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Practical Insights and Advances in Concrete Pumping

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Abstract

This technical letter gives a concise overview of the state-of-the-art in concrete pumping. It outlines the different pump systems, briefly describes the general flow behavior of concrete in pipes, and addresses the main challenges of pumping. It also elaborates upon factors influencing the pumping behavior and how to control the pumping process.

Keywords: Concrete; Pumping; Lubrication layer; Rheology; Quality control; Pressure.

1 Introduction

Pumping of concrete has become an indispensable technology for efficiently placing concrete, especially in hard-to-reach locations. Since its invention about 90 years ago, pumping has advanced significantly and has allowed for fast placement of concrete under challenging conditions. Without the utilization of concrete pumping technology, the construction of numerous contemporary remarkable structures would remain unattainable today. Concrete pumps are instrumental in enabling the realization of modern complex construction projects, such as the Burj Khalifa in Dubai, UAE; the Fehmarnbelt Tunnel in Denmark; or Water Gallery Le Refrain in Haut Doubs, France, among others [1–3].

The control of concrete pumpability and the prediction and evaluation of pumping pressure are the most important requirements for ready-mixed concrete producers, concrete pump manufacturers, and pumping companies. Also, meeting the concrete specification requirements in the fresh and hardened state after pumping is a key issue for project owners, structural design professionals, inspection agencies, concrete producers, contractors, and other involved agencies and professionals. Over the last 20 years, research has made significant progress in understanding the flow behavior of concrete during pumping, the interrelations between concrete rheology and pumping, and the prediction of pumping pressure through analytical and numerical models. This paper offers a brief overview of the current understanding of concrete pumping and discusses the current needs for research and guidelines. It provides an outline of different pump systems, describes the general flow behavior of concrete in pipes, and addresses the main challenges of pumping. It elaborates upon factors influencing the pumping behavior and how to control the pumping process.

2 Pumping systems

Concrete pumps are used in a variety of construction projects to efficiently deliver fresh cement-based materials to a desired location at a high pace. The most commonly used concrete pumps in practice are piston pumps; see Figure 1a.

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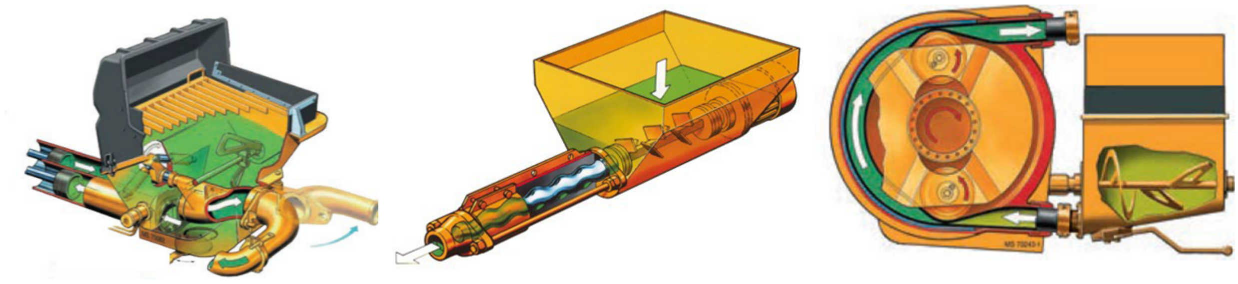
Piston pumps [4] consist of a receiving hopper, two concrete pumping cylinders, and a directional valve system that alternately direct the flow of concrete into the pumping cylinders and from them to the pipeline. They work with high pressure for transporting most types of concrete with different flowability. Some piston pumps can exert up to 250 bar of pressure on the concrete and maximum flow rates reaching up to 200 m³/h. Screw pumps (see Figure 1b) and peristaltic pumps (see Figure 1c) are usually selected for more specialized applications and provide efficient pumping of less coarse materials, predominantly suitable for mortars or concretes with relatively fine aggregates.



(a) (b) (c)

Figure 1. Different types of pumps: (a) concrete pump with double piston, (b) screw pump (c) peristaltic pump.

