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# Pumping of concrete: Understanding a common placement method with lots of challenges

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## ABSTRACT

Several million cubic meters of concrete are pumped daily, as this technique permits fast concrete placement. Fundamental research has been performed and practical guidelines have been developed to increase the knowledge of concrete behavior in pipes. However, the pumping process and concrete behavior are not fully understood. This paper gives an overview of the current knowledge of concrete pumping. At first, the known physics governing the flow of concrete in pipes are introduced. A series of experimental techniques characterizing concrete flow behavior near a smooth wall to predict pressure-flow rate relationships are discussed, followed by recent developments in the use of numerical simulations of concrete behavior in pipes. The influence of the pumping process on concrete rheology and air-void system is reviewed, and the first developments in active rheology control for concrete pumping are introduced. The last section of this paper gives an overview of open research questions and challenges.

## 1. Introduction

Nearly a century ago, Max Giese and Fritz Hull came up with the idea to pump concrete [1]. The industry has massively adopted this placement technique as it enables a much quicker delivery of concrete, resulting in faster construction. New records are continually being set in terms of how far and how high concrete can be pumped. The current record height is 621 m, achieved during construction of the China 117 Tower in Tianjin, China, September 2015 [2], exceeding the previous pumping height record of 606 m established while constructing the Burj Khalifa building in Dubai, April 2008 [3].

However, pumping concrete is not a straightforward task and is indeed potentially dangerous, as numerous accidents happen annually due to blocking, blowouts or breaking of the pump or the pipeline. Practical guidelines have been developed for concrete mix design and pressure predictions, based on experience, not only to select the right pump and pipeline system, but also to avoid injuries and casualties [4–8].

Examples of such guidelines are the ACI 211-P document [7], dealing with proportioning of concrete to ensure pumpability. The main message of this document is to reduce the amount of coarse aggregate, but

additional practical recommendations are included to provide guidance for improving pumpability. Another example that provides general guidance are several empirical pumping nomograms for conventional vibrated concrete [8,9], which helps in predicting pumping pressure and selecting the required pump, as a function of desired flow rate, pipeline diameter, equivalent length of the pipeline and the spread or slump of the concrete. Fig. 1 shows a general schematic of a nomogram, for which one starts on the top vertical axis and moves clockwise through the diagram to obtain pressure on the left horizontal axis. Based on flow rate and pressure, the required pump power can be obtained [9].

During the last two decades, scientific research has focused on the pumping process in an attempt to predict pumpability and pumping pressure. It should be mentioned that research prior to roughly 2000 was mainly focused on pumpability and the surrounding conditions [10–15]. After the year 2000, potentially caused by the introduction of the polycarboxylate ethers water-reducing admixtures and the application of rheology to concrete, research shifted to pumping pressure, shear-induced particle migration, and interrelations between rheology and pumping. More recently, with the introduction of 3D concrete printing, more attention is paid to matching the requirements for concrete pumpability with extrudability and layer stability [16,17].

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This paper provides an overview of the concrete pumping research developments. Its purpose is to point the readers to the most relevant concepts and tools so that this contribution can serve as a guidance to further explore the literature. A short overview is given of typical pumps and pipelines (Section 2), followed by the most relevant physical concepts applicable to pumping (Section 3). Sections 4 and 5 describe a series of experimental test methods and pumping prediction tools, respectively, while Section 6 focuses on the use of numerical simulations to understanding pumping behavior. Sections 7 and 8 discuss the consequences of pumping on key fresh and hardened properties, as well as the latest developments in rheology control to facilitate concrete pumpability. The last section gives an overview of future challenges and research needs.

## 2. Pumps and pipes

Truck mounted dual piston pumps are commonly used for concrete pumping. Invented in 1931, and with subsequent improvements, these pumps utilize an alternating and synchronized movement of two pistons connected to a valve system to push the concrete through the pipe system [18]. While one piston is pushing the concrete into the pipes, another piston is filled with concrete by suction. A stepwise control of pressure and flow rate is nowadays typically enabled through a remote control system. Depending on the design, piston pumps can handle very high pressures, and enable pumping of concrete with larger aggregates. A disadvantage is the very short interruption of the concrete stream while alternating the pistons, accompanied by short-term pressure peaks.

In case a continuous flow is required, as for 3D printing of concrete, screw pumps (also known as worm pumps) can be used, of which an early type was already designed in 1959 [19]. The principle is based on a screw that creates a positive displacement of the cementitious material upon rotation. This creates a continuous flow with a continuously controllable flow rate. However, the maximum aggregate size is

typically limited to 4 mm, or sometimes 8 mm. Because of this limitation, screw pumps are more often used for mortar and grout. Other types of pumps do exist, (e.g. peristaltic), but with very limited application to cementitious materials.

Pumping pipes are typically made of steel, except for those flexible pipes that can be used for connecting the pump to the main pipes or to a moving printing nozzle. Different diameters are available, depending on the application and the required flow rate. Larger diameters can be selected in view of reaching comparable flow rates with lower flow velocities and thus lower pressures. This can be useful for pumping shear-thickening materials like some types of self-compacting concrete [20]. It is to be noted that pipe bends lead to extra pressure losses, possibly due to dynamic effects related to the coarser aggregate particles, e.g. shear induced migration and inertial effects [21]. The magnitude of extra pressure losses due to bends is a current topic of active research. Furthermore, flow geometries like bifurcations or the addition of valves and nozzles also contribute to pressure losses. To address this, specially designed valve systems have been used for the connection of pumping pipes to formwork [22].

## 3. Physical concepts of pumping

This section briefly introduces the different physical phenomena that need to be considered to understand the flow of concrete in pipes.

### 3.1. Fluid mechanics or granular physics: Flow vs. friction

The first question that needs to be answered is: “what are the main phenomena governing the movement of concrete in pipes?” Concrete movement can be governed by either hydrodynamic interactions or by friction between the aggregate particles [15,23]. In the former case, the concrete obeys fluid mechanics laws, while in the latter case, the principles of granular materials apply [15]. In case hydrodynamic interactions govern the movement, the material can be regarded as a

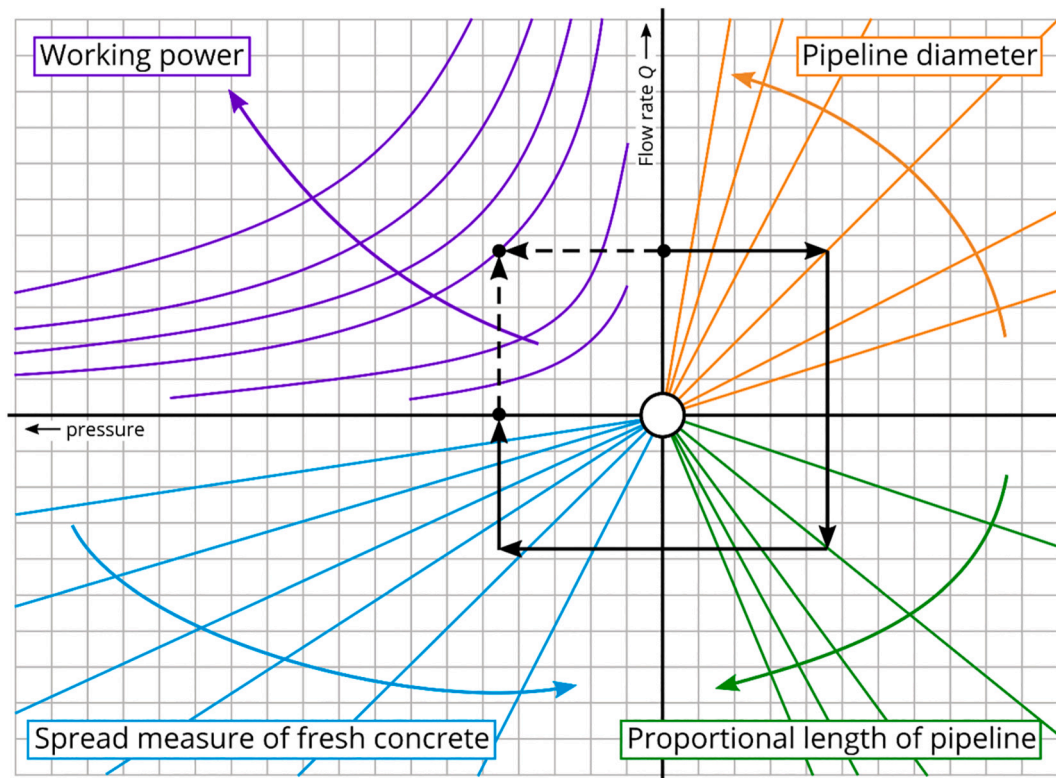


Fig. 1. Example of traditional nomogram determining pumping pressure (left, horizontal) based on flow rate (top vertical), pipe diameter, equivalent pipe length and spread or slump of the concrete. Nomogram adapted from [6,9].

suspension, while in the case of granular physics, the behavior is similar to that of a soil. Which phenomenon dominates the movement behavior has a major consequence. For incompressible fluids, ignoring the presence of air here for simplicity, the rheological behavior and flow profile are independent of the local pressure [24]. However, for granular materials, the tangential shear force is proportional to the normal force, and thus dependent on local pressure in the pipeline [25]. As such, for a straight, horizontal pipe, the pressure decreases linearly from beginning to end of the pipe in case fluid mechanics govern the behavior. However, pressure decreases exponentially in case granular physics are applicable. Browne and Bamforth have made an example calculation to evaluate the distance concrete could be pumped [15]. While for saturated concrete, i. e. dominated by flow, several 100 m could be reached with their pump design, unsaturated concrete, dominated by friction, could reach a mere 1.1 m! As such, friction should be avoided at all cost [15].

Consequently, the practical guidelines for pumping concrete impose a reduction in coarse aggregate quantity and size, and an increase in sand and cement or cementitious materials contents [7]. These measures are recommended to avoid blocking of the pipelines [26,27]. This occurs when a small section of the pipeline contains too many aggregates and the behavior transitions from hydrodynamic interactions to friction. Start-up is one of the most critical parts of the pumping process, as paste sticks to the pipe wall, leading to an increase of the relative quantity of coarse aggregates at the concrete front [26,27]. Pressurized bleeding could also lead to blocking of the pipeline. This is the internal movement of water or cement paste in between the aggregates, creating zones with a larger aggregate concentration. This effect can be reduced by decreasing the amount and the size of the void space in between the aggregates, similar to reducing the permeability coefficient in soils [28]. This can mainly be achieved by increasing aggregate content, but still avoiding friction, and by reducing the fineness modulus of the sand. Alternately, the viscosity of the paste can be increased to counter pressurized bleeding [7,29].

