper pipe, parameters a and b can be calculated from the P-Q plot of Sliper experiments using Eq. (3) which is derived by combining Eqs. (1) and (2):

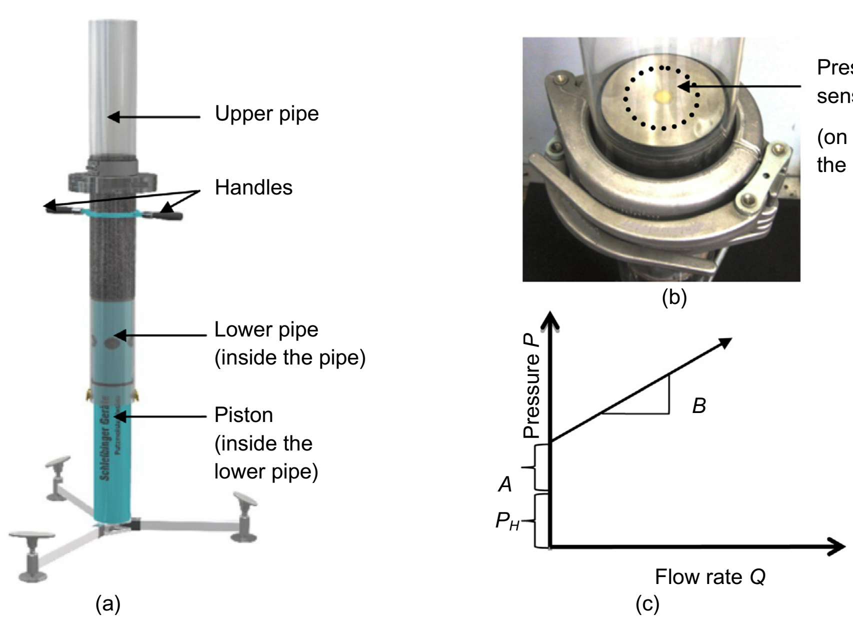

Fig. 2. a) Sliding Pipe Rheometer, courtesy of Schleibinger Geräte T. u. G. GmbH; b) pressure sensor (in dotted circle); c) schematic view of P-Q plot (A = parameter related to yield stress, B = parameter related to plastic viscosity, P_H = deadweight pressure of concrete).