Screw pumps can be used to provide lower pressures at low flow rates. These types of pumps are for example well suited for 3D printing with concrete, when a constant delivery of material at relatively low flow rates is required [5]. Peristaltic pumps do not deliver as much pressure as piston pumps, but they are beneficial with respect to low wear and tear of the pump mechanics. It is foremost the elastic tube that is being exposed to excessive wear. Such pumps are well suited for fine mortars, or minor amount of concrete; as coarse aggregates lead to faster wear of the pumping equipment [6].

The materials for the pipes used to transport the concrete are most commonly rigid steel or heavy-duty flexible rubber for the end placing hose. Bends and reducer elements are often made from hardened steel, to withstand the wear induced by high abrasion [7]. The diameter of pipes used for pumping mortar and concrete ranges between 20 mm and 250 mm, depending on the field of application, aggregate size, and type of pump. A diameter of 125 mm is most frequently found when pumping concrete on regular construction sites, where the nominal maximum aggregate size typically reaches up to 20 mm.

3 Flow behavior of concrete in pipes

3.1 Flow of homogeneous material

Concrete is a highly viscous material with viscosity values ranging from around 10-20 Pa·s in conventional concrete to over 100 Pa·s in high-performance concrete. Yield stress can vary from 0 Pa for some self-consolidating concrete to several 100 Pa for pumpable conventional concrete. While its flow behavior in pipes is complex and difficult to predict, it is an important aspect during the design and engineering of the concrete pumping process [1, 2, 6, 7]. Assuming a no-slip condition at the pipe wall, the cause for the pressure loss during pumping at normal conditions is viscous heat dissipation by shear stresses across a radial profile of the pipe; see Figure 2. Pressure loss increases with increasing flow rate, increasing rheological parameters (mostly viscosity but also yield stress), and a decrease in pipe diameter. Furthermore, assuming at first material's homogeneity, the Hagen-Poiseuille equation describes the laminar flow of Newtonian fluids in pipes [8, 9]. Concrete, however, is neither Newtonian fluid nor homogenous material. It is a yield stress material, meaning a certain stress value needs to be exceeded for flow onset. The Bingham model is the most common model describing concrete rheology, and the Buckingham-Reiner equation gives pressure losses in laminar flow in pipes for such materials [10–12]. However, attempts to validate the Buckingham-Reiner equation have resulted in significant overestimates of the pressure losses [1, 2, 6]. The main reason for these deviations is the heterogeneity of concrete, which significantly impacts its flow behavior in pipes.

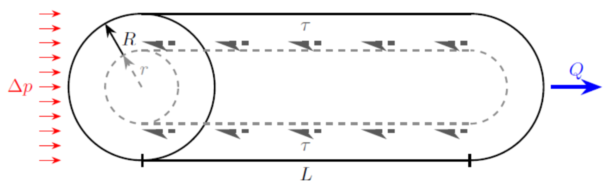


Figure 2. Pressure loss (Δp) occurring in a pipe of length L and radius R during pumping at a flow rate Q in which pressure and thereby energy is lost by viscous heat dissipation by shear stress τ across a radial profile (r) [13].

3.2 Concrete flow in pipes

3.2.1 Lubrication layer

During the flow of concrete in pipes, the shear stress is the highest at the wall of the pipe and linearly decreases towards zero at the center of the pipe [14–16] . Thereby, larger aggregate particles tend to move away from regions of higher shear stresses (or rates) to those of lower shear stresses (or rates). This phenomenon is referred to as shear-induced particle migration (SIPM) during pumping. It leads to the creation of the lubrication layer (LL) at the pipe wall, which is much finer compared to the bulk concrete in the pipe core. SIPM reaches localized equilibrium and stops when the local volume fraction of particles (including the migrated ones) in the lower shear region reaches a certain threshold of local packing density and corresponding high viscosity of the material [7, 16–20]. Furthermore, right at filling the pipe, the pipe wall prevents a uniform distribution of coarser particles within a few millimeters from it (so-called wall effect). This facilitates the formation of lubricating layer and the initiation of SIPM [7, 16–19, 21]. Due to the absence of larger particles in the vicinity of the pipe's wall, the rheological properties of the LL are much lower than those of the bulk concrete inside the pipe. Therefore, the LL facilitates considerably concrete flow inside the pipeline. If LL with proper quality and thickness fails to form, high friction forces between the aggregates and the pipe wall can result in excessive pumping pressure or even blockage. In the past few years, research on thickness, composition, and cause of formation of the LL has led to models and methods for its description and characterization, respectively [18, 19, 22–25].

