Metrology Needs for Predicting Concrete Pumpability

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ABSTRACT:

With the increasing use of pumping to place concrete, the development and refinement of the industry practice to ensure successful concrete pumping is becoming an important need for the concrete construction industry. To date, research on concrete pumping has been largely limited to a few theses and research papers. The major obstacle to conducting research on concrete pumping is that it requires heavy equipment and large amounts of materials. Thus, developing realistic and simple measurement techniques and prediction tools are a financial and logistical challenge that is out of reach for small research labs and many private companies in the concrete construction industry. Moreover, because concrete pumping involves the flow of a complex fluid under pressure in a pipe, predicting its flow necessitates detailed knowledge of the rheological properties of concrete, which requires new measurement science. This paper summarizes the technical challenges associated with concrete pumping and the development in concrete pumping that have been published in the technical literature and identifies future research needed for the industry to develop best practices for ensuring successful concrete pumping in the field.

Keywords: *concrete pumping, pumping prediction, concrete flow, pumpability*

1. Introduction

Concrete pumping has become one of the most widely used approaches to place concrete. Pumping enables the transport of concrete to forms and molds while increasing the speed of delivery and allowing access to hard-to-reach areas. This is not a new technology as it was first used in 1930, but its usage continues to grow due to an increase in demand for super structures such as high-rise buildings and other tall structures. Consequently, the optimization and development of prediction methods for concrete pumping is becoming a crucial issue for the concrete industry. Since concrete pumping requires mixing trucks, pumps and pipes, combined with a large amount of material and instrumentation, it is not surprising that only a few theses and research papers exist on the topic. The goal to develop realistic and simple measurement techniques and prediction tools is a challenge of great importance for the concrete industry.

As concrete pumping involves the flow of a complex fluid under pressure in a pipe, predicting its flow requires detailed knowledge of its rheological properties. However, the proper characterization needed to predict flow is not easy to achieve because it involves understanding a variety of factors such as dynamic segregation, the stability of entrained air, the geometry of the pumping circuit, the dynamics of a slip-layer formed between the bulk concrete and the pipe wall, and the relationship between the pressure and the flow rate. In practice, this is colloquially referred to as the concrete ‘pumpability’. Interestingly, the American Concrete Institute (ACI) guide on terminology does not include a definition of pumpability.

This paper identifies the dominant factors for a concrete to flow in a pipe in an effort to define pumpability. The paper also summarizes the technical advances in concrete pumping that have been published in the technical literature, which is used to identify gaps. The resulting gaps are used to identify future research needed for the industry to develop best practices for ensuring successful concrete pumping in the field.

2. Background

Pumping is increasingly utilized as an efficient and economical method to place concrete in large projects while not compromising its desired performance. To ensure quality, it is important that the fresh concrete properties are not significantly altered as it moves through the pumping system (pump, pipes, etc.). This is not necessarily trivial in that processes like segregation of aggregates can take place as the concrete is pumped.

Several attempts were made to develop metrologies to predict the flow of concrete in a pipe. The most comprehensive state of the art report was prepared by Jacobsen et al. [1]. They established one criterion for concrete flow in a pipe using the slump test for concretes. Here, it was suggested that a slump range of 50 mm to 100 mm will provide acceptable flow in the pipe; below that range the concrete will not flow in the pipe without compromising the desired performance; above that range the concrete may not flow in the pipe as desired. However, this criterion does not encapsulate the effects from factors such as dynamic segregation or a slip-layer, which might play a dominant role in determining the performance during pumping. Further, for concrete pumping, the shear rate is typically around 10 s^{-1} to 100 s^{-1}, whereas for the slump test, it is only 1 s^{-1} or less [2]. Hence, results from the slump test that is carried out in a flow regime different from that of pumped concrete may not be relevant for predicting the ability of concrete to flow in a pipe.

A definition for concrete workability being suggested by Richtie [3] is composed of three components: stability, ability to consolidate, and mobility. Each of these components has associated materials properties/performance requirements as follows:

•	Stability	Bleeding and segregation
•	Ability to consolidate	Density of the concrete after consolidation
•	Mobility	Viscosity and yield stress

However, it is not sufficient to use this definition, as the concept of workability is more complex for concrete flow through a pipe. The concrete must have stability and mobility during pipe flow. Also the mobility needs to take into account the interaction with the pipe walls, not just the rheological properties of the concrete itself. The ability to consolidate will become important after the concrete is pumped or when it flows in the forms.

2.1 Flow in pipe

Fluid flow in a pipe depends on the pressure applied, the radius of the pipe and the viscosity of the fluid. For a Newtonian fluid, the flow is directly proportional to the viscosity, which is a constant. For a non-Newtonian fluid having a viscosity that depends upon the shearing stress, like grouts and concretes, the flow rate is a complicated function of the viscosity.

