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Study on concrete pumpability combining different laboratory tools and linkage to rheology

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HIGHLIGHTS

- Rheological analyses of fresh concrete and lubrication layer material are performed.
- Influence of roughness of the pipe wall surface on the pumping pressure is quantified.
- Lubrication layer material is sampled and especially produced with similar rheological properties as the former.
- Pumping pressure is predicted using a combination of the tools of rheology.

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ABSTRACT

The paper at hand focuses on various methods to characterize the pumpability of fresh concrete. Primarily the rheological behaviours of the concrete as a bulk are described. The study concentrates on the composition and rheological properties of the lubrication layer forming at the interface to the pipeline wall, since this layer is widely considered crucial for concrete pumpability. For this purpose, the material forming the lubrication layer (LL) is sampled from the various concrete mixtures. The results confirm that in addition to the rheological properties of the bulk of fresh concrete, the properties of the lubrication layer and the roughness of the pipe-wall significantly affect concrete flow in pipes. Based on the composition of the concrete and the lubrication layer, it is possible to design the constitutive material of the lubrication layer with properties similar to the one forming in concrete during pumping. It has as well been demonstrated that knowledge of the rheological properties of the lubrication layer is not sufficient to state whether the concrete is pumpable or not. Only a combination of rheological instruments makes the adequate description of concrete pumpability possible.

1. Introduction

1.1. Background and motivation

Pumping techniques are not only used for concrete transportation on construction sites but already as a trend-setting system for automated concrete delivery and placement in precast concrete factories [1]. Very recently, the most innovative construction processes such as contour crafting [2], CONPrint3D [3] and other additive manufacturing technologies [4] have been presented, all based on the pumping of fresh concrete or mortar. The speedy development of modern pumping techniques has been accompanied by corresponding enhancements in concrete consistency: the concrete compositions most suitable for pumping are rather easily flowable and not too sticky. Indeed, over time the evolution of concrete to new generations commonly consisting of six components – binder, aggregates, additions, admixtures, water and air – makes it necessary to reconsider the phenomena taking place in the pumping line. For example, high-performance concretes possess a higher viscosity and "stickiness" than conventional mixtures, resulting in an increase in the pumping pressure needed to achieve a specific flow rate [5]. This leads to markedly different rheological and tribological behaviours of the respective mixtures in comparison to traditional concrete.

Despite all the technological developments and new scientific insights, the term of "pumpability" has to date been quite unspecified, even though numerous approaches have been proposed [6–9]. Specifically, a link between the testing methods for conventional and advanced workability, including instrumented rheometry, to pumpability has not yet come to light. Furthermore, there are no well-founded concepts for adapting concrete design to the

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requirements of pumpability. Finally, there are still neither codes nor any other official regulations for the assessment of concrete pumpability to codify specific requirements with respect to the rheological properties of fresh concrete. The authors are convinced that a combination of existing laboratory tools can greatly advance the understanding of the complex phenomena occurring during pumping, indeed in respect of optimising the pumping process itself.

1.2. Tribometer and lubricating layer (LL)

Tribometer device in the context of concrete rheology and pumping is an instrument applied to investigate the interaction occurring at the boundary layer (interface) between concrete in relative motion and the pipe wall [6,7,10]. This has significant practical relevance and can be related directly to the flow rate of concrete and the corresponding pressure required to pump it [6,11]. It has to be highlighted that the term "tribometer" commonly used in the concrete research community is misleading, since no tribological or friction behaviour of concrete takes place, unless pipe blockage occurs [12]. As a matter of fact, it is the shear in the outermost concrete layer near the wall surface that is measured and not the friction from the perspective of tribology as research field. Nevertheless, in the present study, the term "tribometer" is used, even though, the authors are well aware about the necessity of establishing correct terminology in the field. The respective apparatus (tribometer) is based on the working principle of rheometers. By means of a tribometer the effect of various parameters of concrete composition (aggregates, admixtures, additives, etc.) on the formation of the lubricating layer and on the concrete pumpability can be studied and quantified. The composition, rheological behaviour and thickness of this layer define the interaction between the pumped material and the walls of the pipe as friction or sliding. From a rheological point of view it has been suggested that the lubricating layer behaves similarly to the constitutive mortar of the pumped concrete [9]. This assumption can only partially be true since in terms of paste content and maximum aggregate size, the composition of the lubricating layer is not identical to that of the constitutive mortar. The reason is that the flow-induced migration of particles in fresh concrete [13] is intensified by the high shear rate at the pipe wall altering the composition and rheological properties of the lubricating layer [10]. The lubricating material can be obtained directly by extracting it from the pipeline [14] or indirectly through wet-screening of fresh concrete [7], by employing a high pressure filter press [15], or by collecting it immediately after the completion of a tribometer test [7]. Unfortunately, these approaches are either time consuming, meaning that the properties of the extracted lubricating layer are measured at a later concrete age, or they face the problem that the maximum aggregate size expected to be characteristic of the lubricating layer must be arbitrarily assessed.