3.2.2 Flow zones across the pipe section

When concrete is pumped through a pipeline, three different zones with different flow characteristics and thicknesses can form across the pipe section, due to the linear, radial change in shear stress across the pipe section (zero in the center to maximum at the wall); see Figure 3. The thicknesses of the three zones depend on the type of concrete and its rheological characteristics, pumping pressure, and pipe diameter [16, 26–28].

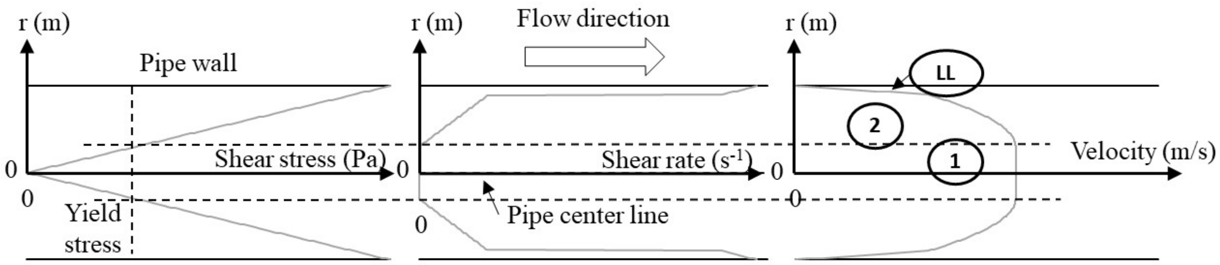


Figure 3. (a) Shear stress, (b) shear rate, (c) velocity profiles in a pipe. Zone 1 indicates plug flow in the concrete where the shear stress is lower than the yield stress. Zone 2 reflects shearing in the bulk concrete while the outer zone (LL) shows the lubrication layer. Figure modified from [7].

The first zone (plug flow zone) constitutes non-sheared concrete extending from the pipe center to a certain distance at which the shear stress caused by pumping is equal to the yield stress of the concrete; Figure 3. Throughout this zone, the shear stress is smaller than the yield stress, and concrete will move ahead in the pipe without being sheared (so-called plug flow). In the second zone (sheared zone), extending from the outer boundary of the first zone to the inner boundary of the LL, concrete is sheared; Figure 3. For concrete mixtures with high yield stress, this zone may not exist. The third zone is the LL located in the vicinity of the pipe wall and is heavily sheared; Figure 3 [26, 28]. The boundaries of different flow zones in the pipeline depend on the concrete mixture's rheological properties and pumping parameters.

4 Challenges during pumping concrete

Pumping concrete is a complex process that involves many challenges. Internal and external parameters affect the pumping process, making it difficult to predict the flow of concrete inside a pipeline in both theory and practice. This section focuses on some of the most pronounced challenges related to the pipe flow of concrete and corresponding analytical predictions.

4.1 Segregation before and/or during pumping

Most equations for pipe flow prediction assume that concrete mixtures remain stable before and during pumping. If segregation occurs before and/or during pumping, the reliability of these equations, and thus the prediction or evaluation of the concrete behavior and pumping pressure, is compromised. Apart from that, a mixture with a strong tendency to segregate makes it more difficult to obtain homogenous and reproducible samples for pumping quality control. Segregating mixtures may also provide challenges during the restart after a stoppage causing a blockage.

4.2 Influence of the filling degree of concrete pump cylinders

Another issue that reduces the validity of the existing equations for pipe flow analytical prediction and their usability in practice is the assumption of an ideal filling degree (full-filled cross-section) of the concrete pump cylinders and pipeline throughout the pumping process. This seldomly occurs in practice [29]. Incorrect estimates of the filling degree also affect the expected flow rate that is included in most pumping prediction equations. The additional air, which gets sucked with strokes from the pump hopper into the pump cylinders and pipeline, induces an imperfect filling and thus, has a notable effect on the flow behavior of concrete in pipes [19]. In practice, a lower filling degree results in longer interruption times between pump strokes. This means, in addition to the technical interruption during the switch from one cylinder to another, there is additional time required before the concrete can be pushed or fed again. This significantly influences the concrete start-stop sequence in the pipe, especially when pumping downwards.