### 3.2. Pipe flow of homogeneous materials

When the main phenomenon governing the movement of concrete is hydrodynamic interactions, the general principles of fluid mechanics apply [24]. It is important to note, at first, that we consider the fluid as a homogeneous material. The next section discusses the causes of heterogeneity. As for any fluid, the contribution to pressure can be divided into two main components: hydrostatic and hydrodynamic [24]. The hydrostatic component can be calculated as  $\rho gh$ : the product of density ( $\rho$ ), gravitational acceleration ( $g$ ), and the height difference between inlet and outlet ( $h$ ).

For the hydrodynamic component, the following principles apply. Due to the high viscosity of concrete ( $10^1$  to  $10^2$  Pa s), the occurrence of turbulence is very unlikely, as Reynolds' numbers for concrete are still one to two orders of magnitude smaller than the upper limit in Reynolds' number for laminar regime ( $Re = 2000$ ) [20,30]. For any fluid flowing through a pipe, based on equilibrium of forces, the shear stress evolves

linearly from zero in the pipe center to the maximum value at the wall [31]. This latter stress, also named the wall shear stress, is directly proportional to the pressure loss per unit of length and the pipe radius. The pressure loss is the difference in pressure necessary to transport the material over a certain length. Knowing the rheological behavior of the material, the shear rate can be calculated from the shear stress (Fig. 2). Two rheological models are employed: the Newtonian and Bingham models: both models have a constant (plastic) viscosity at all shear rates, but the Bingham model shows a yield stress while the Newtonian model does not. In case a yield stress is observed, a portion of the material along the central axis remains unsheared. This zone is called the plug zone and the uniform movement of concrete is named plug flow. Integrating the shear rate profile delivers the velocity profile from which the flow rate can be derived (Fig. 2).

Over the last centuries, theoretical equations to describe laminar pipe flow of a fluid were derived, including the Poiseuille (Newtonian) [32–34] and Buckingham-Reiner equations (Bingham fluids) [35], and extended theoretical equations for more complex rheological behavior (e.g., [20–21]). From these equations, it can be deduced that the pressure loss increases with increasing flow rate, increasing yield stress and viscosity and increasing pipeline length. The pressure loss increases strongly with a decrease in pipe radius.

Applying the Buckingham-Reiner equation to concrete delivers a significant over-estimation of pressure (at least a factor 2, sometimes a factor 10 and more). In fact, for some concrete mixtures with high yield stress, the theoretical equation indicates no flow should occur, while the experiments show flow [36,26,20]. This is mainly attributed to the homogeneity condition of the fluid, and the idealized assumption of a Bingham fluid, not being fulfilled for flowing concrete.

### 3.3. Shear-induced particle migration

Different theories are described in the literature to characterize shear-induced particle migration [37–38]. Regardless of the theory, the net result is that particles move away from zones with high shear rates or shear rate gradients, as long as the packing in the low shear zone allows migration of more particles to this zone. The effect is amplified with increasing particle size and increasing shear rate, and is accelerated in a material with lower viscosity [37]. In equilibrium, a concentration gradient is created with the lowest quantity of particles in the zones with the highest shear rates. As the zone with the highest shear rate is near the pipe wall, a layer with a lower quantity of large particles is created there. This layer is called the lubrication layer. This layer facilitates the concrete flow, as it has a lower viscosity and yield stress, and as a result, causes an even larger velocity gradient (Fig. 2). This explains the discrepancy between the theoretical predictions based on the Buckingham-Reiner equation and corresponding experimental observations. The geometrical wall effect, which is caused by the smooth pipe wall, is expected to accelerate the shear-induced particle migration and thus the lubrication layer generation.

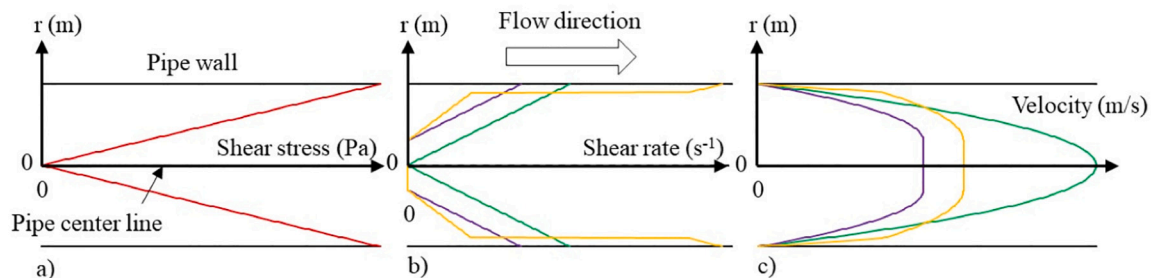


Fig. 2. Shear stress (red) (a), shear rate (b) and velocity profiles (c) for Newtonian (green), Bingham (purple) and Bingham with lubrication layer (yellow). The solid black lines indicate the pipe walls, the x-axis in each graph is the center line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 4. Testing equipment

### 4.1. General

The previous section described the flow behavior in pipes, mentioning the importance of the rheological properties and shear-induced particle migration to form the lubrication layer, on the required pumping pressure. From a physics viewpoint, the rheological property that has the largest impact on pumping is viscosity [24,31,35]. However, the empirical test method used on site is either the slump or the slump flow, which solely relates to the yield stress. As mentioned in the introduction, pumping pressure prediction nomograms were developed in the past for conventional vibrated concrete based on slump or spread as the main workability indicator. It can be assumed that this approach worked reasonably well, as historically the slump was a measure for the amount of water in the mixture, which relates to both yield stress and plastic viscosity of concrete. However, with the development of chemical admixtures such as superplasticizers that affect yield stress and plastic viscosity in a different manner, the slump test is insufficient for predicting pumping pressure for a variety of concrete types. An assessment of viscosity is required.

Furthermore, and even more relevant in most cases, the lubrication layer properties must be properly characterized. This can be done following two main strategies. In the first strategy, the flow resistance of concrete flowing near a smooth wall is directly measured. This approach is related to the field of tribology, as pumpability concerns were historically related to friction. However, recent research has not considered potential slippage, and has focused on the characterization of the lubrication layer. In this case, the term tribology is misplaced and it is recommended to replace it by “interface rheology”. Subsequently, the devices used for characterization of the lubricating layer should be called interface rheometers.

The second strategy is based on the rheological properties of bulk concrete and the lubrication layer. Typically, the lubrication layer is assumed to be a single homogeneous layer with constant rheological properties. This is a simplification of the true behavior, as a concentration gradient of particles is expected. To analytically calculate the pressure–flow rate relationship, one needs the rheological properties of the concrete and the material assumed to form the lubrication layer, along with the thickness of the lubrication layer. The thickness of the lubrication layer can be obtained with different visualization techniques or can be approximated by reverse-engineering the pressure–flow rate using analytical and numerical solutions.

### 4.2. Rheological characterization of cementitious suspensions

If the second strategy is employed, one needs to measure the rheological properties of the bulk concrete and the material that is assumed to form the lubrication layer. A detailed discussion of the execution of such measurements is beyond the scope of this paper. However, the following points are emphasized here:

- During rheological measurements, usually it is desired to match the shear rate range in the rheometer to that of the projected application. However, shear rates in the bulk concrete and the lubrication layer during pumping can be beyond the capacity of the rheometer [21], or, on the contrary, the shear rates in the rheometer might be too high causing a phase separation in the concrete (comparable to the formation of a lubrication layer) during the rheological measurement, which compromises the results [39].
- It is known that different concrete rheometers do not always deliver the same quantitative information for the same mixture [40,41]. Comparing the rheological properties of the bulk concrete with those of the material assumed to be the lubrication layer may be questionable if two different devices are employed to characterize bulk concrete and lubrication layer material.

### 4.3. Characterization of concrete-pipe interface properties

#### 4.3.1. Interface rheometers

In the last two decades, several interface rheometers were developed by Kaplan et al. [26], Chapdelaine et al. [42], Ngo et al. [43–44], Kwon et al. [45], Feys et al. [46], and Secieru [9] (See Fig. 3). Despite differences in design and geometry, all tools are based on the same concept. A smooth cylinder is rotating in a concentric container. The absence of ribs or vane blades encourages the development of the lubrication layer in the vicinity of the cylinder surface during a sufficiently long pre-shearing period. The device registers the torque at each imposed rotational velocity of the non-homogeneous material. The main difference among the devices is how flow at the bottom of the instrument is handled. For more information on this topic, the reader is referred to Refs. [26,42–43,45–46].

The results of an interface rheology test are plotted as stress versus the linear velocity at which the inner cylinder rotates. In contrast to standard rheology results, a shear rate cannot be calculated in an interface rheology test due to the unknown thickness of the lubrication layer. From the interface rheometer test results, the interface yield stress and a viscous constant of the lubrication layer can be calculated. The yield stress has the unit of Pa and is determined as the intercept of the fitted line in a shear stress–linear velocity diagram. The viscous constant (in Pa s/m) is the slope of this line. It should be noted that the viscous constant reflects both the viscosity and the thickness of the lubrication layer, but these two parameters cannot be separated experimentally. At each rotational velocity, the shear stress is calculated directly from the applied torque ( $\tau = T/2\pi R_i^2 h$ , where  $\tau$  = shear stress (Pa),  $T$  = torque (Nm),  $R_i$  and  $h$  are the radius and height of the inner cylinder (m), respectively). If the concrete remains unsheared, the linear velocity, which is in fact the difference in linear velocity over the lubrication layer, can be calculated from the rotational velocity. Feys et al. [46] have developed a procedure to subtract the contribution of the bulk concrete shearing from the rotational velocity, to determine the velocity difference over the lubrication layer. This procedure, however, requires the rheological properties of the bulk concrete. Similarly as discussed in Section 4.2, some concerns may arise when employing results from one rheometer (for bulk concrete) on the analysis of the results stemming from a different (interface) rheometer.

#### 4.3.2. Sliding pipe rheometer (SLIPER)

Although rheometers and interface rheometers can provide valuable information regarding material behavior, their shearing pattern does not fully resemble that of concrete in a pipeline. The range of applied shear rates and the curvature of the streamline in rheological measurements are the two main differences. Moreover, transporting rheometers to the construction site, performing the measurements, accurately analyzing the generated data and inserting the obtained material parameters in a pipe-flow equation for approximating the required pumping pressure are considered problematic for in-situ investigation and with respect to the desired testing frequency (ideally for every concrete mixer that is arriving on site).