The viscosity μ of a fluid is the ratio of the shear stress τ to the shear rate $\dot{\gamma}$: $\mu = \tau / \dot{\gamma}$. This definition is convenient for Newtonian fluids, and certain non-Newtonian fluids. In other cases, an engineering approach to the description of a fluid can simplify the analysis. For instance if the fluid is approximated as a power law fluid, it can be described by eq. (1):

$$\tau = K\dot{\gamma}^n \tag{1}$$

where K is the power law consistency index and n is the power law exponent. The corresponding velocity profile in a circular pipe is then given by eq. (2) [4]:

$$v(r) = \frac{Q(3n+1)}{\pi {R_p}^2 (n+1)} \left[1 - \left(\frac{r}{R_p}\right)^{1+1/n} \right] \tag{2}$$

where v is the fluid velocity as a function of the radial position, r , in the pipe, Q is the volumetric flow rate and R_p is the pipe radius. The fluid power law consistency index can be calculated using the following eq. (3) [4], which requires a pressure drop measurement over a certain length:

$$K = \frac{\Delta P}{2L} \left(\frac{3Q}{\pi} {R_p}^{-3-1/n} \right)^n \tag{3}$$

where ΔP is the pressure drop, and L is the distance between the pressure sensors. The exponent n and the factor K could also be determined via eq. (1) from rheological measurements of the fluid through a rheometer if available. The eqs. (2) and (3) could also be used to determine these parameters from the pipe flow, in absence of a suitable rheometer.

The shear rate at the wall surface is calculated using the following equation [4]:

$$\dot{\gamma}(r = R_p) = \frac{3n+1}{n}\frac{Q}{\pi R_p{}^3} \tag{4}$$

The local shear stress is:

$$\tau = r\Delta P / 2L \tag{5}$$

The eqs. (1) through (5) describe flow of a homogenous fluid in a pipe. However, concrete is more a complex fluid because it contains aggregates with a wide range of sizes. These aggregates interact with the pipe walls and each other, creating inhomogeneities in the fluid. Thus, concrete flow in a pipe typically occurs in three layers or regions [5, 6] as shown in Fig. 1:

- Slip-layer or lubrication layer,
- The shearing region or layer, and
- The inner concrete or layer, also referred to as a plug flow layer

The thickness of the slip layer depends upon the tribology of the material adjacent to the pipe material. Tribology is “the science and technology concerned with interacting surfaces in relative motion, including friction, lubrication, wear, and erosion” [7]. The slip/lubrication layer contains mainly cement paste and possibly very small sand particles [5, 6, 8], while the inner layer contains coarse aggregates. Also, the diameter of the inner layer or the thickness of the slip-layer is unknown. It is conceivable that prediction of concrete flow in a pipe will need the characterization of each of the layers.

2.2 Slip-layer

Several research groups have investigated the slip-layer of concrete flow in a pipe. Choi et al. [5, 6] measured the thickness of the slip-layer using an Ultrasonic Velocity Profiler (UVP) in pumping circuits using industrial equipment and found that there is a 2 mm thick layer along the inner surface of the pipe. However, the layer thickness could vary depending on the mixture proportions and the pipe configuration.

Kaplan [9] reported that the flow of concrete in a pipe is mainly related to the viscosity of the slip-layer and that its properties could be measured by tribometry. He found that the correlation between the properties of the bulk material as measured in a rheometer and the properties of the slip-layer was weak. Jacobsen et al. [10] showed by using colored concrete that the velocity profile of the concrete resembled that of plug flow in the pipe center, and non-moving slip-layer, similar to that shown in Fig. 1.

Kwon et al. [11, 12] measured the rheological properties of concrete before and after pumping while monitoring the pressure and flow rate and found that while there was no correlation between rheological properties of bulk concrete and flow rates, there was a strong correlation between properties of the slip-layer and flow rates. Thus they deduced that the slip-layer is the determining factor to predicting that concrete will flow in a pipe. They also developed a tribometer that is a coaxial rheometer with a smooth bob made of steel or covered with rubber to simulate the slip-layer of the pipe.

Ngo et al. [13] observed that the slip-layer is between 1 mm to 9 mm thick, by visualizing the material flow in the rheometer. He analyzed the layer and found that it contained sand with a particle size less than 0.25 mm. This would imply that there is a migration of coarse aggregates from near the wall to the center of the pipe where the shear rate is lower than that found near the walls.

2.3 Pumping pressure

Another factor in pumping is the pressure applied to the material to move it through the pipe. Rio et al. [8] demonstrated with a large number of pumping tests that the relationship between the pressure of the pump and the flow rate of the material is linear:

$$P = k_1 + k_2 Q \tag{6}$$

where k_1 and k_2 are two empirical parameters that depend on the material and other experimental conditions. They concluded that the two parameters can be used to characterize a specific mixture and the knowledge of these parameters for a specific mixture and pumping circuit could be used as a quality control tool to ensure that the applied pressure is sufficient to ensure the desired flow rate.

