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# A review on the pumping behavior of modern concrete

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**Abstract:** Pumping is the most common technique used to transport fresh concrete in construction sites. The large-scale use of concrete all over the world makes the pumping increasingly important. A wide variety of additives and admixtures are incorporated into modern concrete in order for sustainable development. The performance of modern concrete is rather complex and its pumping behavior differs significantly from that of conventional concrete, especially in the fresh stage. This paper presents a comprehensive overview on the state of the art of concrete pumping. The models and methods used for characterizing the concrete pumpability and lubrication layer are described. The factors influencing the pumping behavior are discussed. A couple of ultra-high pumping engineering of concrete conducted in China are introduced.

**Keywords:** modern concrete; pumpability; lubrication layer; model; review

## 1. Introduction

A broad range of construction techniques of concrete pumping has been developed globally. The pumping enables horizontal and vertical transportation of concrete at one time, which is labor-saving and cost-effective. In the cases where construction sites are narrow and obstacles are present, advanced pumping technique of concrete is of particularly interest (Jiang et al. 2017; Zhao 1985).

Significant progress has been achieved on the pumping behavior of conventional vibrated concrete (CVC) over the past decades, especially in the field of prediction of the pumping pressure, influencing factors of pumpability and rheological properties, and the friction performance of the lubrication layer (Kaplan 2001, Secrieru 2018b). In order to sufficiently utilize various byproducts and wastes and improve the construction performance of concrete, different kinds of additives and admixtures are nowadays incorporated into modern concrete, e.g. self-compacting concrete (SCC) and high-flowability concrete (HFC). The properties of modern concrete are highly sensitive to the raw materials, temperature, age and operation methods, resulting in the pumping behavior of modern concrete to be quite different from that of CVC, particularly in the fresh stage. Unfortunately, the knowledge regarding the pumping behavior of modern concrete is far from sufficient up to date.

This paper presents recent advances on concrete pumping behavior, including the steady flow state, the pumping models, the test methods and the influencing factors. Previous experimental results related to these aspects are provided. The pumping behavior and associated problems facing the engineers are discussed. A few typical cases of the ultra-high pumping engineering conducted in China are introduced eventually.

## 2. Steady flow state of concrete in pump pipe

Fresh concrete is a kind of heterogeneous composite mixture with non-Newtonian fluid characteristics (Jiang et al. 2017). Pumped concrete is often considered as Bingham fluid sliding along the pump pipe under pressure, as shown in Fig. 1. The rheological properties of Bingham fluid can be described with Eqs. (1) and (2). Eqs. (3) and (4) can be deduced directly from Eqs. (1) and (2). From the boundary conditions r = R and v = 0, Eq. (5) is obtained. The velocity distribution of the Bingham fluid during the pumping process can be illustrated in Fig. 2 (Zhao 1985).

$$\tau = \Delta P \frac{r}{2l} \tag{1}$$

$$\tau = \tau_0 + \eta \frac{dv}{dr} \tag{2}$$

$$\frac{dv}{dr} = \frac{1}{\eta}\left(\frac{\Delta P r}{2l} - \tau_0\right) \tag{3}$$

$$\int \frac{dv}{dr} dr = \frac{\Delta p}{2\eta l} \int r dr - \frac{\tau_0}{\eta} \int dr \tag{4}$$

$$v = \frac{1}{\eta}\left[\frac{\Delta P}{4l}(R^2 - r^2) - \tau_0 (R - r)\right] \tag{5}$$

where $r$ [m] is the distance from the axis of the pump pipe, $\tau$ [Pa] is the shear stress of fresh concrete when the distance from the axis of the pump pipe is $r$, ΔP [Pa] is the pressure difference of fresh concrete in the pump pipe, $l$ [m] is the length of fresh concrete in straight pipe section, $\tau_0$ [Pa] is the yield stress of fresh concrete, $\eta$ [Pa·s] is the viscosity coefficient of fresh concrete, $v$ [m/s] is the velocity of fresh concrete.