To directly derive the relationship between the required pumping pressure and the flow rate for different concrete mixtures, a portable testing device, mimicking a pumped concrete scenario, was developed by Kasten [47]. Instead of measuring the material parameters to use as input parameters in pipe-flow equations such as the Buckingham-Reiner equation, the Sliding Pipe Rheometer (Sliper) mimics the actual pipeline and directly measures the material response. The Sliper consists of a 1.5 m long pipe of 125 mm diameter and a 1 m long cylinder that is placed inside the pipe. In contrast to real pumping, it is not concrete which is moving in the pipe but the pipe is moving while concrete remains in place and exerts pressure on the cylinder below. The integrated pressure sensor on top of the cylinder measures the induced pressure by concrete in every single stroke. Various weights are attached to the pipe in measurements to induce varying velocities of the pipe movement



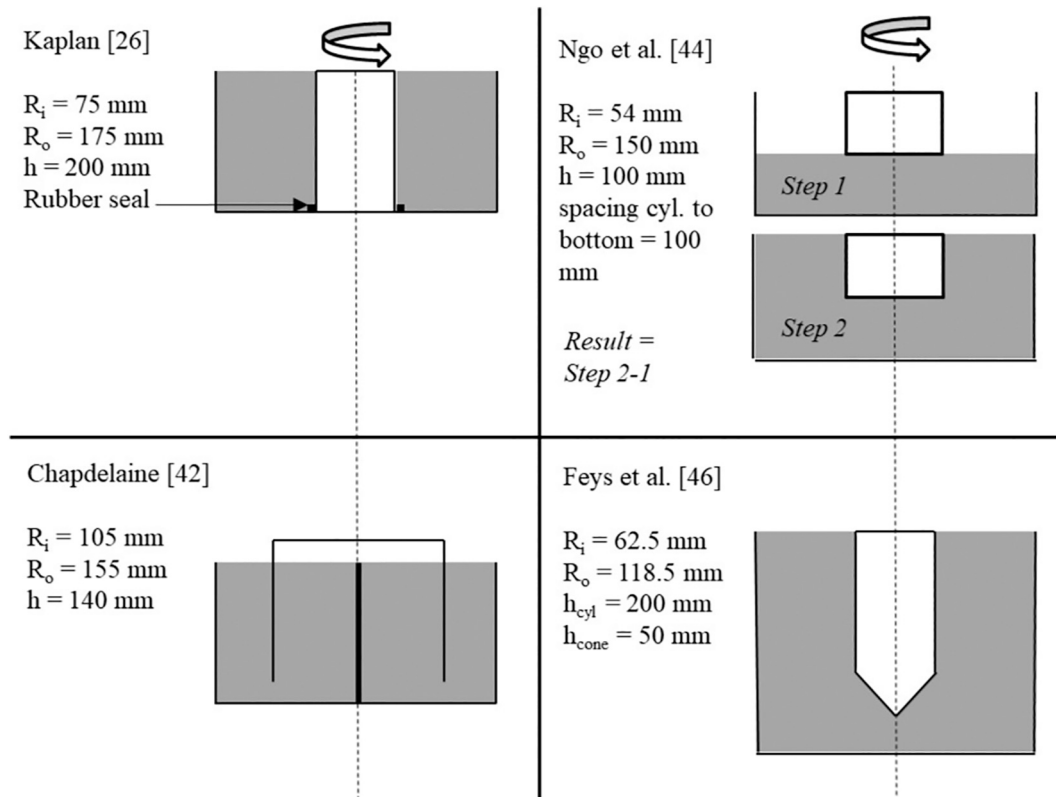


Fig. 3. Overview of interface rheometer geometries, as developed by Kaplan [26], Chapdelaine [42], Ngo et al. [44] and Feys et al. [46]. Figure adapted from [46].

(concrete flow rates).

Since the flow rate and the pressure gradient in the Sliper are in the same range of large-scale pumping, it is expected that whatever happens to concrete in large-scale pumping, happens to the concrete sample inside the Sliper. Thus, the obtained relationship between the pressure gradient and flow rate from the Sliper can be used to predict the required pumping pressure for a large-scale pumping setup [47,9]. More information regarding testing methodology and data analysis can be found in [48].

#### 4.3.3. Limitations with regards to pumping

Section 5 elaborates how the output of various measurement approaches has been successfully used for pressure prediction. However, a number of limitations of such prediction need to be considered first in order to avoid application errors.

While particle migration inside a pipe causes formation of the lubrication layer, it also results in an increase in volume fraction of aggregates in the bulk concrete. Thus, the rheological properties determined on a concrete sample may underestimate the Bingham parameters of the bulk concrete inside the pipe. On the other hand, due to shear-induced particle migration towards the pipe center, the aggregates may form a connected network that can span the pipe cross section occupied by the bulk concrete, causing frictional effects between the aggregates, also enlarging the plug zone compared to estimates based on the rheological measurements.

There is a discrepancy between the lubrication layer formation in the pipe and the lubrication layer formation in an interface rheometer. In the former case, the aggregates need to move inward into a more confined space. In the latter case, the aggregates move outward in a less confined space. As a result, the lubrication layer might be larger in the interface rheometer, compared to that in a pipe. The flow curvature in the interface rheometer may amplify this effect [49]. In similar fashion, each interface rheometer has a fixed thickness for the flow domain, while pumping with different pipe diameters may induce different

thicknesses and composition of the lubrication layer.

Although fresh concrete can be regarded as an incompressible fluid, at least some air will become dissolved under pressure, altering the rheological properties. This change in rheology is not captured by most rheometers, the interface rheometer, or Sliper tests, as all occur under atmospheric pressure. Performing rheological tests under pressure has been practiced for cement paste and fine mortar thus far [50], but not for concrete. More details on the influence of pumping on air content in concrete can be found in Section 7 below.

Bleeding and segregation may be more pronounced and may have a stronger effect on the rheometer, interface rheometer, or Sliper tests in comparison to the situation during pumping. Some field experiments have shown higher flow resistance in the Sliper compared to actual pumping conditions, and even jamming in some cases in the Sliper where no blockage was observed in the pipeline.

The last effect that none of the existing testing tools can capture is the effect of dilation: the volume increase of unconfined concrete as aggregates pass each other. Pumping is classified as confined flow, while previously described methods are free surface flows. Dilation occurring in the testing equipment may cause significant under-estimation of the pumping pressure. No solution is currently available, but this concern will be more extensively discussed in Section 9 below.

#### 4.4. In-line measuring and monitoring systems

The experimental investigations mentioned to this point are all off-line measuring methods. To investigate the flow behavior of concrete during pumping, in-line measuring systems are required. Two well-known in-line devices are pressure sensors and flowmeters, which are commonly used in large-scale pumping investigations [36,51,21,52,9]. In addition to the standard measurements of pressure and flow rate, other measurements are discussed below.

#### 4.4.1. Ultrasonic velocity profiler (UVP)

Ultrasound real time flow monitoring equipment as developed in the food industry [53] can be adapted and installed on pumping pipes for cementitious materials. The Ultrasound Velocity Profiling (UVP) instrument, based on the Doppler echo effect, contains specially designed transducers that are mounted to the pipe surface, which eliminate disturbing coupling effects by using appropriate acoustic couplers in the contact zone between the ultrasound transducers and the pipe wall. The measurement technique is non-invasive, and does not interfere with the material flow. The UVP monitoring technique enables measuring velocity profiles of cementitious materials flowing in a pipe but typically to a depth of the order of 10 mm. Nevertheless, this is sufficient to measure the velocity profile near the pipe surface, focusing on the lubrication layer. Fig. 4 shows a closed-loop pumping circuit for mortar through 25 mm diameter pipes instrumented with the UVP equipment, as available at Ghent University. At a larger scale, the principle of the UVP technique has been used by Choi et al. [54] to study the lubrication layer while pumping concrete. Combined with pressure difference measurements (UVP-PD), the setup could also be used for in-line rheometry [53].

#### 4.4.2. Visual approaches

Jacobsen et al. [55] used colored concrete to visualize the velocity profile of pumped concrete. First, the pipe was filled with uncolored (gray) concrete. Afterwards, colored (dark) concrete was introduced, after which flow was resumed for a short time, sufficient to develop the velocity profile. After hardening and cross cutting, the velocity profile was obtained visually, showing the lubrication layer.

Another visual approach was developed by Le et al. [56]. An open half pipe was mounted in an inclined position. Driven by gravity, concrete flowed in the half pipe. On the surface, small styrofoam particles were distributed, and their movement was tracked with a high-speed camera. Based on Particle Image Velocimetry (PIV), the velocity profile in the flowing concrete was experimentally determined, clearly showing the formation of the lubrication layer. Although this approach did not consider a closed pipe under pressure, the results have contributed significantly to estimating the thickness and the composition of the lubrication layer.

To determine the thickness of the lubrication layer and to show the non-uniform particle distribution resulting from pumping, Fataei et al. [57] let concrete mixtures set and harden in the Sliper device after the

actual test, thus, after the formation of the lubrication layer. Eventually, the samples were cut longitudinally for further visual analysis of the cross-section. In an on-going investigation, the same group of researchers is working with model concrete mixtures, containing glass spheres of 1 mm, 2 mm, 4 mm and 8 mm in diameter, each particle size having a different colour. The aim is to derive lubrication layer thickness and changes in the volume fraction of each size class, over the cut section, with higher accuracy in a poly-dispersed granular suspension. The lubrication layer thickness is the maximum distance from the wall above which the particle volume fraction no longer significantly changes. By doing this, a reliable data base for comprehensive numerical analysis of shear-induced particle migration is being created. Fig. 5 compares images of real and model concrete mixtures investigated in this way.

#### 4.5. Stability and bleeding control

As mentioned in Section 3.1, internal stability of the water or paste is essential for good pumpability. Several test methods were proposed in recent literature [15,26,59–62], and despite their variability, these are mainly based on the same principle. A cementitious material is subjected to an external force or pressure gradient, while the movement of the (coarser) particles is hindered. A couple of these devices use a set of sieves and filters to keep the particles in place. The pressurized or forced bleeding is measured as the amount of separated material (water or paste), sometimes expressed as a function of time. Such tests have also been used in research to estimate the lubrication layer properties and thickness [63].