Feys et al. [14] established an empirical relationship between the plastic viscosity of the concrete at a shear rate of 10 s^{-1} and the pressure gradient in a pipe. If the pressure gradient is too low, the material will not move through the pipe. They mentioned two issues relevant to the prediction of flow in a pipe: 1) the slip-layer influence is very important, but it is not well understood and is difficult to measure; 2) the shear rates in the pipe are spatially and temporally varying. One solution for the effect of the slip-layer would be to measure its rheological properties, if it could be isolated and extracted. Modeling of the flow in a pipe might help resolve the second issue. They also observed that the pumping of self-consolidating concrete (SCC) requires a higher pressure, while the yield stress is almost zero, but the plastic viscosity is higher than that for normal concrete. This could be due to the slip-layer (Fig. 1) that would require a higher shear stress at the same shear rate due to the increased viscosity.

2.4 Segregation

Dynamic segregation is an additional factor that can influence concrete flow in a pipe. A concrete can display no segregation while at rest, but undergo segregation during shearing. Segregation during shearing, i.e., pumping, can involve a number of phenomena: 1) aggregates moving to the center of the pipe where the shear rate is lower; 2) aggregates moving ahead of the surrounding mortar; 3) water is pushed out of the concrete [15], either by moving to the walls or in front of the concrete.

An important factor in segregation is the pumping process and the type of pump used. The most common pumps used with concrete are piston pumps. They are characterized by a piston cycle having two phases: 1) the piston retracts and closes the out-valve while opening the in-valve and the material fills the chamber in front of the piston; 2) the in-valve is closed when the piston pushes the material forward through the chamber. During phase 2, the material, mortar and aggregates, moves forward. During the second and subsequent cycles, the material that was pushed forward stops, during the retraction of the piston. But it has been observed that by inertia the aggregates keep moving forward relative to the paste. Kaplan [9] has calculated that, for concrete, the coarse aggregates could move by 0.2 m relative to the matrix fluid during one cycle of the piston. He also states that depending on the matrix (mortar or paste) yield stress or viscosity, the forward motion of the aggregates could be further propelled to the front of the mixture. This longitudinal advance of the aggregates can be mitigated by pumping a mortar buffer before introducing the concrete in the pipe, so that the mortar would receive the coarse aggregates. It is important that this mortar have the correct rheological properties and suitable volume, to prevent the coarse aggregates from separating from the concrete mixture. Moving the aggregates that are in front of the concrete mixture would likely require a pressure that is beyond the capability of the pump, due to the dry friction between the aggregates and the walls. This will result in blockage of the pump.

Water moving radially toward the pipe walls is a direct result of aggregates moving toward the center. Ovarlez et al. [16], using a coaxial tribometer, showed segregation during shearing but not at rest. Dynamic segregation would increase the concentration of aggregates in the plug flow layer, resulting in an increased yield stress and viscosity of that layer and, consequently changing the concrete flow rate in the pipe or the required pressure to move the concrete in the pipe.

An instrument called a “sliding pipe rheometer” [17] has been used to predict concrete flow in a pipe. In this instrument, the concrete is pushed through a Plexiglas tube and the pressure and flow rate are measured. From ref. [17], it could be inferred that this instrument is actually measuring the slippage ability of a concrete in a tube. A robust interpretation of such measurement requires an understanding of slip phenomena in the slip-layer at the pipe surface. From this short overview of the concrete flow in a pipe, the following statements may be extracted: 1) The flow of concrete in a pipe has three layers: slip-layer, shearing layer and plug flow layer. Each layer’s behavior depends on the properties of its component materials and material proportions. 2) A slip-layer at the pipe surface, of order less than 10 mm thick, is the major factor determining the ability of the concrete to flow in a pipe. Characterization of the slip-layer remains a challenge. 3) The shearing layer is also difficult to characterize. Here it is believed that the rheological parameters of viscosity and yield stress play a significant role. 4) Dynamic segregation plays a major role in the distribution of the aggregates inside a pipe.

From this brief overview, the ability of concrete to flow in a pipe under pressure is governed mainly by the slip-layer properties and the dynamic segregation. Thus, it could be noted that tribology plays an essential role in predicting the concrete pumping. This paper will, therefore, concentrate on this aspect of the flow of concrete in a pipe.

3. Analytical approaches to pumping

3.1. Tribology and rheological properties of the slip-layer

The slip-layer is formed under shear near the smooth surface of the pipe wall when pumping concrete. In order to characterize this layer for cement based materials, a device called a tribometer has been developed [4, 7, 9, 11]. A tribometer is a special coaxial rheometer with a bob purposely made with a smooth surface. The shearing over the smooth surface induced by the rotation of the bob forms a slip-layer, which is presumed to be similar to the slip-layer formed in the pipe during flow of pumped concrete. Coaxial rheometers output the revolution speed of the cylinder and the applied torque. When accounting for the rheometer geometry, the shear stress, τ, between the cylinder and the wall of the container can be expressed by the following equation [6, 11, 18]:

$$\tau = \frac{\Gamma_s}{2\pi h r^2} \tag{7}$$

where h is the cylinder height [m], Γ_s is the measured torque [Nm], and r is the distance from the center of the tribometer in the radial direction [m]. The shear stress is linearly proportional to the torque. The relationship between the torque and the angular velocity can be written as the following equation,