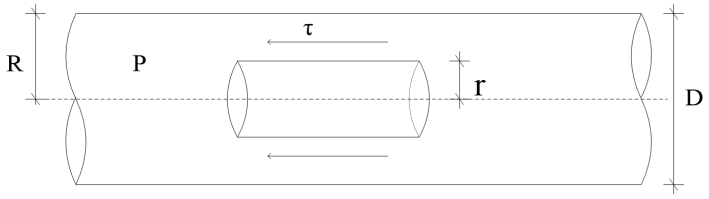



**Figure 1.** Bingham fluid sliding Model.

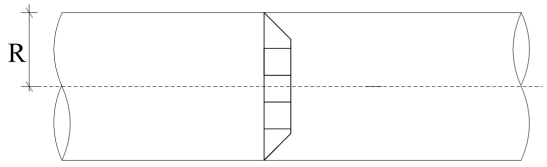
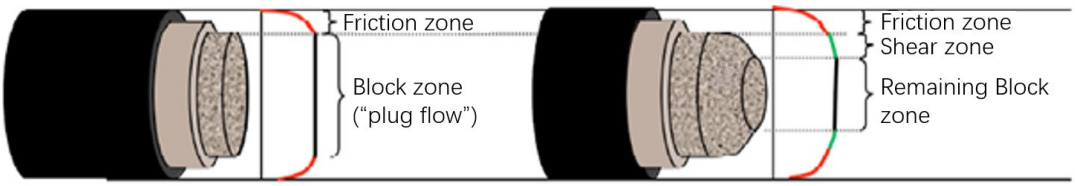



**Figure 2.** Velocity distribution of sliding Bingham fluid (Zhao 1985).

Kaplan (2001) stated that when sliding at low speed, the pumped concrete could be regarded as friction flow, also known as plug flow. The middle part of the plug flow, cylindrical in shape, is called block zone. According to Yan and Li (2018), the shear stress at each point of the cross section of the pump pipe is linearly distributed along the radius, and the shear stress is zero in the axis of the pump pipe. The maximum shear stress is near the inner wall of the pump pipe. The shear stress near the axis of the pump is less than the yield stress of the fresh concrete. This part of concrete will not produce relative slippage during the pumping process, thus forming the block zone. A friction layer known as lubrication layer

will be formed between the block zone and the pipe wall, as illustrated in Fig. 3 (a). During the pumping process, the formation of the lubrication layer can greatly promote the pumping process of the fresh concrete. When the flow rate of concrete mixture is larger, the pumping pressure is higher. Then the shear stress near the inner wall of the pump pipe may exceed the yield stress of the fresh concrete. In addition to the formation of lubrication layer and block zone, the fresh concrete will also form a shear zone between block zone and lubrication layer. This kind of flow state is known as friction flow and viscous flow, as illustrated in Fig. 3 (b). It is usual that CVC only has block zone and lubrication layer during the pumping process because of the high yield stress. SCC and HFC have high workability, resulting in their low yield stress. Besides the block zone and the lubrication layer, the shear zone can be formed during the pumping process of SCC and HFC.




(a) (b)

**Figure 3.** Sliding model for the flow of fresh concrete in pipe (Kaplan 2001).

## 3. Lubrication layer

The concrete pumped in the pipe comprises two parts: bulk concrete and lubrication layer. The pipe flow of the pumped concrete is predominated by the lubrication layer. The relatively thin lubrication layer has a lower viscosity than the bulk concrete (Choi et al. 2013). Morinaga (1973) and Secrieru et al. (2018b) stated that concrete cannot be pumped without formation of the lubrication layer formed at the interface between the concrete and the wall of the pipe. The lubrication layer with appropriate thickness and stable state can reduce the effect of friction and make the concrete mixture have a better pumpability. In this respect an experimental investigation, as well as numerical verification, was carried out by Secrieru and Mechtcherine (2020).

### 3.1. Formation of lubrication layer

The hydraulic pressure gradient created during pumping facilitates the formation of lubrication layer (Secrieru et al. 2018a). The lubrication layer is a mortar-like layer formed on the pipe wall during the pumping process. The pumping resistance is in essence determined by the friction between the pipe and the lubrication layer (Kwon et al. 2013; Jo et al. 2012). The friction at the pipe-concrete interface occurs when fresh concrete flows (Ngo et al. 2010a, 2010b). The pumping can be operated only when the pump pressure is larger than the friction (Eda 1957; Browne et al. 1977; Le et al. 2015). During the pumping process, the concrete mix is filled in the pipe and pushed forward by the high pressure. Rossig et al. (1974) pumped colored concrete and observed a paste rich zone at the vicinity of the pipe wall. Jacobsen et al. (2009) prepared colorful concrete for pumping experiment and also observed an enriched mortar area near the wall. A redistribution of the particles takes place in the pipe under the shear action during pumping. In the process of concrete pumping, migration of the sands (fine particles) is ignorable as compared to migration of the gravel (coarse particles). Feys et al. (2015) stated that the lubrication layer is formed because of the coarse aggregate migrating to the pipe center (low shear zone) and leaving more micro mortar in the boundary region. The lubrication layer can therefore be considered as the constitutive mortar of the pumped concrete (Choi et al. 2013).