### 5. Prediction of pumping pressure

#### 5.1. General

All testing devices and experimental methods introduced in Section 4 are focused on answering open questions regarding pumpability by investigating some aspects of concrete flow in a pipe: the material characteristics, the lubrication layer composition and thickness, the velocity profile of concrete inside a pipe, and so on. However, as long as a general flow equation such as Buckingham-Reiner is used [35], the pressure loss values are over-estimated. Thus, researchers are beginning to establish more specific pipe-flow equations for concrete and other

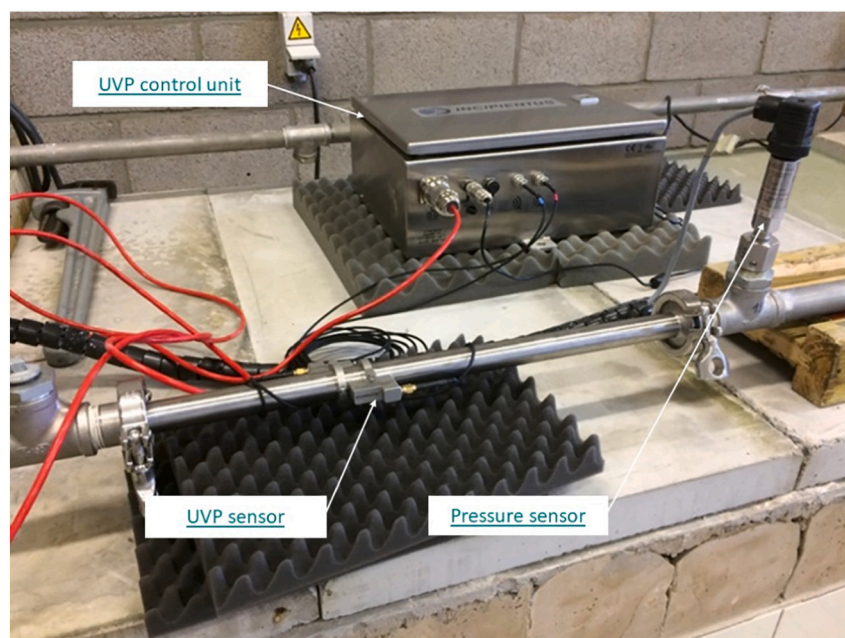
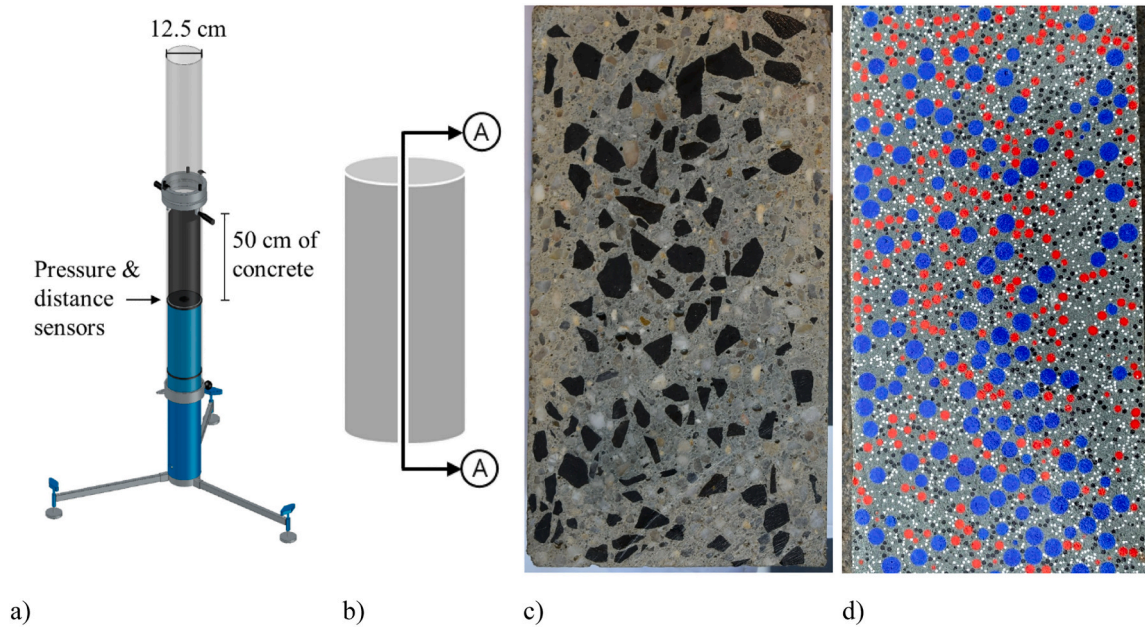


Fig. 4. Closed-loop pumping circuit for mortar instrumented with UVP equipment (G. De Schutter, Ghent University).



**Fig. 5.** a) Sliding pipe rheometer [58], b) the cutting pattern of the cast sample [57], c) the longitudinal cross-section for an ordinary concrete containing dark basalt aggregates of 8–16 mm, and d) the longitudinal cross-section for poly-dispersed model concrete with colored particles (Fig. 5c, d: S. Fataei, V. Mechtcherine, TU Dresden).

granular mixtures that are susceptible to forming a lubrication layer during pumping. The formation of the thin lubrication layer with lower plastic viscosity compared to the bulk concrete viscosity eases the concrete flow in a pipe significantly and reduces the required pumping pressure - therefore, it cannot be neglected in the pipe-flow equation. In this section, two types of pipe-flow equations are presented. Additionally, modern nomograms and questions or concerns regarding the lubrication layer are discussed.

### 5.2. Prediction equations based on interface properties

To include the influence of the lubrication layer without actually answering the questions above, Kaplan et al. [26,36] derived pipe-flow equations based on concrete-pipe interface properties that can be measured experimentally using a so-called “tribometer” or “interface rheometer”, see Section 4.3.1. They assumed that, for most concrete mixtures, all shearing is concentrated in the thin interface layer. Depending on its yield stress, the concrete bulk either flows as a solid plug or partially deforms under the induced shear stress by the pump. For the explained flow regimes, the required pumping pressure  $P$  [Pa] for maintaining the flow rate of  $Q$  [m<sup>3</sup>/s] in a pipeline of radius  $R_{pipe}$  [m] and length  $L$  [m] can be calculated using the following analytical equations:

1. Major deformation in interface layer, and no deformation in bulk concrete

$$P = \frac{2L}{R_{pipe}} \left[ \frac{Q}{\pi R_{pipe}^2} \cdot \eta_i + \tau_{0,i} \right] \quad (1)$$

2. Major deformation in interface layer, plus partial deformation of the bulk concrete

$$P = \frac{2L}{R_{pipe}} \left[ \frac{\frac{Q}{\pi R_{pipe}^2} - \frac{R_{pipe}}{4\mu} \tau_{0,i} + \frac{R_{pipe}}{3\mu} \tau_0}{1 + \frac{R_{pipe}}{4\mu} \eta_i} \cdot \eta_i + \tau_{0,i} \right] \quad (2)$$

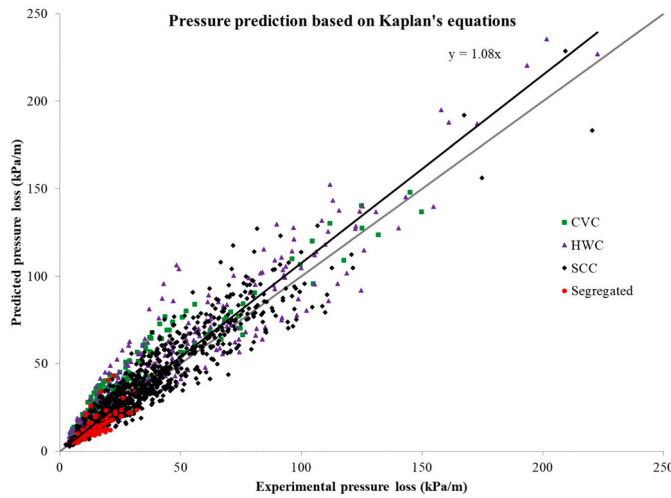
where,  $\tau_{0,i}$  [Pa] and  $\eta_i$  [Pa·s/m] are the interface yield stress and viscous constant, measured with an interface rheometer and  $\tau_0$  [Pa] and  $\mu$  [Pa·s] are the yield stress and plastic viscosity of the concrete, as measured with concrete rheometers. To validate the proposed method, a full-scale pumping circuit of 148 m with 125 mm-diameter steel pipes was designed and used to measure the pressure loss and flow rate while pumping mixtures [26,36].

Feys et al. [46] extended this approach for highly-workable concretes by means of a new interface rheometer and data analysis procedure that accounts for the contribution of concrete shearing during these measurements. They validated the new interface rheometer and the proposed data treatment by pumping 25 concretes, including 18 self-consolidating concrete mixtures, in a 30 m-long loop [52]. It was concluded that the approach proposed by Kaplan et al. [26,36] was capable of predicting the pressure losses, with great accuracy, if the shearing of the concrete bulk is accounted for during the interface rheology measurements (Fig. 6). It was also shown in [52] that the flow behavior of the bulk (plug or shear flow) depends on pumping characteristics, pipe diameter and concrete rheological and interface properties.

### 5.3. Flow equations based on rheological properties and thickness of lubricating layer

In another approach the lubrication layer and bulk concrete are considered as two separate immiscible fluids that are pumped inside a pipeline. The lubrication layer is the fine cementitious mortar that is formed due to shear-induced particle migration. It exhibits the highest shear stress and deformations within the thickness of few mm. The bulk concrete is surrounded by this layer and depending on its yield stress, the bulk concrete might partially or fully shear under the applied pumping pressure. Kwon et al. [51] derived the velocity profiles for the lubrication layer and the bulk concrete as well as the flow equation,





**Fig. 6.** Validation of Kaplan's equations predicting pumping pressure [26,36], based on interface and bulk concrete rheology, pipe radius and flow rate. Measurements are performed on pumpable concrete mixtures with varying consistencies (CVC = conventional vibrated concrete, SCC = self-consolidating concrete, HWC = highly workable concrete with consistency between CVC and SCC). Figure adapted from [52].

when the rheological behavior of the lubrication layer and the bulk concrete can be described by the Bingham model. Accordingly, the relationship between pressure loss per unit length  $\Delta P/L$  [Pa/m] and flow rate  $Q$  [m<sup>3</sup>/s] in a pipeline of radius  $R_{pipe}$  [m] is defined as:

$$Q = \frac{\pi}{24\mu_{LL}\mu} \left( 3\mu \frac{\Delta P}{L} (R_{pipe}^4 - R_{LL}^4) - 8\mu\tau_{0,LL} (R_{pipe}^3 - R_{LL}^3) + 3\mu_{LL} \frac{\Delta P}{L} (R_{LL}^4 - R_{plug}^4) - 8\mu_{LL}\tau_0 (R_{LL}^3 - R_{plug}^3) \right) \quad (3)$$

where  $\tau_{0,LL}$  [Pa] and  $\mu_{LL}$  [Pa·s] are the yield stress and plastic viscosity of the lubricating layer, and  $\tau_0$  [Pa] and  $\mu$  [Pa·s] are the concrete yield stress and plastic viscosity.  $R_{LL}$  [m] is the distance from the center of the pipe to the lubrication layer and  $R_{plug}$  [m] is the radius of the concrete plug.  $R_{plug}$  depends on the yield stress of the bulk and the local shear stress inside the pipeline. Therefore, it can be calculated as the radius at which shear stress and yield stress are equal:

$$R_{plug} = 2\tau_0 \frac{L}{\Delta P} \leq R_{LL} \quad (4)$$

Referring to Fig. 2,  $R_{plug}$  is the radius at which the shear rate changes from zero to non-zero, and where the velocity profile changes from constant to non-constant.  $R_{LL}$  is the radius at which there is a jump in shear rate (yellow curve – a consequence of assuming two homogeneous materials) and at which there is an abrupt change in velocity gradient.