4.3 Changes in the air void system of fresh concrete during pumping

The air-void system of concrete can alter during pumping, mainly due to the pumping pressure, imperfect filling of the pipeline with concrete, or the generation of air in presence of some types of water-reducing admixtures caused by high shear rates [30]. This change in the air-void system (especially in air-entrained concrete) can cause a change in the rheological properties of concrete inside the pipeline, resulting in some deviations from the assessed rheological properties of the mixtures as observed under atmospheric conditions. The most prominent issue is the coarsening of the air-void system due to the pressure-induced dissolution of small air-bubbles, bubble growth, and coalescence when downward flow induces pressures below the atmospheric pressure. Practical guidelines for conventional vibrated concrete have been developed to limit the negative effects, but recent work has shown a more complex interaction between shear stress/strain, pressure, and time, affecting the coarsening of the air-void system [7].

4.4 Insufficient formation of lubrication layer for special concrete mixtures

When using piston pumps to transport special types of concrete, such as ultra-high-performance concrete, highly-viscous high-strength concrete, mixtures with a high volume fraction of coarse aggregates, or mixtures with a low volume of cementitious paste, SIPM may be limited resulting in a non-existent or negligible lubrication layer. While this can make it difficult to pump such mixtures, the prediction or evaluation of their pumping behavior requires a thorough consideration of the conditions at the vicinity of the pipe's wall.

4.5 Effects of the structural build-up and break-down of concrete during pumping

When pumping concrete through long pipelines, under hot weather conditions, or with extended interruptions of the pumping process, reversible and irreversible bonds can form between the cement particles of the concrete mixture. This can lead to increasing yield stress and viscosity of concrete. Such change in rheological properties induces an increase in required pumping pressure, which the pump may not be able to deliver. Recent studies evaluated the effect of an increase in yield stress on the pressure needed to restart the process [6, 31, 32].

At the same time, the high shear rates in the mixture due to pumping cause microstructure break-down inside the mixture. A systematic decrease in concrete viscosity has been observed, while the effect on yield stress can go either way. Altogether, this can lead to either segregation of concrete, or loss of its fluidity, depending on whether yield stress decreases or increases. Anyway, the concrete that exits the pipeline is very unlikely to have the same properties as the concrete that entered the pump.

4.6 Effect of complex pipeline geometries (bends and reducers)

Studies have shown that the flow of concrete through complex geometries such as bends and reducers in the pipeline system can cause considerable pressure loss during pumping [6, 12, 19]. Because of the complexity of the concrete flow in bends and reducers, it is difficult to accurately predict the local pressure losses over these parts of the pipeline. Existing pipe-flow analytical prediction equations primarily focus on concrete behavior in straight pipes with uniform cross-sections. Consequently, there are currently no analytical solutions available for precise predictions of concrete flow in complex geometries. To address this challenge, researchers are actively developing semi-analytical methods, which combine elements of both analytical and numerical techniques. These semi-analytical methods can be integrated into numerical solution approaches, with the aim of enhancing our ability to make more accurate predictions regarding the flow behavior of multi-granular suspensions.

5 Pumping and pumpability: influencing factors and effects

Pumpability is the ability of fresh concrete to flow through a delivery pipeline under pressure without considerable segregation during pumping. It is a critical feature of fresh concrete. In this section, some important factors that affect pumpability as well as the effects of pumping on fresh concrete properties are discussed.