Lubrication layer is also termed boundary layer. Its capability to reduce friction plays an indispensable role in the pumping process. Shearing takes place in the lubrication layer owing to its lower plastic viscosity and yield stress relative to the bulk concrete. Based on the torque and the angular velocity of the rotary cylinder, the plastic viscosity $\mu$ and the yield stress $\tau$ of the lubrication layer can be determined as follows:

$$\tau_s = \frac{\Gamma_0}{2\pi h R^2} \tag{6}$$

$$\mu_s = \frac{k}{4\pi h}\left(\frac{1}{R_c^2} - \frac{1}{R_s^2}\right) \tag{7}$$

where $\Gamma_0$ is the initial torque to start the shear flow, h stands for the difference of the two filling heights, k is a parameter by fitting the linearity between the angular velocity and the torque, $R_c$ refers to the radius of the rotary cylinder, $R_s$ represents the distance from the end of the lubrication layer to the center of the rotary cylinder.

In many cases the obtained rheology properties of concrete fluid are not consistent with those predicted from the Bingham fluid or Herschel Buckley fluid theory. The main reason can be ascribed to the ignorance of the properties of the lubrication layer (Kaplan et al. 2005b; Feys et al. 2009). Most of the existing studies about lubrication layer are based on the CVC while the research on modern concrete such as SCC and HFC is quite inadequate. The quantitative relationship between lubrication layer parameters and concrete composition remains a pending issue. To what extent can the rheological properties of concrete affect the properties of lubrication layer requires further research.

### 3.2. Parameters of lubrication layer

(1) Composition

Complete description and detailed characterization of the lubrication layer are not easy. The results reported in the literature are far from sufficient. However, significant progress has been made in the composition of lubrication layer. As noted by Ngo et al. (2010a, 2010b), the lubrication layer is normally composed of water, cementitious materials and fine sand. The diameter of the fine sand is smaller than 0.25 mm. The content of water and cement is basically consistent with that in the concrete, but the volume of fine sand in the lubrication layer is higher.

(2) Thickness

Feys et al. (2009) stated that the rheological properties and the thickness of the lubrication layer depended mainly on the mix proportion of the concrete under study. Choi et al. (2013) reported a 2 mm thick of lubrication layer as measured by using ultrasonic velocity profiler in the full-scale pumping circuits. Kaplan et al. (2005b) found the lubrication layer has a thickness of approximately 1～5 mm. Ngo et al. (2010b) stated that the thickness of lubrication layer for different concrete mixtures varied between 1～9 mm, and it was increased with the increase in water-cement ratio, superplasticizer content and the volume of cement paste but was decreased with the increase of the volume fraction of fine sand. From the viewpoint of rheology, it can reduce the apparent plastic viscosity and increase the thickness of the lubrication layer in a desirable range by reducing the content of fine sand, increasing water-cement ratio and increasing superplasticizer content. Choi et al. (2013) carried out further research on the lubrication layer through ultrasonic velocity profiler. They found that the thickness of lubrication layer, which was 2 mm roughly, was not influenced by the flow rate but mainly by the diameter of pipeline and volume of sand and gravel in the concrete mixture. In previous reports the thickness of the lubrication layer was in most cases determined directly from the velocity profile. Limitations still exist in precisely acquiring the

pure profile of the pumped concrete. In addition, there is a high need to consider carefully the lubrication layer thickness and associated rheological properties.

(3) Rheological parameters

Feys et al. (2014) suggested that the viscous constant $\eta_{LL}$ (which was from Kaplan's equation $\tau_{LL} = \tau_{0,LL} + \eta_{LL}V$ (Kaplan 2001)), the slope of shear stress and velocity can be used to describe the property of the lubrication layer. According to Kaplan's model, the larger the viscous constant, the larger the pressure loss. Feys et al. (2014) also found that the viscous constant of the concrete mixture without fly ash was larger because of the lower thickness and higher viscosity of the lubrication layer. The viscous constant of the lubrication layer is decreased with decreasing the fine sand content and the increase of the paste volume and water-cement ratio (Feys et al. 2016). A higher content of fine sand corresponds a higher specific surface. A larger volume of paste is then needed to wrap and the viscosity is increased subsequently. The paste volume is generally considered important in the formation of lubrication layer, and it governs the amount of cement paste migrating to the lubrication layer. The increase of water-cement ratio results in the paste viscosity to decrease.

A correlation between the viscous constant of lubrication layer and the plastic viscosity of concrete has been found, which is affected by a number of factors. There is a complex dynamic equilibrium between the shear and the formation of the lubrication layer. The rheological properties of concrete will affect the formation, thickness and properties of the lubrication layer. The quantitative relationship between rheological parameters of the lubrication layer and pumpability of the concrete is not clear yet, and more research is well worth carrying out.