To be able to use these equations, the thickness of lubrication layer should be experimentally measured first, using any of the techniques described in Section 4. Then, the lubrication layer material must be sampled and its rheological properties must be determined. Several attempts have been made to study the lubrication layer in more detail. Further discussion on this topic can be found in Section 5.5.

#### 5.4. Modern nomograms to predict pumping pressure

In the introduction, pumping nomograms were introduced where the main input to characterize the concrete is its slump or spread. For modern concretes with more complex compositions, the viscosities of

the lubricating layer and the bulk concrete are independent of the yield stress parameters [64]. For such mixtures, the common tests for consistency – the slump test or the spread table test – yield information on yield stress parameters only. Since viscosity is more important with respect to the prediction of pumping pressure, alternative material parameters need to be used in nomograms. The nomograms in the form as shown in Fig. 1 can accommodate only one material parameter representing concrete's pumpability. Secrieru [9] suggested to use the viscosity parameter  $b$  from the Sliper measurements for this purpose (Fig. 7) and demonstrated a very good prediction of the pumping pressure for various types of concrete including ordinary to SCC. The accuracy of such prediction could be further improved by introducing the second rheological parameter, the yield stress parameter  $a$  from the Sliper measurements. A straightforward way to do that would be in providing the second nomogram of the same style, and then sum up the readings of the pumping pressure from both nomograms. Such an extension makes the approach more laborious and so has not yet been developed.

#### 5.5. Lubrication layer composition and properties: a controversy?

Two approaches to characterize and predict the concrete flow in pipes were discussed in Chapters 4 and 5. The interface rheometers and the Sliper do not provide direct information on the composition and thickness of the lubrication layer, but the overall flow resistance is grouped in specific parameters. Correlations between bulk concrete and interface properties have been attempted, with varying successes [26,46]. The other prediction approach is based on the rheological measurement of bulk concrete and the material assumed to form the lubrication layer. Analytical equations, with a measured or assumed

thickness of the lubrication layer, enable a relatively simple prediction of pumping pressure [66]. However, and there is no uniform answer in literature, what is the composition of the lubrication layer, and how thick is it?

The most reliable method to determine the lubrication layer thickness would be measuring techniques or visual approaches, such as UVP [66], PIV in half-open pipes [56], or to let concrete harden in the pipes [55,57]. Conclusions from these measuring techniques, based on a sharp change in velocity gradient, is that the lubrication layer is approximately 2 mm thick for most mixtures. However, there is no clarity on what this material in the lubrication layer is. Some authors assume that it is the constituent mortar, with up to 5 mm particle size. This assumption has delivered relative accurate predictions of pumping pressure, although one can question how 5 mm particles in diameter fit in a 2 mm thick layer.

Other authors suggested, rather that the lubrication layer is a micro mortar, with a maximum particle size of approximately 1 mm. This was measured by extracting and sieving the lubrication layer, either from a half-open pipe [67], or from an interface rheometer [43].

A third approach to retrieve the lubrication layer thickness is to reverse-engineer the results from interface rheometry [68] or Sliper tests [58]. For these approaches, either multiple devices are employed and combined to retrieve the lubrication layer thicknesses [58], or the rheological properties of the composing cement paste, mortar with different particle sizes, and concrete are measured or predicted [68]. With the former approach, lubrication layer thickness varied considerably with concrete composition, while the latter approach revealed multiple analytical solutions to the problem. For example, Salinas and

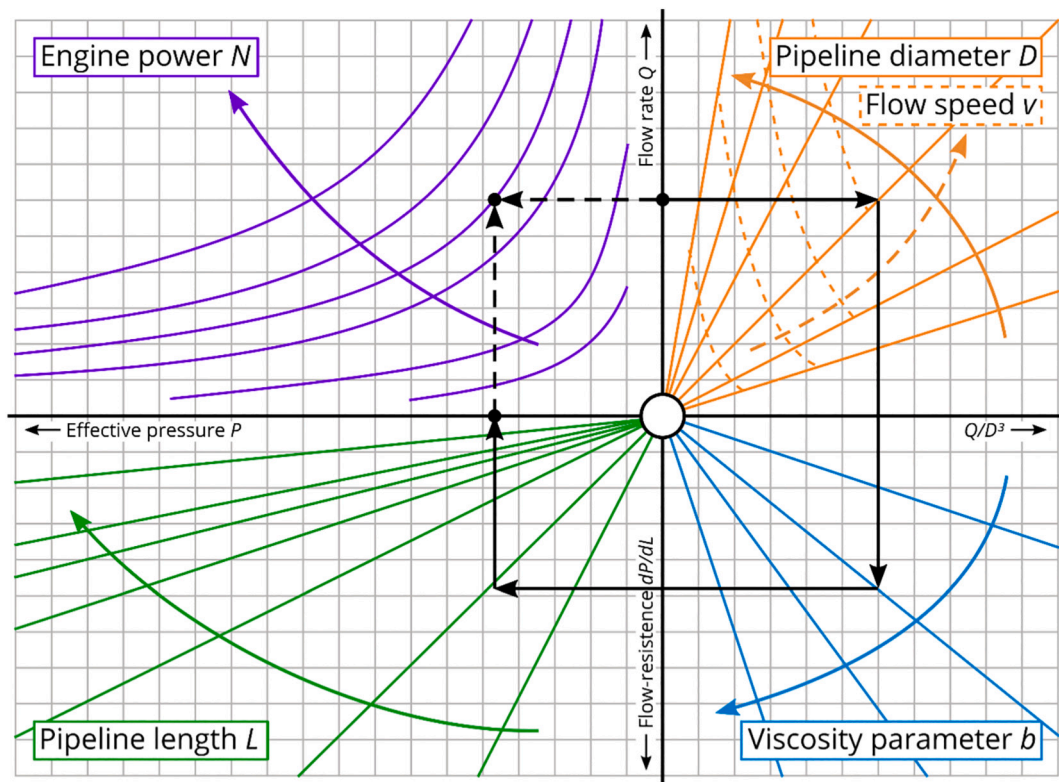


Fig. 7. A modified nomogram adapted from [9,65]; colour arrows show the directions in which the parameters' values increase.

Feys reported, based on their selected mixtures, that the following solutions were equally possible mathematically [68]:

- 2 mm to 10 mm thick mortar layer with up to 4.75 mm particles;
- 0.5 mm to 2 mm thick mortar layer with 2.36 mm particles;
- 30  $\mu\text{m}$  to 125  $\mu\text{m}$  thick cement paste layer.

The question is, which one is physically right? The basic physics of the process might suggest an answer. Shear-induced particle migration theories indicate that the rate of migration is proportional to the diameter of the particles squared, and logically, coarse aggregates will migrate more quickly [37,57]. However, finer particles will also undergo particle migration, but the time during which they are pumped, which depends on the length of the pipeline, might be too short for the phenomenon to occur. Furthermore, the migration of the finer particles is limited by the already migrated coarser particles [49]. Secondly, an equilibrium is achieved. According to prominent shear-induced particle migration theories, particle migration is limited by a local increased particle concentration, which increases locally the viscosity and pushes the particles back to the higher sheared zones [37]. This would mean that particles are in a dynamic equilibrium with a random complex oscillatory radial motion when flowing through the pipes. On the other hand, if a portion of the bulk concrete remains unsheared and the maximum packing density is approached [26], the formation of the lubrication layer could be enhanced. Even in other suspensions in coaxial cylinder rheometry, with particle volume fractions close to maximum, local shear-banding due to jamming has been observed [69]. A simplified physical model was recently derived by Fataei et al. [70] to consider the influence of shear-induced particle migration on the formation of the lubricating layer and the general flow behavior of dense granular suspensions. Despite its simplicity, the model could explain the flow behavior of concrete mixtures in both Sliper and interface rheometer.

As such, there is currently no uniformly accepted answer to

lubrication layer composition or thickness. It could be a mortar, micro mortar or even a cement paste layer, depending on the available space for migration and how quickly migration is established. Experimental studies of this topic are complex, difficult, and time-consuming. The next section explores the potential for numerical simulations to solve this problem.

## 6. Numerical simulations

Despite advances in testing equipment and derivation of more specific analytical equations for dense granular suspensions, there are still many unanswered questions with regard to concrete flow behavior in a pipeline. To understand concrete flow behavior in greater depth and to answer some of the open questions, numerical simulations and computer modeling can be of value. Unfortunately, modeling of a concrete mixture in full detail remains a challenging task due to the wide range of particle size. However, computer simulation does enable us to model concrete in more detail than analytical models. Regardless of this potential, one must employ a strategy that targets the important features of flow, e.g. flow near a surface, to better understand lubrication effects or simplifying assumptions to model bulk flow. One of the best strategies in modeling concrete flow is to use a multiscale approach where the modeler describes the concrete on three different length scales. These length scales correspond with typical solid inclusion size: 1) the cement paste (10 to 100  $\mu\text{m}$ ), 2) the mortar (mm size sand) and 3) concrete with cm scale aggregate. Although an over-simplification, the mortar can be treated as sand in a paste medium, or the concrete as “rocks” in a mortar medium. Regardless of the modeling strategy, it is crucial that computer simulation results are validated by either analytic solutions when possible and/or experimental results. Further, given its complexity, it may make much more sense to use modeling as a tool to develop a conceptual framework for understanding the flow of concrete and determine the important features that have the biggest impact on flow rather than a predictive tool for a particular concrete. Several

computational approaches have been utilized to act as a predictive tool and develop physical insights into the flow behavior of concrete in a variety of conditions, although a precise prediction of concrete flow and placement remain elusive.

There are generally two modeling approaches utilized. Continuum based models that treat the suspension as a homogeneous fluid and models that account for the explicit motion of solid inclusions. There are also hybrid approaches that can incorporate and utilize information from each approach. Each approach has its strengths and weaknesses.