5.1 Effects of constituent materials and mixture design parameters on pumpability

Constituent materials and mix design parameters are crucial factors that influence pumpability. In construction projects, increasing content of cementitious materials has been the first quick and common solution to mitigate the pumping difficulties, particularly when dealing with mixtures that have poor particle gradation, specifically a very low volume fraction of finer sand particles (less than 600 µm). However, the addition of extra cementitious materials in mixtures with low water-to-cement ratio (w/cm) and high dosage of polycarboxylate-based high-range water-reducing admixtures can increase concrete viscosity, and thus the pumping pressure. While polycarboxylate-based admixtures generally decrease yield stress and improve flowability, in these specific mixtures, the combined effect of low w/cm and high cementitious content may lead to higher viscosity and increased pumping pressure. For a given w/cm, the replacement of Portland cement with supplementary cementitious materials (e.g., silica fume, fly ash, slag, or a blend of these) up to a certain level or in a certain range can partly lower the plastic viscosity of concrete without negative effect on segregation and consequently, reduces the pumping pressure and improves the pumpability. [33, 34].

Aggregate-related parameters including the combined aggregates gradation, maximum size, volume fraction, gradation of finer particles of sand (less than 600 µm), and particle shape can individually or in a combination affect the characteristics and parameters related to pumping. Aggregate volume fraction and size and grain size distribution affect the occurrence of friction, rheological properties of concrete and LL, the LL thickness, and even the behavior in bends and reducers due to possible inertia effects. Therefore, upscaling results obtained on mortar to concrete scale requires the necessary caution, as some but not all factors can be translated from the lab to the real world.

Chemical admixtures can considerably influence the workability and rheological properties of concrete and thus affect its pumpability. Normal, mid, and high-range water-reducing admixtures can increase the flowability of concrete and reduce the pumping pressure. When the efficiency and/or dosage of high-range water-reducing admixtures is increased, the potential for bleeding and segregation also increases, which can negatively affect the pumping behavior of concrete. Rheology and viscosity-modifying admixtures (VMA) can increase the stability, cohesion, and robustness of high-slump and highly-flowable concretes and thus improve their pumpability. However, a high dosage of VMAs can increase the viscosity and pumping pressure, and may also lead to an increase in yield stress, which can further affect the pumping behavior of the concrete [33, 34]. Hydration (or set) controlling (or retarding) admixtures can provide workability retention during the pumping process and improve the pumpability, especially in hot weather and long-distance pumping. The addition of accelerating admixtures may decrease concrete flowability and pumpability and increase the pumping pressure if a high dosage of an accelerator is used or if there is a delay between the accelerator addition and the discharge of concrete from the truck mixer. Air-entraining admixtures may improve pumpability, especially when the volume fraction of finer particles of sand is not enough (sand with coarse, irregular particle size distribution can make the concrete mix less workable). However, the efficiency of air-entraining agents to reduce pumping pressure is limited, as air bubbles reduce in size and get dissolved under pressure [33–35].

A low volume of cementitious paste in concrete mixtures can decrease the inter-particle distance between the aggregates and result in higher viscosity and higher pumping pressure [36]. If frictional interactions occur, the potential for blockage and difficulties in pumping can increase due to deficiencies in the formation of the lubrication layer, negatively affecting pumpability. Increasing the paste volume can reduce viscosity, and consequently, the required pumping pressure [37]. However, beyond certain limits, increases in paste volume have no considerable effect on pressure loss but can increase the risk of segregation and blockage and cause other instability issues [38]. Therefore, for every mixture design, there exists a range of paste volumes in which flowability and stability are in harmony; outside of this range, the concrete becomes less appropriate for pumping applications [28].

By reducing the w/cm of concrete to produce high strength and high durability mixtures, the viscosity of the bulk concrete and that of the lubrication layer increase, and the thickness of the lubrication layer decreases, resulting in the need for higher pressure to obtain the same flow rate for pumping [16, 19, 28]. This issue is intensified when high dosages of polycarboxylate-based high-range water-reducing admixtures are used [33, 34].