## 4. Pumping pressure loss estimation models of pumping concrete

### 4.1. Conventional theoretical models

Concrete is a kind of highly concentrated suspension. A few models including Bernoulli's principle, Poiseuille's law and Buckingham-Reiner's equation have been used to calculate the pumping pressure loss (Feys et al. 2014b, Secrieru 2018c). These models are given in Table 1. Based on energy conservation, Bernoulli's principle describes the pumping process of concrete from one point to another. But the ΔF, defined as the energy dissipation due to friction, is difficult to be determined. Both Poiseuille's law and Buckingham-Reiner's equation are inappropriate to describe the flow rate of pumped concrete because Poiseuille's law is valid only for incompressible Newtonian fluid with a steady laminar flow. Buckingham-Reiner's equation can significantly overestimate the experimental pressure. The pressure loss determined from Buckingham-Reiner's equation can be more than 3.8 times than the actual condition (Le et al. 2015).

Table 1. Theoretical models for calculations of the pumping pressure loss.

| Name | Theoretical models | Requirement |
|---|---|---|
| Bernoulli's principle | $h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + \Delta F$ | Incompressible fluid, steady flow |
| Poiseuille's law | $Q = \frac{\pi r^4 \Delta p}{8\eta L}$ | Newtonian fluid |
| Buckingham-Reiner's equation | $Q = \frac{3R^4\Delta p^4 + 16\tau_0^4 L^4 - 8\tau_0 L R^3 \Delta p^3}{24\Delta p^3 L \mu_p}$ | Bingham fluid |

Morigana's empirical formula, as shown in Eq. (8), is recommended by the Architecture Institute of Japan to calculate the pressure loss of CVC during the pumping progress (JGJ/T

20-2011, 2011). But the rheological properties of SCC and HFC are different from those of CVC, and the actual pumping pressure loss is much larger than that obtained from the formula (Eq. (8)). Morigana's empirical formula results in the pumping pressure loss to be around 1/5 of the actual value (Li et al. 2016; Farris 1968). It is obvious that the empirical formula is not suitable for calculating the pumping pressure loss of SCC and HFC.

$$\Delta P = \frac{2a}{r}\left[K_1 + K_2\left(1 + \frac{t_2}{t_1}\right)v\right] \tag{8}$$

where $\Delta P$ is the pressure loss per unit of length of the pipeline (Pa / m), $a$ is the radial-axial pressure ratio, $r$ is the pipeline radius (m), $K_1$ and $K_2$ are the coefficients, $t_2/t_1$ is the ratio of valve's switching time and piston's push time, and $v$ is the concrete velocity (m / s).

### 4.2. Kaplan model

Previously reported theoretical models usually considered the influence of lubrication layer and block zone on the pumping pressure, but that the shear zone was neglected. These models are therefore not suitable for SCC and HFC with low yield stress. An important mathematical model for describing the pressure loss was proposed by Kaplan based on the pumping state with or without the shear zone of concrete in straight pipe (Kaplan 2001). The size of the wall shear stress is taken into account in Eq. (9). When the wall shear stress is less than the yield stress, Eq. (10) can be used to calculate the pressure loss in the concrete flow. Eq. (11) can be used to calculate the pressure loss when the wall shear stress is larger than the yield stress of the concrete.

$$\tau_w = \frac{\Delta p_{tot}}{L} \cdot \frac{R}{2} = \Delta p \cdot \frac{R}{2} \tag{9}$$

$$\Delta p_{tot} = \frac{2L}{R}\left(\frac{Q}{3600\pi R^2 k_r}\eta_{LL} + \tau_{0,LL}\right) \tag{10}$$

$$\Delta p_{tot} = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi R^2 k_r} - \frac{R}{4\mu_p}\tau_{0,LL} + \frac{R}{3\mu_p}\tau_0}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{0,LL}\right) \tag{11}$$

where $\tau_w$ is the wall shear stress (Pa), $\Delta p_{tot}$ is the pressure loss over the entire pipeline length (Pa), $\Delta p$ is the pressure loss per unit of length of the pipeline (Pa / m), $L$ and $R$ are the pipeline length and the pipeline radius, respectively (m), $Q$ is the flow rate ($m^3$ / h), $k_r$ is the filling coefficient, $\eta_{LL}$ is the viscous constant of lubrication layer (Pa · s / m), $\tau_{0,LL}$ is the yield stress of concrete (Pa), and $\mu_p$ is the plastic viscosity of concrete (Pa · s).

According to above equations, the calculation of pumping pressure needs not only the rheological parameters of concrete but also the rheological parameters of the lubricating layer. Kaplan's model can be well applied for CVC, HFC and SCC (ACI 304.2R-96, 1996). However, there are still some problems to be solved when applying Kaplan's model. Firstly, the Bingham model, as adopted by Kaplan to describe the rheological behavior of fresh concrete, has been proved to have large deviations when describing the fresh concrete with shear thinning and shear thickening, but that many HFC and SCC have the rheological behavior of shear thinning or shear thickening. Secondly, the Kaplan model does not consider the influence of aggregate migration induced by shear stress on the pumping pressure loss, so it cannot well describe the performance of shear zone and block zone.