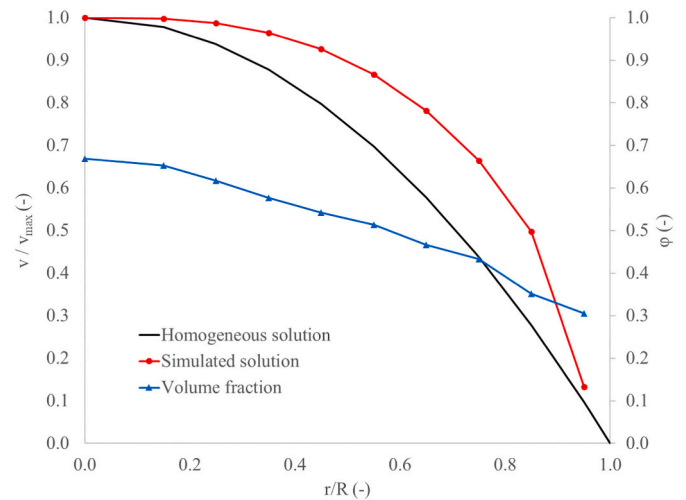
At the coarsest scale, where the concrete composite can be approximated by a continuum, it is in principle possible to use a computational fluid dynamics (CFD) approach, i.e., a Navier-Stokes solver of choice to model concrete flow in a pipeline [71] and other geometries like a slump cone or L-box [72,73]. However, what is needed for success of this approach, and is generally missing, is a constitutive relation that describes the viscosity (or stress) vs. shear rate of the concrete [74]. Ideally, we would know this from the mix design. However, due to the variability and complexity of concrete's constituents this is nearly an impossible task from ab initio calculations. A constitutive relation can be obtained through experimental measurements and can be typically modeled using phenomenological equations (e.g. Bingham, Herschel Bulkley, thixotropy based models like the Roussel model [75]). Increasing this complexity is the fact that the fresh concrete is subject to hydration; hence the rheological properties are time dependent. In addition, one must know how to properly incorporate boundary conditions, including driving forces and the concrete/wall interaction. Therefore, while one may attempt to measure such quantities, it remains to be seen how robust and accurate these measurements can be. Even interpretation of concrete flow in a rheometer can be challenging as one must account for many flow artifacts [39].

An important feature missing in continuum models is the granular aspect of concrete. As concrete will have coarse aggregates, effects like shear-induced migration, segregation and a lack of homogeneity, especially near a solid surface, lead to effective slip and other physical phenomena [73]. There are efforts to account for such phenomena by modifying the constitutive relationship to account for local density variations of coarse aggregate and the history of flow, although it remains to be seen how predictive using such modifications work in realistic flow conditions.

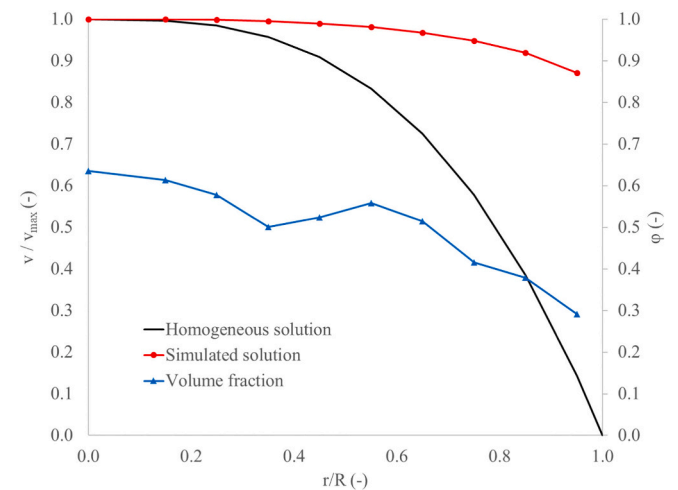
The second approach involves a greater effort where the concrete is treated as a suspension of particles. As, described earlier, it is impossible to simulate the entire system simultaneously over all relevant length scales. Hence, it is practical to take a divide and conquer approach, or in this case, a multi-scale approach. An example of a multi-scale approach was the development of standard reference materials for the calibration of concrete rheometers and other cement-based materials [76–77].

Further, one may use such models to determine boundary conditions that can then be incorporated into continuum models. Multiscale models can also be used to build a constitutive relation between the viscosity and shear rate that depends on volume fraction, local shear rates and other factors. With this information one may, for example, more accurately model pumping using continuum models. Other factors such as shear-induced migration and thixotropy can also be accounted for in a similar manner. In addition, random shaped particles have been included in such simulation. For example, X-ray tomographic images of rocks have been used in Dissipative Particle Dynamics (DPD) [78] and Smoothed Particle Hydrodynamics (SPH) [79] based simulations of suspensions in Newtonian or Non-Newtonian matrix fluids.

An example of how detailed suspension modeling, relevant to cement-based materials, can help develop a framework for understanding pipe flow, considers the following simulations. Here a mortar-like fluid moving through a pipe is simulated using a SPH approach. While details of the simulation are beyond the scope of this paper, let it suffice to say that the simulation models a hard sphere suspension embedded in a matrix fluid that was chosen to be either Newtonian (viscosity is constant) or shear thinning (viscosity decreases with



**Fig. 8.** The radial dependence ( $r$  = radial parameter,  $R$  = pipe radius) of the axial velocity ( $v$ ), relative to the maximum velocity ( $v_{max}$ ) at the pipe center, and volume fraction ( $\phi$ ), for the case of a suspension with a Newtonian matrix fluid. The black line represents this theoretical homogenous solution for the velocity profile (in this case Poiseuille), while the red curve is the simulated solution of the velocity profile taking particle migration into consideration. The extent of particle migration is depicted by the blue curve. Figure after [80]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 9.** The radial dependence ( $r$  = radial parameter,  $R$  = pipe radius) of the axial velocity ( $v$ ), relative to the maximum velocity ( $v_{max}$ ) at the pipe center, and volume fraction ( $\phi$ ), for the case of a suspension with a shear-thinning matrix fluid. The black line represents this theoretical homogenous solution for the velocity profile, while the red curve is the simulated solution of the velocity profile taking particle migration into consideration. The extent of particle migration is depicted by the blue curve. Figure after [80]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increasing shear rate). The matrix fluid is generally described by the Navier-Stokes equations whereas the spheres are solids that interact with the matrix fluid as well interacting with other spheres and the pipe wall through lubrication forces. Note that due to computational constraints the lubrication forces cannot be directly modeled by the Navier-Stokes solver but are instead included by analytic equations. Figs. 8 and 9 compare the flow profile for when the spheres are in a Newtonian fluid matrix and in a shear thinning matrix [80]. When the matrix fluid is shear thinning, like a paste or mortar, the velocity profile is much flatter,

and it appears as if there is an apparent slip effect near the pipe wall. Note that in both cases, there is shear-induced migration of the spheres towards the center of the pipe. As a result, the volume fraction of spheres has a pronounced radial dependence. This is in line with the experimental results and prediction methodologies that a lubrication layer with lower rheological properties (e.g. smaller viscosity and yield stress) is formed near the pipe wall.

Such detailed simulations have a shortfall in that they are limited in the system size that one may study because of current computer limitations. However, by proper coarse-graining, they can provide valuable insight to formulation of boundary conditions at the fluid wall interface and the construction of a constituent equation describing the coarse grained fluid. In addition, through visualization of the simulation, one may actually see what the lubrication layer looks like, its width, and temporal behavior to help develop critical insights into its behavior.

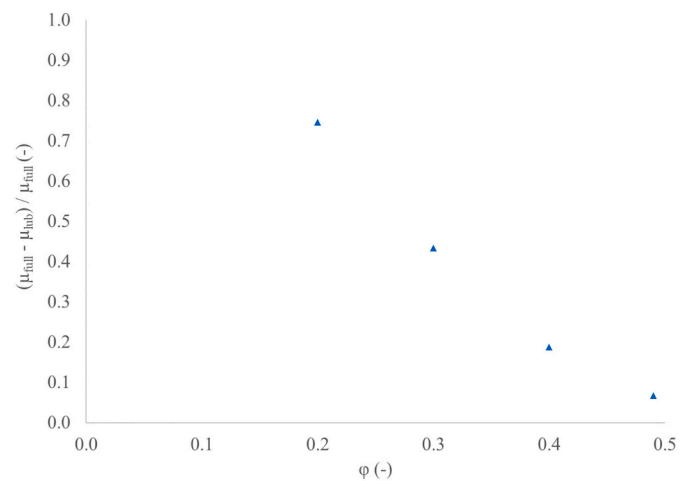
To help overcome computational limits on the detailed modeling of suspensions, so as to describe larger systems with greater number of aggregates, researchers have turned to another approach, the Discrete Element Method (DEM) [72–73,81–82]. DEM is a minimalist approach to modeling suspensions that utilizes a set of semi-empirical rules describing the interaction between aggregates. In DEM, the detailed flow evolution of the “matrix” fluid is ignored in favor of simple rules that approximate the fluid behavior of the suspension. Typical DEM models describe a suspension as a collection of spheres that interact via a “spring-dashpot” model. The spring part usually prevents spheres from overlapping and the dashpot produces a viscous dissipation effect. The parameters of the spring-dashpot model can be calibrated to reproduce experimental results. A frictional interaction between spheres is also used in DEM. Friction is especially important to address phenomena like jamming. However, at this stage, the addition of friction is still phenomenological and needs further investigation, including, as in the case of the spring-dashpot model, close comparison to experiments to determine parameters for input into simulations.

While DEM may appear ad-hoc as it is not directly constructed from the Navier-Stokes equations, as long as it conserves mass (satisfies the continuity equation), conserves momentum, and is Galilean invariant, then, at some degree of coarse graining, it will be consistent with the Navier-Stokes equation. Indeed, this thought framework has been used in the development of alternate models of fluid flow like Dissipative Particle Dynamics (DPD) and Lattice Boltzmann method that on the surface bear no resemblance to Navier-Stokes; yet in certain flow regimes, reproduce solutions of Navier-Stokes [83].

DEM has been used to model slump tests and flow in an L-box with some success [72,81]. It has also been used to study segregation of granular materials in pumping that relies on double piston pumps, which is a complex flow scenario to model. Such simulations have demonstrated a strong radial dependence of volume fraction as friction is varied. While DEM modeling results may not be exact, such modeling provides insight into flow behavior during pumping.

A simple physics-based DEM can be constructed that ignores the general effect of the matrix fluid and only allow lubrication forces to play a role. Such an approach has been used to study jamming in dense suspensions.

These models only work well at sufficiently high volume fractions. It has been found that at volume fractions of approximately 40% and higher, modeled flows are produced that are reasonably consistent with the fully detailed simulations. The reason being that at higher volume fractions, the surfaces of the solid inclusion are close enough such that the lubrication forces dominate over others and are sufficient to represent flow (Fig. 10). In summary, computational modeling of suspension flow is showing great promise as a tool to develop a fundamental understanding of concrete flow and becomes a prediction tool for engineers interested in pumping and related flow problems, such as 3D printing of concrete.



**Fig. 10.** Comparison between the estimated viscosity of suspension using full simulation (matrix fluid + lubrication – denoted by  $\mu_{full}$ ) to simulation of suspension with lubrication forces only ( $\mu_{lub}$ ), as a function of volume fraction ( $\phi$ ). (N. Martys, NIST).

## 7. Changes in concrete properties induced by pumping

Previous sections discussed how several concrete properties can be used to predict pumping pressures experimentally or numerically. It has also been shown that the lubrication layer, and potentially the bulk concrete, are exposed to extensive shear rates of several  $100 \text{ s}^{-1}$  in the lubrication layer and several  $10 \text{ s}^{-1}$  in the bulk concrete in case of SCC [20]. In addition, the material is also exposed to high pressure during the process. This section discusses how shear and pressure affect concrete properties, focusing on rheology and the air-void system.