$$\Omega_M = \Omega_s = \frac{\Gamma_s}{4\pi h \mu_{pl}} \left[\frac{1}{R_c{}^2} - \frac{1}{R_s{}^2} \right] + \frac{\tau_{l,0}}{\mu_{pl}} \ln \left[\frac{R_c}{R_s} \right] \tag{8}$$

which is known as the Reiner-Rivlin equation [19]. In eq. (8), Ω_M [rad/s] is the angular velocity of the cylinder, Ω_s [rad/s] is the angular velocity of the slip-layer, and μ_{pl} [Pa·s] and $\tau_{l,0}$ [Pa] are the viscosity and the yield stress of the slip-layer, respectively. R_c is the radius of the cylinder and R_s is the distance from the center of the bob to interface of the slip-layer and bulk material.

The measured torques and the applied angular velocities have the following relationship,

$$\Gamma_s = k\Omega_s + \Gamma_0 = k\Omega_M + \Gamma_0 \tag{9}$$

where k [Nm·s] is the parameter optimally fitting the slope or the linearity between the torque and the angular velocity, and Γ_0 [Nm] is the initial torque to start the shear flow in the lubricating layer. The yield stress, $\tau_{l,0}$ [Pa], can be related to the initial torque (Γ_0) by following equation.

$$\tau_{l,0} = \frac{\Gamma_0}{2\pi h R_c{}^2} \tag{10}$$

The viscosity of the lubricating layer is related to the parameter, k, from eq. (9) and is expressed as follows,

$$\mu_{pl} = \frac{k}{4\pi h} \left[\frac{1}{R_c{}^2} - \frac{1}{R_s{}^2} \right] \tag{11}$$

Through the relationship between the torque and angular velocity of the tribometer, the rheological properties of the slip-layer could be determined.

3.2 Estimation of the flow in a pipe

Based on the slip-layer properties determined by a tribometer measurement, an analytical method for determining the flow of concrete in a pipe could be obtained [1, 4, 10]. When pump pressure is applied, a shear stress inside the pipe is induced, creating a shear rate both in the slip-layer and in the shearing layer of the concrete. The shear rate within the slip-layer can be written as follows

$$\dot{\gamma} = \frac{\tau(r) - \tau_{l,0}}{\mu_{pl}} \quad \left(R_L \le r \le R_p\right) \tag{12}$$

where $\dot{\gamma}$ [s^{-1}] is the shear rate inside the slip-layer, R_p is the radius of the pipe, R_L is the distance from the center of the pipe to the slip-layer. The difference between R_p and R_L is the thickness of the slip-layer. The same idea, that the thickness of the slip-layer should be considered in calculating the flow rate, has been adopted in the existing research [1, 3, 4, 9, 10]. The shear rate of the plug flow area of the concrete is only induced when the applied shear stress is larger than the yield stress of the concrete and the size of the shearing layer should first be determined, as follows,

$$R_G = 2\tau_{b,0}\left(\frac{L_{pipe}}{P_{inlet}}\right) \le R_L \tag{13}$$

where R_G is the radius of the inner concrete (Fig. 1), and $\tau_{b,0}$ is the yield stress of the inner concrete. The shear rate of the inner concrete exists between R_G and R_L, and is expressed by the following equation.

$$\dot{\gamma} = \frac{\tau(r) - \tau_{b,0}}{\mu_{pb}} \qquad (R_G \le r \le R_L) \tag{14}$$

where μ_{pb} is the plastic viscosity of the inner concrete. The inner region which has a lower yield stress than the concrete has zero shear rate (plug flow).

$$\dot{\gamma} = 0 \qquad (0 \le r \le R_G) \tag{15}$$

The velocity is the integral of the shear rates from the wall to any position in the radial direction, and is expressed by the following equations,

$$U_l = \frac{1}{\mu_{pl}}\left[\frac{\Delta P(R_p{}^2 - r^2)}{4} - \tau_{l,0}\left(R_p - r\right)\right] \qquad \left(R_L \le r \le R_p\right) \tag{16}$$

$$U_{p1} = \frac{1}{\mu_{pl}}\left[\frac{\Delta P(R_p{}^2 - R_L{}^2)}{4} - \tau_{l,0}\left(R_p - R_L\right)\right] + \frac{1}{\mu_{pb}}\left[\frac{\Delta P(R_L{}^2 - r^2)}{4} - \tau_{b,0}\left(R_L - r\right)\right] \qquad \left(R_G \le r \le R_L\right) \tag{17}$$

$$U_{p2} = \frac{1}{\mu_{pl}}\left[\frac{\Delta P(R_p{}^2 - R_L{}^2)}{4} - \tau_{l,0}\left(R_p - R_L\right)\right] + \frac{1}{\mu_{pb}}\left[\frac{\Delta P(R_L{}^2 - R_G{}^2)}{4} - \tau_{b,0}\left(R_L - R_G\right)\right] \qquad \left(0 \le r \le R_G\right) \tag{18}$$