## 5. Test methods of concrete pumpability

### 5.1. Conventional methods

Slump or slump flow test is generally used to test the pumpability of fresh concrete. An increase of slump normally reduces the pump pressure and improves the pumpability (Feys et al. 2014). The relationship between pumping slump and pumping height is shown in Table 2. The ACI 304.2R-96 (1996) suggests that the slump from 50 mm to 150 mm is the most suitable for pumping. This method, however, cannot simulate the key parameters for the actual pumping process, for instance, the pump pipe lengths. More importantly, the crucial mixture proportion parameters such as aggregate shape, grading and paste volume cannot be taken into consideration while testing the pumpability of concrete (Farris 1968). In view of the rheology, slump or slump flow test can only represent the yield stress of fresh concrete, but not the plastic viscosity. In other words, the method recommended in ACI 304.2R-96 cannot fully account for the flow state of fresh concrete, and it is not suitable for modern concrete with complex components.

The rate of pressure bleeding, an important index during the process of pumping, can be used to estimate the risk of blockage. Browne et al. (1977) considered that the volume difference of the pressure bleeding at 140s and 10s, noted as $\Delta = V_{140} - V_{10}$, could to some extent characterize the concrete pumpability. A larger value means a higher content of effective water for lubrication and a better pumpability. The relative rate of pressure bleeding should not be greater than 40% at 10s according to JGJ/T 20-2011 (2011). It should be pointed out that the test of pressure bleeding can only be used to judge the excess water volume and the risk of plugging of the mixture for improving the mix proportion design, but it cannot be used to judge the pressure loss during the pump process.

Table 2. Relationship between slump and pumping height (JGJ/T 20-2011, 2011).

| Maximum pumping height (m) | 50 | 100 | 200 | 400 | > 400 |
|---|---|---|---|---|---|
| Slump (mm) | 100~140 | 150~180 | 190~220 | 230~260 | - |
| Slump flow (mm) | - | - | - | 450~590 | 600~740 |

### 5.2. Pumping circuit

Testing the properties of pumped concrete by simulating flow state of concrete in the rotary circular pipe has been widely recognized (Kaplan et al. 2005a). The condition of pumping engineering is simulated and the results can be used to guide the construction engineering directly. Whereas, the related device is not suitable to be installed in laboratory because of its huge volume and complicated operation. For application of this method, considerable labor force, financial resources and material resources are required.

### 5.3. Tribometers

(1) Rectilinear motion tribometer

The principle of the rectilinear motion tribometer is that the concrete is pressed by the steel plate which slides on the surface of the compressed concrete, and the friction test is carried out by the sliding steel plate and the concrete sample, as illustrated in Fig. 4. The rectilinear motion tribometer can directly test the friction during the process of sliding by the sensor. The properties of the interface layer are obtained accordingly. The influencing factors such as roughness, sliding speed and demolding oil can be analyzed. The sealing of the test process is of primary concern. Truthfully simulating the flow rate of concrete is rather difficult.