### 7.1. Effect of pumping on concrete rheology

In the case of SCC, large portions of the concrete are exposed to high shear rates for long periods of time. The total energy applied (shear combined with time) in the pumping process is expected to be greater than the amount of energy applied during mixing [64]. In fact, even in high shear mixers, the concrete is only subjected to elevated shear rates for short time intervals. Therefore, the application of a higher shear rate should result in more dispersion of cement and other fine particles [75]. Consequently, lower rheological properties are expected. Feys et al. have demonstrated the sensitivity of pressure loss for SCC to the applied flow rate [21,64] by following a stepwise protocol with an applied maximum flow rate increasing stepwise, as the concrete was continuously recirculated in the circuit. The results indicated that each time the applied flow rate increased, the pressure loss at a lower flow rate decreased (Fig. 11). However, this is a single occurrence phenomenon, as a repetition of this procedure on the same concrete mixture did not reveal any more differences.

Measurements in a different pumping circuit by Feys et al. have also shown that the viscosity of highly flowable mixtures decreased each time the concrete was pumped [64]. Other results confirm the decrease in viscosity due to pumping [63,84]. As pumping pressure can be strongly related to viscosity, this explains the results in the above figure. However, Feys et al. also discussed results on yield stress, for which a more ambiguous behavior was observed [64]. Yield stress decreased, remained constant or increased, although Secieru et al. indicated that the increase in yield stress occurred more often [63]. Feys et al. hypothesized that the availability of any dispersing admixture in the mixing water at the time of pumping could determine the outcome. Shear causes more dispersion of fine particles. If these surfaces could be coated with the remaining dispersant, the yield stress should decrease. If not, the yield stress should increase. Both situations were observed, but



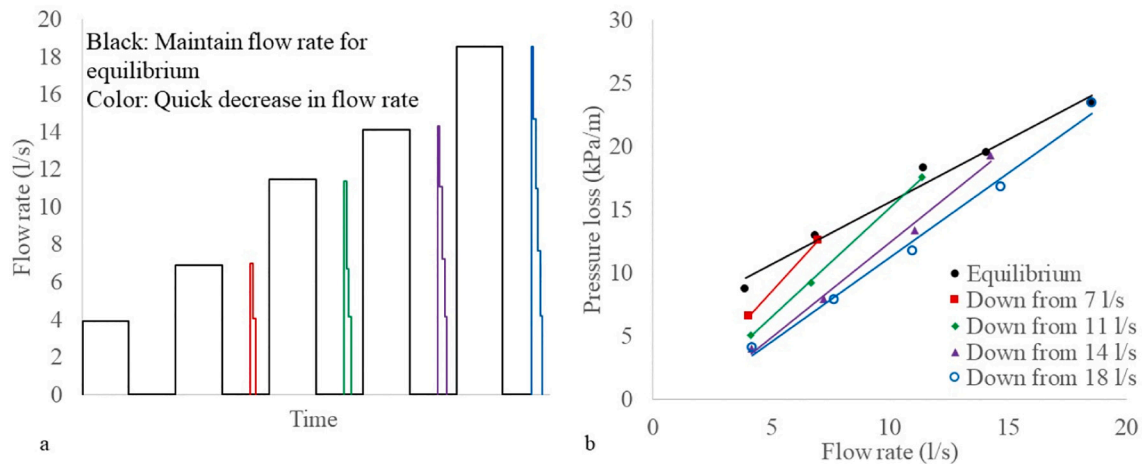


Fig. 11. Experimental procedure to investigate effect of pumping on rheology. a: applied procedure. b: resulting pressure loss – flow rate diagrams. Figure adapted from [64].

no confirmation of this hypothesis could be provided.

However, a combination of the effects on yield stress and viscosity could result in pumping-induced static segregation of SCC or a significant loss of fluidity, potentially compromising the self-consolidating characteristics.

## 7.2. Effect of pumping on the air void system

It is well-known that concrete exposed to frequent freeze-thaw cycles shows more adequate durability if a sufficient number of closely spaced small air bubbles are entrained [85]. Numerous studies have been performed on the effect of pumping on the air content and air-void system of concrete [86–96], but any effect is still not fully understood. Based on a series of experiments, Hover stated that “pumping could cause the air content to increase, decrease, or remain constant” [89]. Other experiments indicated that a decrease in entrained air content and a coarsening of the air-void system is more likely. The two main conditions responsible for this effect are dissolution of air under pressure and the coalescence of air bubbles under negative pressure (below atmospheric). The universal gas law states that, under constant temperature, the volume of a gas is inversely proportional to the applied pressure. This means that when pressure below atmospheric is occurring, it increases bubble volume, which could cause smaller bubbles to merge into larger bubbles.

Henry's law states that the capacity of a liquid to carry dissolved gas is proportional to the applied pressure. This means that more air can be dissolved in the mixing water at higher pressure. At lower pressure, this dissolved air needs to reappear, and one of the preferential places for air to reappear are at existing air bubbles. As such, air dissolution and reappearance should result in a coarsening of the air void system, and more likely in an air loss if appropriate consolidation is applied.

However, imperfect filling of pumping cylinders, impact of concrete when being discharged, or air generation due to high shear for certain types of dispersing admixtures could lead to increases in air content. As such, the prediction of the changes in air content and the air void system are not straightforward. Furthermore, for more flowable concrete types, shear can have both a positive and negative effect on the air-void system: shear can break large air bubbles into smaller ones, but higher shear rates have also been shown to facilitate the dissolution of air in the water [50]. Recent tests on air-entrained pastes with SCC consistency have shown that the dissolution rate of air is dependent on the initial air void system, as finer bubbles dissolve more quickly, and on the applied shear rate. Under dynamic conditions, it seems that air reappearance is nearly immediate, although much slower reappearance rates have been hypothesized under static or quasi-static conditions [50].

As a consequence, there is still much uncertainty on how the air void

system is affected by pumping, as many different effects play a significant role. As long as these changes cannot be predicted, no available tool can accurately estimate the freeze-thaw durability of pumped concrete. The only item which has become clear in recent research is that the change in fresh concrete air content due to pumping is not a reliable indicator for changes in the air-void system or freeze-thaw durability.

## 8. Rheology control

It is well understood how the rheological properties of fresh concrete can be modified through mix design [97] and further influenced by mixing procedure [98–99]. However, once mixed, the fresh concrete shows its intrinsic rheological behavior, which is only influenced by initial hydration processes, environmental conditions e.g. temperature, and shearing procedures [100–102], with no obvious means to actively modify the flow properties if needed. Nevertheless, active adjustment of rheological properties could be very useful, especially in case of pumping, as the required rheological behavior while pumping (high flowability) is often contradictory to rheological requirements later on during processing, like 3D printing (extrudability and buildability) or formwork casting (thixotropy). Unfortunately, the few active methods currently in practice to adjust concrete properties, as illustrated in the recent (p)review paper [103], do not include rheological aspects.

The ERC SmartCast project [104] studies active adjustment, in real time and post-mixing, of the rheology and stiffening of fresh cementitious materials. Utilizing external trigger signals, e.g. electromagnetic, the flowability of the fresh cementitious material is controlled at intended target levels depending on the considered stage in the process. The most innovative route to achieve active rheology control (ARC) is based on newly developed switchable polymers that can be added to the fresh cementitious material, enabling rheology control by means of an external trigger signal. *Comb*-type polymer plasticizers can be extended with linker elements incorporated into the side chains. Upon electric triggering, the linker element can be activated to release the side chain, reducing (in a non-reversible way) the steric hindrance. Another approach consists of controlling the charge density of the backbone by redox triggering, enabling a reversible adsorption control of the *comb*-type polymer plasticizer to the cement grains. These solutions, as well as other potential mechanisms using switchable plasticizers, are described in a recent patent application [105].

Another route is based on the implementation of magnetizable mineral products in the mix design, giving the mixture magneto-rheological properties. Magneto-rheological fluids (MRF) have already proven their benefits in some fields [106], but unfortunately not yet in the field of cementitious materials. Nevertheless, magneto-responsive

materials that could be successfully added to cementitious suspensions are available, like magnetic nanoparticles (MNP) almost entirely (>99%) consisting of  $\text{Fe}_3\text{O}_4$  (magnetite) [107]. Adding magnetizable particles to cement paste can make it responsive to magnetic fields, as already illustrated in [108,109] using carbonyl iron powder. Other mineral materials more commonly used in construction industry could also give magneto-responsive properties to a cement paste, like some types of fly ash. From studies on magneto-responsive cement pastes containing MNP or other mineral particles with magnetic properties, it can be concluded that constant magnetic fields (with long application time) lead to improved development of microstructure and thus stiffening, while variable or pulsating magnetic fields can lead to internal movement or vibration of the magnetic particles leading to less microstructural development and increased flow ability [110].

The concept of active rheology control for the case of pumping of cementitious materials has been introduced in [111]. The velocity profile in the pumping pipe is obtained by integrating the shear rate profile, which in itself can be obtained from the linear shear stress evolution (see Section 3.2) by means of the constitutive laws of the material. For example, when considering a cementitious material as a Bingham fluid, two main parameters are important: namely the yield stress and the plastic viscosity. Both of these parameters can be actively controlled. As illustrated in [110], these rheological parameters can be increased or decreased (within certain limits) depending on the control field (static or dynamic magnetic field), involving mechanisms like internal microstructural development and internal vibration. By controlling the rheological parameters, the relation between pressures and flow rates can be controlled. In a recent study by Sanjayan et al. [112], the potential of active rheology control has been illustrated also for the case of 3D printing (pumping and extrusion), using the application of mechanical vibration as the control mechanism.

Control of concrete pumping operations by applying adequate and well-positioned external magnetic fields along the pumping pipe is a realistic option. A proof-of-concept pumping loop is currently being studied at Ghent University (Fig. 3). However, practical and logistic issues still remain at this moment, related to the installation, functioning and safety of the equipment to provide the control fields. Further studies will clarify whether a bulk control of the pumped concrete will be needed, or whether a control limited to the lubrication layer will be sufficient.

## 9. Future challenges

### 9.1. Understanding lubrication layer composition, thickness and properties

Understanding the composition and properties of the lubrication layer is a challenge for a variety of reasons. The viscosity of pumped concrete can dramatically change over small distances near the pipe wall due to the wall-effect and shear-induced particle migration. Since viscosity is largely controlled by the volume fraction of particles, the local viscosity ranges from an estimated 50 Pa s in the bulk concrete to few Pa s in the fine mortar, all the way down to 1 mPa s for the water film right at pipe surface. This is several orders of magnitude of change that happens within a thickness of few mm. This creates challenges for both experimentalists and modelers. For example, one cannot simply measure the shear viscosity of the bulk concrete and then expect to insert that value into a simulation and accurately predict flow in a pipe. Furthermore, the shear rates near a pipe wall are so high there is no rheometer that can measure the viscosity at that rate.