5.2 Effects of concrete pump and pipeline system on pumpability

The concrete industry mostly uses double-piston pumps, where concrete flows due to the pulsating action of two pistons. However, this pulsating (or stroke-related) flow can cause inertia-induced particle migration in the concrete mixture, as coarse aggregates may move further ahead than the mortar. This could affect concrete homogeneity over the length of the pipeline and can potentially cause air bubble coalescence in the concrete mixture. The inertia-induced movement of coarse particles during the pressure shocks (due to intake and discharge strokes) can cause the accumulation of these aggregates at the bottom of a downward slope pipe section [29]. This can lead to the blockage of the entire system. The selection of an appropriate piston pump for various projects depends on a number of factors: the type, flowability, and rheological properties of the concrete; the length, configuration, and direction of the pipeline; the diameter of the pipe; the required pumping pressure; the necessary flow rate; and the accessibility to the area where concrete is to be placed. One of the most important steps in designing and engineering the pumping process is the selection of the proper pipe diameter because it influences the properties and thickness of the lubrication layer [27] and thus affects the concrete behavior and pressure loss during pumping. Increasing the pipe diameter can be the most efficient way of reducing pumping pressure, as an increase in pipe diameter from 100 mm to 125 mm has been shown to reduce pressure by over a factor 2 (Figure 4) [16, 39].

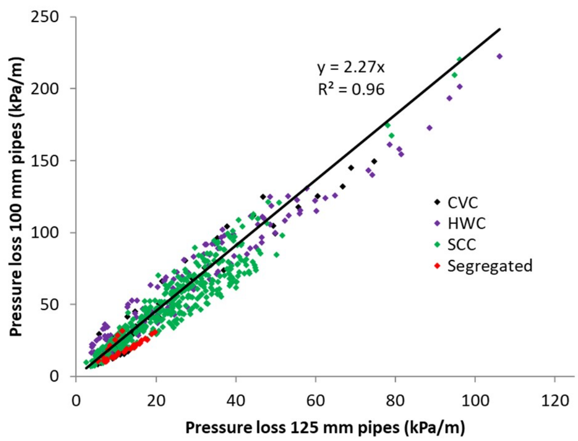


Figure 4: The experimentally measured pressure loss in 100 mm diameter pipes is over a factor 2 larger than the measured pressure loss in 125 mm pipes. Figure modified from [39].

Priming the pipeline with proper lubricating cementitious grout is a critical phase. The grout coats the inner walls, creating a smooth layer that reduces friction and helps the concrete flow more easily. It also reduces the forward inertia effect on the coarse aggregates caused by the sudden flow stoppage in case of piston pumps. Successful priming depends on a variety of factors: the proportions of the lubricating grout mixture and concrete, the flow rate, the configuration, diameter, and length of the pipeline, as well as the priming methodology. If not properly designed and executed, blockages at the priming stage are quite common even in the case of mixtures that exhibit no subsequent problems during steady-state pumping. In the case of long-distance pumping, the priming phase becomes more critical [40, 41].

5.3 Effects of pumping on fresh concrete properties

Pumping results in the shearing of the lubrication layer and the bulk concrete, which decrease or increase their yield strength and viscosity. For instance, if the shearing induces dispersion in cement particles, structural breakdown of the concrete, and enhancement in the effectiveness of the water-reducing admixtures, the yield stress and viscosity of the bulk concrete and lubrication layer would decrease. Meanwhile, the viscosity and yield stress would increase if the shearing enhances the internal structural build-up of the concrete due to the dissipation of heat or other factors [2, 12, 17, 19].

Moreover, studies [7, 42–45] have shown that the total air content of the concrete can change during the pumping process. The discharge process also has an effect on the air content of the concrete after pumping. General models do not yet exist to describe the dissolution, resurfacing, coalescence, generation, and bursting of air bubbles during pumping, and the introduction of air from the unfilled pump hopper into the pipe cylinders.

Concrete temperature may increase during pumping due to viscous heat dissipation, extended pumping time in hot weather, and possible acceleration of cement hydration due to high shear rates in the pipeline. This increase in concrete temperature during pumping can reduce workability, affect the yield stress and viscosity of the concrete and increase the risk of blockages. In some lab tests, mortar and concrete is recirculated through the pump hopper, amplifying the effect of viscous heat dissipation, compared to situations where concrete is pumped once [1].

6 Control of concrete pumping process

Recent developments in the control of concrete pumping processes have led to advancements in pumping pressure prediction, pumping quality control, digitalization, and active control of pumping processes. Control of concrete pumping processes is essential to facilitate concrete construction, maintain the required concrete quality at a minimum cost, and enhance on-site safety.