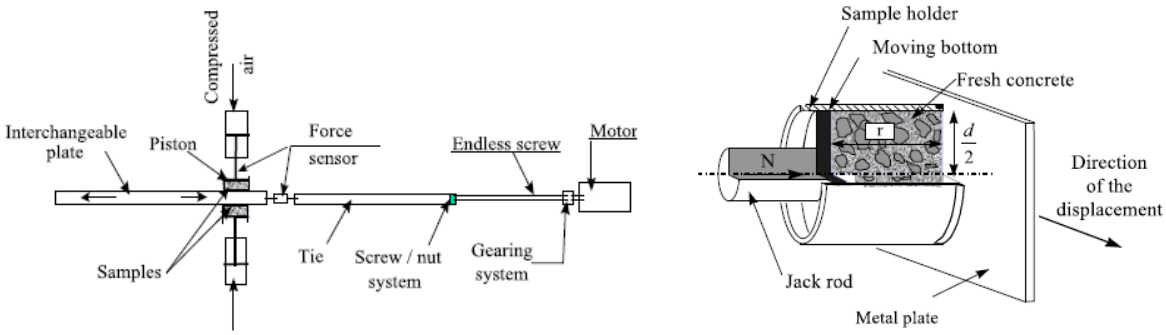


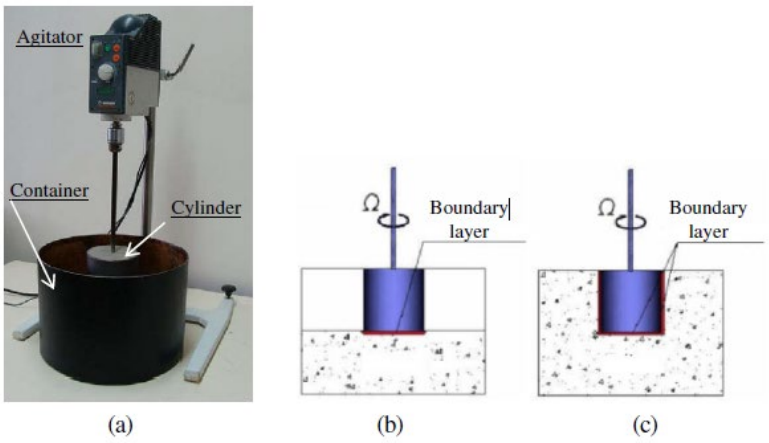

**Figure 4.** Principle of tribometer and details of sample holder (Vanhove et al. 2004).

(2) Coaxial cylinder tribometer

In order to overcome the inherent problems in rectilinear motion tribometer, Kaplan (2001) invented the coaxial cylinder tribometer (Fig. 5). The coaxial cylinder tribometer was very similar to the rheometer, and the rotation axis was not the blade but a smooth cylinder. The torques were measured at different rates to obtain the rheological parameters of the lubrication layer after the steel concrete interface was produced. It was found that the pumping data from the coaxial cylinder tribometer agreed well with the real condition. The results obtained can be used to well describe the properties of the lubrication layer, but that a high sensibility of the coaxial cylinder tribometer to test the yield stress of lubrication layer has been found. Repeated measurements are required to obtain accurate results.

Part of the tribometer is sealed and the additional friction is unavoidable in the rotation test process. Hence Ngo et al. (2010a, 2010b) developed another kind of coaxial cylindrical tribometer, as shown in Fig. 6. In addition, Feys et al. (2015) stated that the coaxial cylinder tribometers developed by previous scholars were used mainly to test the CVC and were not suitable for HFC and SCC with low yield stress. As such, Feys et al. (2014) developed a new kind of coaxial cylinder tribometer (Fig. 7), by which the properties of lubrication layer of HFC and SCC can be characterized by appropriate measurement procedures and data processing. It is worthwhile to note that there may be deviation during the measurement of the coaxial cylinder tribometer, because of the dynamic segregation of concrete that results from blades turning (Yan 2018).

**Figure 5.** Coaxial cylinder tribometer developed from Kaplan (2001).

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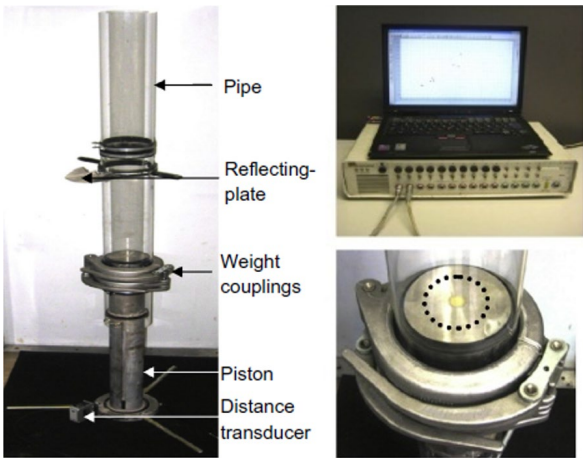
297 **Figure 6.** Coaxial cylinder tribometer developed from Ngo et al. (2010a, 2010b).

298

299 **Figure 7.** Coaxial cylinder tribometer developed from Feys et al. (2014).

300 (3) Sliding pipe rheometer

301 Sliding pipe rheometer, as displayed in Fig. 8 (Kasten 2009), enables to simulate
302 concrete pumping and readily obtains pumping parameters. The lubrication layer in sliding
303 pipe is formed while concrete sliding in the pipe. The sliding pipe rheometer is equipped with
304 different falling weight, and the pressure and sliding speed of the top piston are tested
305 simultaneously. The relationship between the pressure and the flow rate is obtained by the
306 data processing after measurements.




307

308 **Figure 8.** Sliding pipe rheometer and its components (Yan 2018).

309 Sliding pipe rheometer is convenient. The rheological parameters of low slump concrete
310 can be tested by the sliding pipe rheometer, as opposed to the coaxial cylinder tribometer.

The test results are in good agreement with the experimental data (Zhao 2014). However, the sliding pipe rheometer only considers the friction zone, with the shear zone not considered, and it cannot reflect the real pumping velocity due to limitations of the device. The fact that sliding pipe rheometer is in general an effective tool to study the properties of pumped concrete makes it suitable for studying the pumping properties in the laboratory.

## 6. Factors influencing the concrete pumpability

The pumpability of concrete has been studied since the last century. The pumpability of concrete is influenced by a range of factors (Djelala et al. 2004). Using a single parameter to represent the concrete pumpability is certainly not reliable. This section reviews the influencing factors of concrete pumpability from four different aspects including the composition, rheological parameters, workability, and the external factors.