where U_l, U_{p1} and U_{p2} [m/s] are the velocities within the slip-layer, in the shearing layer of the concrete, and in the plug flow layer, respectively. It shows the typical velocity profile in the pipe during flow of the pumped concrete. The flow rates are the integral of the velocity over the radius as shown in eq. (19):

$$Q = \int_{R_L}^{R_p} 2\pi r U_l dr + \int_{R_G}^{R_L} 2\pi r U_{p1} dr + \int_{0}^{R_G} 2\pi r U_{p2} dr \tag{19}$$

$$= \frac{\pi}{24\mu_{pl}\mu_{pb}}[3\mu_{pb}\Delta P(R_p{}^4 - R_L{}^4) - 8\tau_{l,0}\mu_{pb}(R_p{}^3 - R_L{}^3)$$

$$+3\mu_{pl}\Delta P(R_L{}^4 - R_G{}^4) - 8\tau_{b,0}\mu_{pl}(R_L{}^3 - R_G{}^3)]$$

Thus, the characteristic flow rate can be analytically determined using rheological properties of each region along with the prescribed pumping pressure [20].

3.3 Dynamic Segregation

As stated in the section 2, along with the slip-layer, dynamic segregation plays an important role in characterizing concrete flow in a pipe. During pumping of concrete, three types of dynamic segregation can be considered: a particle migration radially (from the wall to the center), a longitudinal motion of particles to the front of the flow, and bleeding (water either at the wall or at the front of the flow). Although all types of dynamic segregation can affect the flow of concrete in a pipe, in the present paper, the focus will be on the characterization of the slip-layer that could be defined as the particle migration toward the center balanced by a paste migration toward the wall surface.

There are several conjectured mechanisms that could lead to the formation of the slip-layer and that have been investigated by experimental test methods [21]. First, the ability of a concrete to flow in a pipe has been estimated through bleeding tests. The propensity of a concrete to bleed could be linked to the formation of the slip-layer because the migration of particles toward the center of the pipe is compensated by the water bleeding toward the walls. Secondly, the pipe wall prevents the uniform distribution of the solid particles near its surface. The exclusion of solid particles near the wall induces a region with a lower particle concentration. Another possible mechanism is the shear induced particle migration [21, 22, 23]. This mechanism, as descried by Leighton et al. [22, 23], assumes that particles have a tendency to migrate away from region of higher shear rate to regions of lower shear rate. Thus, as the higher shear rate is near the walls, particles would migrate away from the wall of the pipe forming a slip-layer. The inhomogeneous distribution of the particle concentration across a section of the pipe (radially) leads to spatially varying rheological properties in the suspension as they depend on the particle concentration.

Leighton et al. [22, 23] suggested phenomenological models for particle migration in non-homogeneous shear flows that typically result from spatial variation in irreversible interaction frequency and effective viscosity. Phillips et al. [24] adapted the scaling arguments of Leighton et al. [22, 23] and proposed a diffusive flux equation to describe the time evolution of the particle concentration based on a two-body interaction model. In this study, the particle diffusive model proposed by Phillips et al. [24], combined with general flow equations, was extended to solve the flow of concrete and predict the particle concentration distribution of suspensions in a pressure driven pipe flow.

The general governing continuum equation of the shear-induced particle migration for the Poiseuille flow is as follows [24], which describes the concentration of particles as a function of radius and time:

$$\frac{\partial \phi}{\partial t}+\frac{\partial (u_z \phi)}{\partial z}=\nabla \cdot \left\{ a^2 K_c \phi \nabla \left(\phi \frac{\partial u_z}{\partial r} \right) + K_\eta \phi^2 a^2 \frac{\partial u_z}{\partial r} \frac{\nabla \eta}{\eta} \right\} \tag{20}$$

where ϕ is the particle concentration, t is the time, u_z is the velocity component in the flow direction, a is the particle radius, z is the flow direction, r is the radial direction, η is the apparent viscosity of the concentrated suspension, and K_c and K_η are dimensionless phenomenological constants. Here, the stress gradient is a driving force to move particles toward the center of the pipe as described in the first term of the right side in eq. (20). The increase of the particle concentration due to the migration may increase the viscosity and the yield stress, which hinder the additional migration of the particles as described in the second term of the right side in eq. (20). As a result, the concentration of the particles inside the pipe is determined by the balance between the two actions, namely, the migration due to the stress gradient and the hindrance due to the increased viscosity. Through the analysis of the shear-induced particle migration, which is one type of dynamic segregation, the formation of a slip-layer can be simulated and its layer properties could be determined.

An alternative approach for modeling suspension flow is called the “suspension balance model” [25] in which the suspension is described as a continuum fluid whose dynamics is described by the macroscopic mass, momentum, and energy balance equations. As in the case of the particle diffusive model, this approach also predicts an increased particle concentration near the pipes center. Indeed, close examination of the equations of this model indicate that the conservation of particles and momentum follow the same form as that of Phillips model [24].