6.1 Pumping pressure prediction

Predicting the behavior of concrete during the pumping is crucial to effective process control. Several methods can be used to predict pumping behavior.

Analytical equations can be used to predict pumping behavior and required pumping pressure for a specific flow rate. Many analytical equations exist to predict the pumping behavior. Kaplan's equation [46] or the dual Bingham Poiseuille flow extension [4, 6, 16, 19, 47, 48] account for lubrication. Still other equations were derived in the literature to additionally account for shear thickening [49] and even time-dependent thixotropy [6, 13].

Nonetheless, equations need specific input parameters about the fresh concrete and LL, like viscosity, yield stress, and LL thickness (explicitly or implicitly). This information can be collected on site from concrete samples and subsequently used in analytical equations to evaluate the pumping behavior. Lastly, one can also commit to on-site empirical predictions. As such, the Sliper returns easily interpretable or convertible parameters to estimate the pumping behavior (Equation 1, Figure 5).

Equation 1: Inserting and calculating pressure predictions using the Sliper model [50].

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

$$a = \frac{\mathrm{Y} \cdot Ds}{4 \cdot Ls}$$

$$b = \frac{\mathrm{M} \cdot \pi \cdot Ds^3}{16 \cdot Ls}$$

With P = pressure [N/mm²]

a = yield stress parameter [bar]

L = length of delivery pipe [m]

D = diameter of the delivery pipe [m]

b = viscosity parameter [bar·h/m]

Q = discharge rate [m³/h]

ρ = sample density [kg/dm³]

g = gravitational acceleration at 10 m/s²

h = delivery height [m]

Y = y-axis intercept of regression line of measurements in p-q diagram [bar]

Ds = diameter of Sliper pipe [m]

Ls = Length of Sliper pipe [m]

M = slope of regression line in p-q diagram [bar·h/m³]

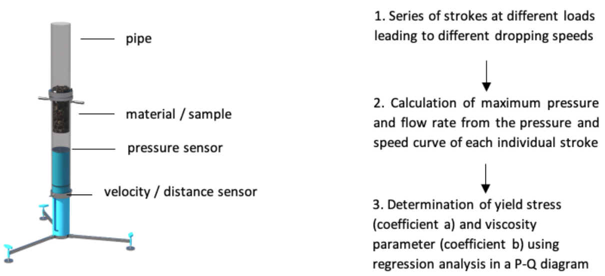


Figure 5. Sliper setup and measurement procedure [51].

Nomograms depict the required pumping power needed as a function of flow rate, equivalent straight pipe length, given a certain workability or rheological characteristic, and pipeline diameter. One recent development is a nomogram, which was developed for Self-Compacting Concrete (SCC) based on input from the Sliding pipe rheometer (Sliper) instead of the slump [52], see Figure 6.

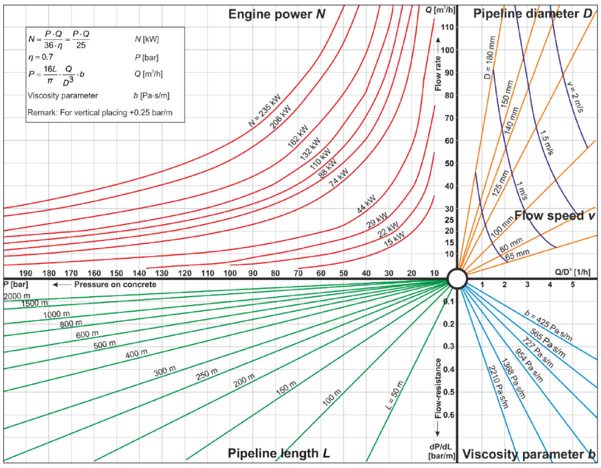


Figure 6. Adapted nomogram for practical use to determine pumping parameters [19].

6.2 Quality control for the pumping process

Quality control (QC) is an essential part of any concrete manufacturing and placement process. Control of concrete pumping processes is achieved through QC in all three stages: before, during, and after pumping. On-site quality control tools and methods for monitoring the pumping process are needed to facilitate concrete placement, enhance on-site safety, and maintain the required concrete quality at a minimum cost.