### 6.1. Concrete composition

(1) Raw materials

Concrete pumping depends on the properties of the concrete in the pipe. Mechtcherine et al. (2014) analyzed changes of pumping performance by pump pressure-flow curves for different concrete mixtures. The results indicated that in case other factors are the same, using granular aggregate has a higher pumpability than using crushed aggregate. The crushed aggregate has a larger specific surface area than the granular aggregate. Therefore, the crushed aggregate needs more pastes to enwrap during pumping (Ragan 1981; Bouquety et al. 2007). In addition, the flowability of the mixture is worse because of the interlocked effect of the crushed aggregates (Aissoun et al. 2015; Fung et al. 2013). An increase of the aggregate volume-fraction by around 10% results in a decrease of the concrete pumpability by at least 30% (Fataei et al. 2020). This finding is particularly pronounced for CVC (Fataei et al. 2019). Blockage can take place due to arch formation of the roughest particles. A higher content of coarse aggregate particles will increase the risk of blocking of the pipe. Hardened blocked concrete in pipes has been reported, among others, by Kaplan et al. (2005a). The blocking mechanism can be ascribed to forward segregation, owing to acceleration of large particles during the stroke of piston pumps (Jacobsen et al. 2009). Bend pipes have a higher risk of blocking than tapered ones. A severe segregation of mixture components should be avoided in order to prevent blockage (Mechtcherine et al. 2014). Adding silica fume with appropriate content enables to obtain a better pumpability than adding fly ash (Vanhove et al. 2004). The mixture with fly ash has lower viscous constant and viscosity than the mixture without fly ash (Djelala et al. 2004).

(2) Mix proportion

Zhao (2014) analyzed the effects of factors, including water-cement ratio, paste volume, air content, coarse aggregate and mineral admixture, on the pumping performance of concrete. The results showed that for CVC in the appropriate range, increasing paste volume, entraining air, and using larger size of aggregate were favorable to reduce the pumping resistance and thus improving the pumpability (Best et al. 1980). Supplementary cementitious materials such as fly ash and granulated blast furnace slag have been reported to increase the flowability due to the densified particle packing density and the ball bearing effect of particles (Ferraris et al. 2001). The silica fume, normally very fine in particle size, will affect the flowability and pumping behavior of fresh concrete. The yield stress of cement-based materials is normally deceased when incorporating ultra-fine admixtures. The viscosity, however, varying significantly with different types of admixtures, decreases with the addition of ultra-fine slag, fly ash and silica fume, but increases by adding anhydrous

gypsum. Superplasticizer plays an important role, and its dosage is almost linearly correlated with the pumping performance, as reported by Jeong et al. (2016).

The concrete pumpability can be enhanced by increasing the cement paste volume, water-cement ratio and superplasticizer dosage (Ling et al. 2015; Ngo et al. 2012). Although the increase of the water-cement ratio can improve pumpability, it is easy to induce segregation, bleeding and pipe blockage in the pumping process (Mai et al. 2014; Felekoglu et al. 2007). The pumpability is highly associated with both the workability and stability of the fresh concrete. Based on the principle of balancing effect, Anderson (1977) suggested ten relevant guidance that can be used to analyze raw materials and mix proportion for preparations of pumping concrete with good pumpability.

### 6.2. Rheological parameters

The rheological behavior of concrete can be described using the pressure loss-flow relationship. A good correlation between the two exists for self-compacting concrete. For normal concrete the yield stress is a dominant factor. The rheological parameters can be influenced after changes of the concrete composition (Siddique et al. 2012), and the pumpability is affected accordingly. Zerbino et al. (2009) established a relationship between rheological parameters and pressure loss based on studies of fresh concrete with different mix proportions. The yield stress and plastic viscosity of all concretes were measured. They found a good correlation between the plastic viscosity and the pressure loss, regardless of the type of concrete. For yield stress, a clear relationship could only be observed for CVC, but not for SCC and HFC. This can be ascribed to the fact that the yield stress-to-plastic viscosity ratio is the dominant factor for shearing flow. The yield stress becomes increasingly important at lower viscosity. Different values of rheological parameters may be acquired for the same mixtures when testing by different instruments (Mai et al. 2014).

Kaplan et al. (2005b) reported that the viscous constant (rather than the yield stress) of the lubrication layer was the major factor for pumpability. Differently from other workers (Felekoglu et al. 2007), Feys et al. (2014) measured the values of viscous constant of lubrication layers and found a good relationship between the measured pressure loss and the viscous constant. Unfortunately, it is not clear whether the observed relationship results from the viscous constant of the lubrication layer or the plastic viscosity of the bulk concrete. From Kaplan's model, the rheological parameters of concrete play important roles in the pumping pressure loss. The change of rheological parameters will lead to the change of pumpability (Ngo et al. 2011).