4. Numerical Simulation approach to predict pumpability

4.1 Numerical methodology for pumped concrete

Numerical simulation using computational fluid dynamics could potentially be used for the prediction of the pumpability of concrete from its rheological properties and the pumping circuit. Computational modeling techniques found in the literature may be divided into three categories [26, 27]: single phase fluid approach, particle suspended in a fluid approach, and discrete particle approach. The first approach considers concrete as a homogeneous matrix. From a macro point of view, the flow characteristics of concrete can be considered as a continuum flow. Mori and Tanigawa [28] used the viscoplastic finite element method (VFEM) and the viscoplastic divided element method (VDEM) to simulate the flow of fresh concrete. Both the VFEM and VDEM assumed that the concrete could be described as a homogeneous single fluid. Thrane et al. [29] also simulated self-consolidating concrete (SCC) flow during L-box and slump flow tests based on a single fluid approach assuming Bingham behavior.

In the second approach, from a micro point of view, materials that constitute concrete such as cement, sand, and aggregate can be considered in the effects of each component. There are two material formations in this method: a primary phase and a granular phase. The primary phase is a fluid-like flow consisting of cement, water, and sand and the granular phase is particle flow consisting of coarse aggregate. Mori and Tanigawa [28] also used the viscoplastic suspension element method (VSEM) to simulate the concrete flow in various tests with this method. Moreover, as stated in Section 3.3, the shear-induced particle migration analysis that is used to illustrate the formation of slip-layer is also included in this approach.

In the third approach, the concrete flow by nature is dominated by granular media. Chu et al. [30] used the discrete element method (DEM) to simulate the SCC flow during various standard tests: slump flow, L-box, and V-funnel tests. Petersson and Hakami [30] and Petersson [32] also adopted this method to simulate the SCC flow during L-box and slump flow tests, and J-ring and L-box tests. These three different approaches could be used to simulate the concrete flow in a pipe.

4.2 Simulation examples

Among three types of numerical approaches, firstly, Choi et al. [5] used the single-phase fluid approach to simulate a full scale pumping system. Figure 2 shows the pressure range with the distance from the pump and after several bends in the pipe system. For the analysis of pumped concrete with this single phase fluid approach, the computational zone was divided into two layers, i.e. inner concrete layer consisting of concrete and slip-layer consisting of mortar constituents, to consider the properties of a slip-layer which is regarded as the dominant factor to facilitate pumping. To represent each layer's properties, different rheological properties obtained by different rheological measurement (i.e. concrete rheology test and mortar tribology test), were used as input parameters. Although this approach is simple and it is easy to simulate the entire physical system, some assumptions about the thickness of the slip-layer and its rheological properties are required, which are not easy to clearly define.

A second approach, based on eq. (20), is shear-induced particle migration (Fig. 3). This continuum approach can account for particle migrations by modeling particle collisions in highly sheared and/or highly concentrated zones that force particles to migrate from these zones. This effect is counterbalanced by the local increase in the suspension viscosity resulting from this migration. Shear-induced particle migration finds its origin in the competition between gradients in particle collision frequency and gradients in viscosity of the suspension. In this approach, concrete is regarded as a concentrated suspension of solid particles in a viscous liquid, (i.e. paste or mortar, and aggregate characteristics and contents influence the flow of concrete). Through this approach, the formation of a slip-layer can be numerically simulated and used to estimate the velocity profile across the pipe and flow rates of pumped concrete, implying that this approach can be an effective tool to predict the pumpability of concrete.

Finally, the discrete particle approach could be used for the direct modeling of the movement and interaction of aggregates in the pipe. Although potentially useful, the fluid dynamics and particle interaction are derived from a phenomenological approach that lacks physical consistencies, including a correct description of the matrix fluid properties and being faithful to the continuity equation. Thus, in order to use this approach for simulation of pumped concrete, more research, including further validation is still needed.

4.3. A realistic simulation of pipe flow

As is often the case in developing continuum or numerical models of fluid flow for pumping, it is crucial to properly implement boundary conditions at the fluid-solid interface. Indeed, any variation to the slip/no slip boundary condition can have a dramatic effect on simulation results. The situation is, in many respects, the same for actual pumping. In other words, the key to successfully pumping concrete lies in controlling its rheological behavior near the fresh concrete-pipe interface. Understanding the tribological behavior of concrete near the pipe wall is a great challenge because of many factors: concrete is a complex fluid with granularity, the matrix fluid is non-Newtonian with a viscosity that is both time and shear rate dependent, and the location of aggregates near the pipe wall can give the concrete a different flow property than that found in bulk or central flow. Detailed computational modeling of suspension flow that incorporates such phenomena near a pipe surface is needed to develop proper boundary conditions for continuum models of flow in pipes to improve predictions of pumpability. Earlier attempts of modeling pressure driven flows of suspension using the Stokesian Dynamics approach [25], can, for example, account for particle migration to the center of a pipe. While providing valuable insights into such flow phenomena, application of such models has been limited to modeling quasi 2D systems and, further are only valid for suspensions with a Newtonian fluid matrix, which is generally not representative of cement based materials. Currently, an excellent candidate for the realistic modeling of suspensions composed of cement based materials is based on the Smoothed Particle Hydrodynamics (SPH) method [33] as shown in Fig. 4. SPH is a Lagrangian formulation of the Navier Stokes equations and has the flexibility to model non-Newtonian fluids and the motion of rigid bodies. This approach can be used to model suspensions with a non-Newtonian fluid matrix and flow in complex geometries like a vane rheometer. The same methodology could be used to simulate flow in a pipe.