To overcome this challenge, one possibility is to infer the radial dependency of viscosity in pipe by trying to measure pumping pressure and flow rates and then properly varying viscosity in analytical and/or numerical calculations to match experimental results, similar to what was done by Salinas and Feys in [68]. But this is an inverse problem and solving it does not necessarily mean that the right solution is obtained.

Another possibility is modeling suspension flow in pipes with particle size variations to capture general trends, although simulation cannot model the complete particle size variation in typical concrete. A multi-scale approach can be helpful to better understand what is happening with the controlling factors at each typical length scale.

### 9.2. Limitations on current testing and prediction procedures

In several parts of this paper, attention was paid to the formation and potential composition of the lubrication layer. In case the aggregate content of the concrete is too high, no lubrication layer can be formed. If it can be formed it is expected that the thickness and maximum particle size of the lubrication layer will increase with decreasing aggregate content. However, some structural specifications requiring high *E*-modulus or low shrinkage or creep lead to the development of concrete with an increased aggregate content. As such, there is a competition between the structural specifications and the requirements or guidelines to adequately place this concrete. Inadequate communication between partners involved with design and construction could lead to problems during placement. This has been experienced during the construction of the Vista tower in Chicago, IL as the average *E*-modulus specification was 48 GPa, requiring a high volume fraction of carefully sourced coarse aggregates. Similarly, it can be questioned what modifications are needed to pump ultra-high-performance-concrete (UHPC), or any other granular concrete mixtures. The prediction of pumpability of problematic concrete compositions is a subject of an ongoing project at the TU Dresden.

While the prediction of pumping behavior based on the results of rheological measurements is part of the current state-of-the-art, such predictions only seem to work well for relatively stable concrete mixtures with relatively high content of fines and sand (well saturated concrete). Excessive bleeding and segregation of concrete can not only compromise the reliability of rheological tests, but also make the estimation of conditions in the pipeline highly speculative. It is clear that in addition to rheological experiments some testing of stability, bleeding, or robustness of such mixtures are needed to assess possible risks/effects with respect to pumpability. Some suggestions exist already for the assessment of bleeding/filtration under pressure. The main challenge seems to be quantifying possible consequences for pumping on the basis of such results, specifically for complex pipelines with several bends.

### 9.3. Changes in pipe geometry or flow direction

A majority of the discussion in this paper focused on predicting the pressure loss in straight pipes with uniform diameter. As is known from fluid mechanics, reducers and bends can induce additional pressure losses due to changes in streamline direction. Practical guidelines assume that a 90° bend is equivalent to 3 m of straight pipe. However, there are apparently contradictory results in the literature. Some researchers report no significant influence by bends and reducers [26,9], while others reported an additional pressure loss in a 90° bend larger than 3 m of straight pipe [20–21]. The answer for this complex fluid mechanics problem most likely needs to consider the inertia of the aggregates (density, size, velocity and bending radius), as well as the damping characteristics of the paste or mortar (mainly viscosity and yield stress). It is thus possible that these apparent contradictions are caused by significant differences in the ratio of inertial forces to viscous damping for the evaluated mixtures.

Another consequence of inertia of the coarse aggregates is that they can be pushed ahead of the concrete with each stroke of the pump [27]. This is especially important in case of downward pumping, followed by a horizontal or upward section. The higher kinetic energy of the coarse aggregates, compared to the mortar, could lead to a local accumulation at the end of the downward section, resulting in blockage of the system. It is, however, unknown what the critical parameters are that control this phenomenon.

#### 9.4. Time and shear dependency of concrete properties

Some other challenges are linked to the dependency of the pumped material on the pumping process itself. A first issue in this respect is the effect of temporary halts of the pumping process. Due to thixotropic behavior of the pumped material, resuming the pumping operation after the interruption can be cumbersome and in case of pronounced thixotropy even impossible [113]. Duly avoiding or controlling the effect of structural build-up in a stop-start situation needs further attention. However, related to the previous discussions, which static yield stress needs to be overcome? Theoretically, it should be the static yield stress of the lubrication layer, assuming no significant influence of bends or reducers. However, as the composition and properties of the lubrication layer are unknown, a solution to this problem is not straightforward.

Another challenge remaining is how the concrete properties change due to pumping. It has been shown that the viscosity mainly decreases and that the yield stress could go either way, but the change in rheological properties is dependent on the applied shear rate, which varies, especially for the lubrication layer, unknowingly, over the radius of the pipe. More research is needed on the local shear-dependency of the rheology of cement-based materials, as this becomes a complex problem. Similarly, recent research work has shown dependency of the air dissolution rate on the shear rate. Obtaining full comprehension on how pumping affects the air-void system, and thus freeze-thaw durability, requires not only the full shear rate profile, but also the combined effect of shear, time, pressure and air dissolution.

#### 9.5. Further development of active rheology control

Active rheology control (ARC) and active stiffening control (ASC) are emerging technologies, with huge potential, as described in Section 8. Further challenges remain: obtaining a more in-depth understanding of the control actions and mechanisms and developing practical implementation guidelines for control equipment, logistics, and safety. Newly-developed switchable admixtures and responsive nano-particles need to be further refined and optimized. More traditional approaches like mechanical vibration of pipes should also be studied in more fundamental detail. Active rheology control mechanisms will facilitate daily pumping operations, possibly combining the control features with in-line rheometry equipment in the pump truck. In case of major pumping operations, e.g. high-rise towers requiring pumping heights of several hundred meters, rheology control could also be combined with set control, retarding the concrete returning from the pipes at the end of the working day and accelerating hydration upon resuming operations the next day. A further challenge is the combination of ARC and ASC with on-site 3D printing of concrete.

### 10. Summary

Despite several million cubic meters of concrete being placed daily by pumping methods, and the fact that concrete has been pumped for nearly a century, a full understanding of this process has not yet been accomplished. It is clear from analytical calculations, experiments, field work and numerical simulations that the formation of a lubrication layer facilitates the flow of concrete in a pipe. This is caused by the geometrical wall effect and shear-induced particle migration of the coarse aggregates. The lubrication layer composition, while debated, is known to be variable, depending on concrete composition and pumping parameters, and could be composed of cement paste, micro-mortar, or mortar according to the literature. If the concrete contains a too-large volume fraction of coarse aggregates, the lubrication layer cannot be formed and the behavior switches to frictional, causing blocking and potentially leading to dangerous work conditions. This could become a more significant problem with more specific structural requirements and ultra-high performance concretes. This could also become a problem with unstable concrete mixtures, or low viscosity mixtures that experience

significant pressure-induced water migration.

If the concrete is capable of forming a lubrication layer, several approaches were developed to assess the flow properties and predict pumping pressures. The first approach is based on interface rheology, by utilizing concrete rheometer hardware equipped with a smooth cylinder, or by mimicking the flow behavior in a pipe in a sliding pipe rheometer. These approaches measure flow properties of the lubrication layer, or the combination of lubrication layer and bulk concrete, without resulting in detailed rheological properties or thickness of the lubrication layer. Analytical equations can then be employed to predict pumping pressure. A second approach consists of visualizing the lubrication layer thickness and potentially the velocity profile. Based on the rheological properties of the bulk concrete and the assumed composition of the lubrication layer, analytical equations or numerical simulations can be employed to predict pumping pressure.

Continuum Fluid Dynamics (CFD) simulations have been employed to estimate pumping pressure, when considering concrete as one homogeneous material, or a combination of two homogeneous concentric materials: the bulk concrete and the lubrication layer. However, to accurately understand and numerically predict the flow of concrete in pipes, the presence of a solid fraction is required. Due to the limitation in computational power, not all solid particles can be considered, so the most common approach is to suspend coarse aggregates in a continuous mortar. The Discrete Element Method (DEM) can be employed to simulate concrete flow, but this method requires calibration of the forces in between the particles to mimic the mortar properties. Dissipative Particle Dynamics (DPD) or Smoothed Particle Hydrodynamics (SPH) are two methodologies to simulate the behavior of particles in different matrix fluids. SPH has been recently employed to predict the volume fraction evolution of particles over the pipe radius, and as such the velocity profile for different matrix fluids.

The concept of a homogeneous lubrication layer, one with constant composition and properties over its thickness, does not fit with the underlying physics of particle migration. Instead, one should expect a continuously varying volume fraction, as a function of the radial parameter, different for each particle size class, with a strong dependency on the behavior of coarser particle sizes and matrix rheology. The current test methods or numerical simulations are not yet capable of determining or predicting this specific behavior due to the complexity of the flow problem. Considering bends and reducers, which require inclusion of the inertia of the coarse particles in the flow problem, only further increases the complexity of pumping concrete.

Fresh concrete properties have a strong dependence on shear history. Flow reactivation after stoppage could lead to potential pump or pipe failure due to excessive pressures, dependent on the thixotropic development of the concrete. Comparing rheological measurements before and after pumping indicates, in the majority of cases, a decrease in viscosity, but the behavior of yield stress is still unclear. Some changes are considerable in magnitude and may alter the workability classification of the material. Many studies have been performed on the change in the air-void system due to pumping. Although most results indicate a coarsening of the air-void system tied to the physics of air bubbles in pressurized fluids, accurate prediction of such outcomes is still not possible. Recent work has shown the dependency of air dissolution rates on the bubble size distribution and applied shear rate, making the macroscopic changes in the air void system strongly dependent on the pipe flow profile. In order to further investigate changes in rheology due to applied shear and time, as well as changes in the air-void system, comprehension on the lubrication layer formation is required.

Advances have been made in actively controlling the rheological response of cementitious materials through magneto-rheology or by developing admixtures that can be triggered by external signals. These technologies could significantly alter the behavior of concrete during pumping, potentially increasing construction speed or safety on-site, or reducing the negative effects of pumping on concrete properties. More research is required on these technologies before further development



and implementation will be possible.

As can be seen from this paper, significant advances were made in the last two decades to demystify concrete pumping, but many open research questions remain. The authors hope that in the coming years, similar advances can be made on these open research questions in order to facilitate concrete construction by means of pumping while maintaining concrete quality and to enhance on-site safety.

### Author statement

This reviewer paper was requested by the Editor in chief of Cement and Concrete Research as part of a special edition in conjunction with the ACI Conference on Advances in Concrete Technology and Sustainability.

Dimitri Feys led the effort and composed the team of co-authors: Geert De Schutter, Shirin Fataei, Nicos Martys and Viktor Mechtcherine. As there are no new data and no new findings in the paper, the contributions from the team are the conceptualization, writing, reviewing and editing. The team met virtually on a regular basis to discuss paper lay-out, contents and common views, to assign writing tasks to each of the co-authors, and reviews of completed portions. As such, each author contributed to the concept of the paper, writing portions of the original draft, as well as reviewing and editing of the other components of the paper.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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