On-site monitoring of the pumping process by sensors provide a trouble-free measurement method for determining the most important parameters for the pumpability of concrete. The pumpability of concrete can, for example, be monitored by real-time measurements of pump pressure and flow rate. Several quality control parameters can be used to detect changes in the pumpability of the concrete [53]. This real-time control method has shown promise for quality control during the pumping process. In this context, for example, Barluenga et al. investigated the influence of various quality control parameters on the pumping behavior of self-consolidating concrete (SCC) and their effects on the concrete's setting behavior such as early strength and other hardening properties [54]. Pumpability was monitored online by real-time measurements of pump pressure and flow rate. Temperature, capillary pressure, dimensional stability, and P-wave ultrasonic pulse transmission were measured simultaneously to monitor early age microstructure development. These QC parameters have been shown to be able to detect changes in the pumping behavior of the concrete, as well as in the early age and cured state.

6.3 Digitalization

Digital transformation of concrete technology aims to integrate advanced concrete technologies with novel sensors, virtual reality, or internet of things to create self-learning and highly automated platforms controlling design, production, and long-term usage and maintenance of concrete and concrete structures. Advances in digital technologies such as digital twin (DT) [55] have enormous potential in digitally advanced industries, including 3D Concrete Printing (3DCP) [56]. However, applications of DT technology in large-scale pumping of concrete are scarce, and more studies are anticipated in this area, following the developments in 3DCP and the implementation of Industry 4.0 in the construction sector [57].

6.4 Active control of pumping process

In view of the existing technical possibilities, it is obvious that the control of the pumping process of concrete lags behind today's technical possibilities. A concept of active rheology control (ARC) has been developed recently, with successful lab-scale proof of concept [58, 59]. This ARC-technology will in principle also be applicable to concrete pumping, in view of which further upscaling studies are ongoing. At this moment in practice however, the active control of the pumping process is limited to the human pump operator controlling the pump and mostly relying on experience and personal assessment. Sensors can be used to monitor and control the pressure of a pump and lead to a significant optimization of the pumping process. With the help of an in-line system, impending difficulties during the pumping process of concrete, such as the formation of blockages, can be detected at an early stage. At this early stage of detection countermeasures can still be initiated effectively, avoiding system blockage, damage to equipment and potential danger to on-site workers. Further developments regarding active control of the pumping process are also essential for modern construction techniques like 3DCP.

7 Summary and outlook

Pumping of concrete is a widely used process in everyday construction practice and has advanced significantly over the past 90 years. This paper provides a brief overview of the current understanding of different pump systems, concrete flow in pipes, pumping challenges, factors affecting the concrete pumpability, effects of pumping on concrete properties, and control of the pumping process. The complex process of pumping concrete is influenced by various internal and external factors, making it difficult to predict and control. The methods currently available for predicting pumping behavior, which include nomograms, analytical equations, on-site investigations of fresh concrete properties, and rheological examinations, all have strong potential and limitations. Increasing digitization of construction processes not only holds great opportunities for quality control and in-line monitoring but also enables the implementation of assistance and automation systems. Such systems can significantly reduce the manpower needed, enhancing efficiency and potentially lowering costs. The control of concrete pumping processes is a critical aspect of modern concrete construction and manufacturing, especially in horizontal or vertical long-distance pumping. The rapid development of high-rise buildings and skyscrapers in different cities around the world has necessitated the proper selection, design, and engineering of the pumps, pipeline system, concrete mixtures, and QC system. Recent developments in this area have focused on predicting the flow behavior of concrete and the required pumping pressure during pumping, improving quality control before, during, and after pumping, digitalization, and active control of the pumping process. As concrete technology continues to evolve and new construction techniques like 3D Concrete Printing emerge, researchers will continue to explore new methods and technologies to optimize the pumping process and improve the overall quality and efficiency of concrete manufacturing and construction.

8 Author contribution

This paper was created by a taskgroup of RILEM TC 305-PCC: Pumping of Concrete, with all authors contributing to the document. No experiments or simulations were performed for this paper.

This paper is approved by RILEM TC 305-PCC.

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