The SPH approach could be utilized to study the following three flow scenarios to better understand and predict the flow of pumped concrete.

1. A detailed study of flow near a pipe surface is needed to characterize the typical flow fields that result as a function of the aggregate concentration and matrix fluid properties. The flow velocity profile should strongly depend on the shear rate dependence of the matrix fluid (i.e. shear thinning and shear thickening). The results of this study could be linked to improving inputs for boundary conditions into continuum models and provide insights into designing the matrix fluid properties to optimize flow.
2. A second set of simulations should focus on flow in the cross section of a pipe and to determine to what degree the rheological properties of the matrix as well as aggregate composition affects segregation or homogeneity of the concrete fluid. This in turn could affect the tribological behavior of concrete near the pipe surface as the volume fraction of aggregates will be different at the pipe surface from that along the central axis of the pipe. Understanding this behavior will help in the optimization of pipe flow.

3. Finally it is also important to find a link between measurements of the matrix or concrete flow properties using rheometers and successful pumping. This entails detailed modeling of concrete flow in rheometers and pipes and linking such measurements to real physical properties of concrete.

The integrated results from such simulations would provide insight into predicting the successful flow of pumped concrete for many of the challenging flow scenarios found in the construction industry. Costs can be reduced as fewer tests will be needed and optimal, robust blends can be more easily formulated by the concrete producers.

5. Conclusions and suggestions

The pumping of concrete is an important issue in concrete construction. In this paper, the authors attempted to summarize the main factors for successfully pumping concrete. This was achieved by the literature review and by identifying the key parameters for concrete flow characterization. The following major conclusions were drawn:

1. From the literature review, it was found that concrete flow in a pipe is governed mainly by the slip-layer and dynamic segregation. The slip-layer, which is formed between the pipe and the concrete, plays a dominant role in facilitating the concrete flow. Dynamic segregation can be radial, resulting in plug flow, or, longitudinal leading to blockages in the pipe.

2. In order to characterize the slip-layer, tribology tests were mainly investigated using a tribometer which is a special coaxial rheometer whose bob is purposely made with a smooth surface. Through the relationship between the torque and

angular velocity of the tribometer, the rheological properties of the slip-layer can be determined.

3. An analytical prediction of the flow rate and pumping pressure in a pipe was obtained based on the assumption of three layers in a pipe.

The critical research needs are also identified:

1. Computational modeling of flow near a pipe surface is needed to develop accurate boundary conditions for input into continuum models of pipe flow for predicting pumping performance. Such models need to effectively simulate non-Newtonian fluids and the motion of rigid bodies to investigate the tribology phenomena and provide insight into predicting concrete flow in a pipe. Obviously, this model will also need to be validated with experimental testing.

2. A standard methodology should be developed to measure the relevant rheological properties of the concrete and correlate them with the flow of the concrete in a pipe.

    - A calibrated tribometer test to allow for the evaluation and characterization of the slip-layer for a specific concrete composition and pipe material.

    - A test method to predict the forward dynamic segregation depending on the pressure of the pump, the composition of the concrete and the rheological properties of the matrix.

A suggested definition of pumpable concrete is:

A property of a concrete, mortar or grout to flow through a pipe, for a given diameter and length, that can be discharged with the desired performance, i.e., homogenous, non-segregated, and with the specified rheological properties needed for the application.

The definition of pumpability or the quantification of how pumpable a concrete is would require the knowledge of values of viscosity, yield stress and tribological properties of the concrete. To obtain these values further studies would be needed that would combine both modelling and experimental measurements.

The present paper was mainly focused on a literature review and providing ideas on how to characterize the flow of concrete and demonstrate the basic principles needed to analyze the tribology. Thus, through a more specific investigation of tribology, the relationship between the tribology and the pumpability as defined is needed to be examined.