1.3. Research significance

The insights gained in present research are oriented to facilitating the transfer of the existing approaches from laboratory to the application field. The research concept is illustrated in Fig. 1 and is summarised as follows:

- Analysis and comparison of various existing testing methods in terms of their suitability, reliability and acceptance for the characterization of concrete pumpability;
- Analysis of the dependence among the related phenomena and conditions, including formation of lubricating layer, pipeline geometry, pumping pressure, and the rheological behaviour of fresh concrete, including concrete composition;

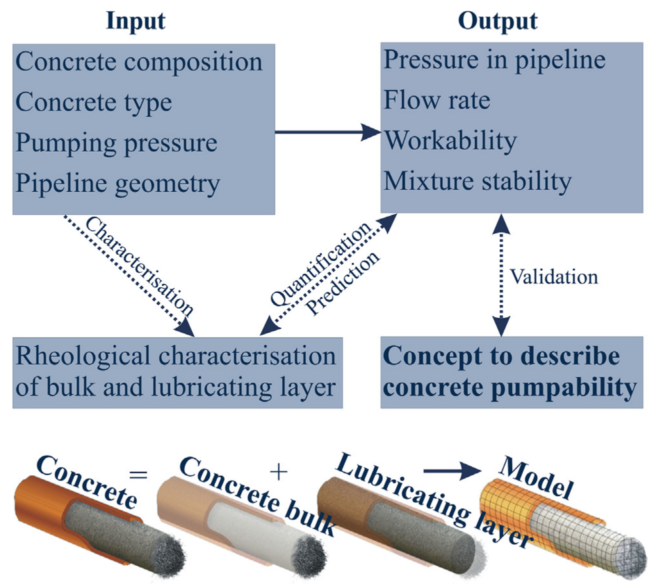

Fig. 1. Schematic representation of the research concept.

- Characterisation and quantification of concrete pumpability based on the tribological and rheological properties of the bulk concrete and lubricating layer;
- Analysis on impact of different concrete constituents on its pumpability.

The research posited here addresses a large range of concretes, including both ordinary and high performance concretes with different rheological properties in terms of yield stress τ_0 and plastic viscosity μ. As will be discussed later, concrete composition is crucial to its tribological and rheological behaviour as well as to its ability to build a sufficient amount of lubricating layer for an adequate pumpability.

2. Experimental investigation

2.1. Mixture design parameters

The respective compositions of the concrete mixtures were developed in earlier studies and implemented here; see Table 1. The materials used are listed below:

- Cement CEM II/A-LL 42.5 N, Schwenk Zement, production plant Bernburg/Germany;
- Quartz sand 0.06/0.2, Röderau/Germany;
- Quartz sand 2/4, Ottendorf/Germany;
- Gravel fractions 4/8 and 8/16, Ottendorf/Germany;
- Basalt split fractions 2/5, 5/8 and 8/16, Mittelherwigsdorf/Germany;
- Fly ash (FA) "steament H4" (from black coal), Herne/Germany;
- Silica fume (SF) Elkem 971, obtained from Elkem Refractories, Kristiansand/Norway;
- Polycarboxylate-based superplasticizer Sky 593, aqueous solution, 23 % cont. of active agent, with an extended workability retention, BASF, Trostberg/Germany.

Each mixture was given a specific name, e.g.:

- M1 and M2 – ordinary concrete with rounded (M1) or coarse (M2) aggregates with no additions;