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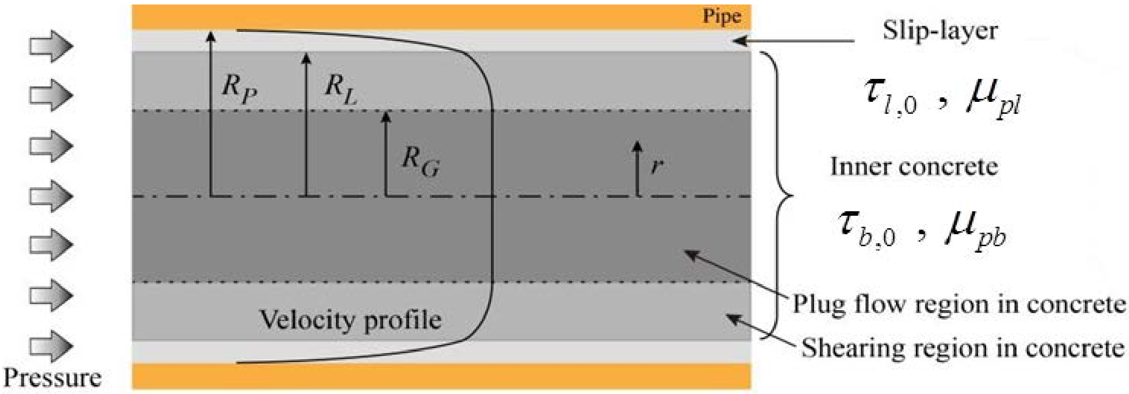
Fig. 3 Schematic representation of particle positions based on evaluation of the concentration of particles using the shear-induced particle migration approach

Fig. 4 Simulation of a vane rotating in granular material using the SPH based approach



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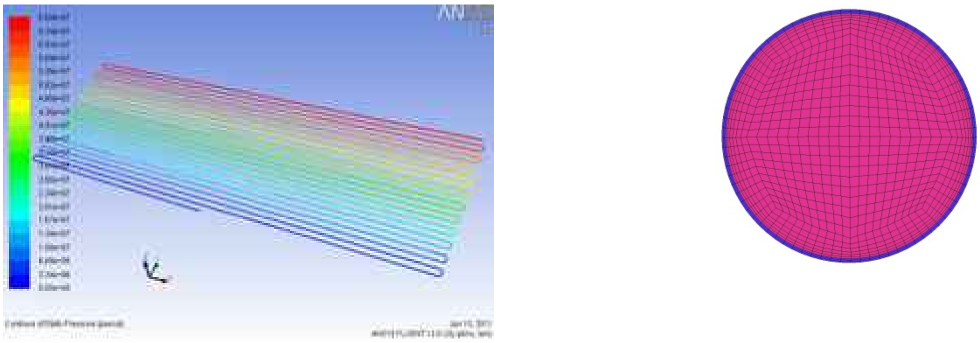
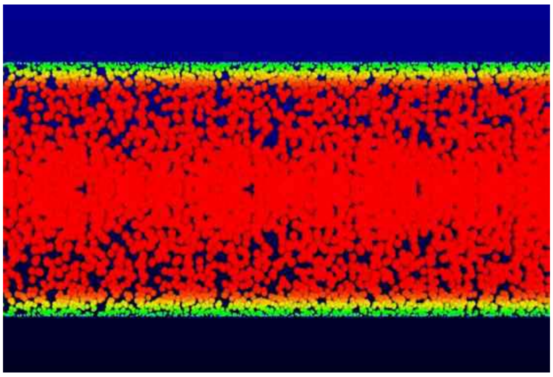


(a) Numerical simulation of full scale concrete pumping system

(b) Cross section including slip-layer (blue region)

Fig. 2 Modeling for single phase fluid approach



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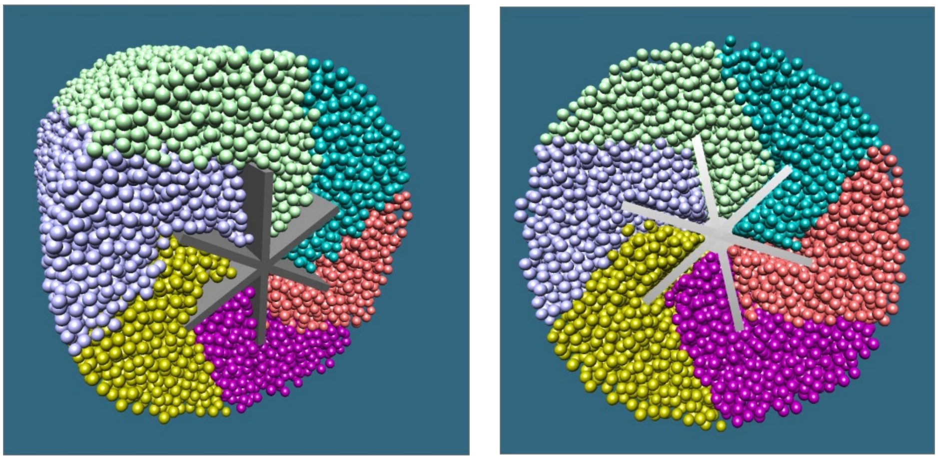

Fig. 4 Simulation of a vane rotating in granular material using the SPH based approach. (Here the flow of suspended spherical particles in a non-Newtonian fluid matrix is modeled. Simulations were carried out using resources of the Argonne Leadership Computing Facility at Argonne National Laboratory. [Image was created with the assistance of William George and Stephen Satterfield of NIST].)