### 6.3. Workability

It is difficult to measure the pumpability in laboratory by the full-scale simulation of pumping owing to the large space required and the high cost. On the other hand, the pumpability can be investigated according to the performances of multiple sections that can be tested and evaluated separately. As stated earlier, the slump and rate of pressure bleeding have been used to estimate the pumpability in a few codes. Entraining air (about 3-5%) has advantages in preventing bleeding and improving the workability. A high entraining air content, however, results in the compressibility to be increased, leading to unstable pumping pressure (Aissoun et al. 2015).

There is a very good correlation between the pump pressure loss and the V-funnel flow time of SCC (Yun et al. 2015). The pressure loss of SCC with low yield stress is affected mainly by the plastic viscosity, and there may be a direct correlation between the V-funnel flow time and the plastic viscosity of concrete mixture.

The traditional tests are easy to operate and can rapidly figure out the workability in a qualitative manner, and are therefore suitable to be used in the construction site (Laskar 2009). It is meaningful to establish a relationship between the traditional tests and the rheological parameters in order for guiding the pumping construction in practical projects.

## 6.4. External factors

Apart from the concrete itself, other external factors such as the diameter of pump pipe and the equivalent length of bent pipe can also affect the concrete pumpability. By establishing 148m test pipeline to simulate the full-scale pumping process, Kaplan (2001) found that the poor design of pumping pipeline system and the inappropriate operation would induce blockage. It is appropriate to pump at low speed at the beginning for lubricating the pipe. The diameter of the pipe should be 4 times larger than the maximum size of the aggregate used in the mixture. Otherwise the air would easily get into the pipe forming gas bubbles disrupting the stable flow state of fresh mixture. The bent pipe increases the additional pressure loss for SCC but not for CVC (Kaplan et al. 2005b), and the real pressure loss is higher than the value calculated from the rule of thumb. By studying the flow behavior of two pipes with varying diameters, Feys et al. (2016) found that the pressure loss was increased by a factor of 2 for a 20% reduction in the pipe diameter.

Vanhove et al. (2008) studied the friction behavior between SCC and steel plate with different roughness. A summary of the friction mechanism is shown in Fig. 9. As indicated, there are different critical pressures in the sliding process. According to Kaplan's model, the flow velocity, the diameter and the pipe length all affect the required pumping pressure and pumpability. In principle more energy is required in case of an increase of pumping height.

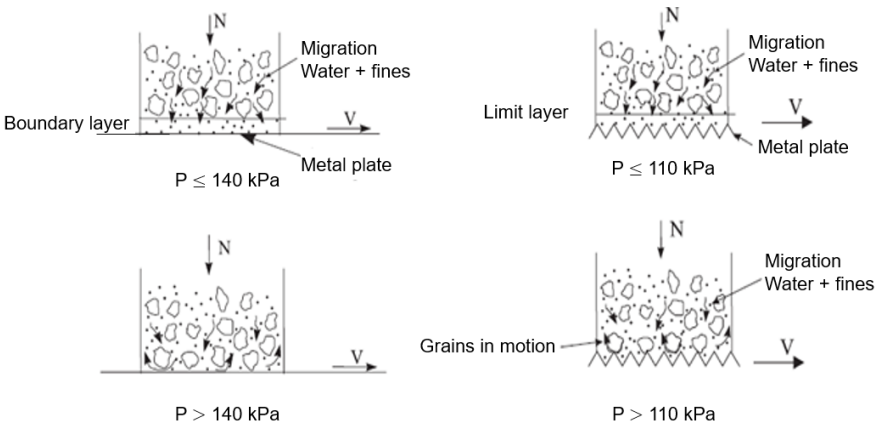



**Figure 9.** Friction mechanism of different steel plates and pressures.

## 7. Typical constructions of ultra-high pumped concrete in China

There is a growing demand globally for large-scale constructions, such as long-span bridges, high-rise buildings, long-distance tunnels, etc., which has triggered the large-scale pumping research all over the world (Choi et al. 2014, De Schutter 2017, Secrieru et al. 2018a, Secrieru et al. 2020). Knowledge of the pumping flow rate and rheological properties, particularly yield stress and plastic viscosity, is often required. Related parameters, including concrete composition, strength grade, pumping height, etc., are of paramount importance in the large-scale concrete pumping. Numerical simulation and experimental verification were intensively combined to characterize and predict the concrete pumping behavior. Chio et al. (2013) applied the Computational Fluid Dynamics (CFD) approach to study the properties of the lubrication layer. The influence of the yield stress on the lubrication layer was neglected. The concrete velocity profile and rheological properties were measured by means of Ultrasonic Velocity Profiler and Brookfield DV-II viscometer, respectively. An analytical relation was proposed that can be roughly estimate the pumping pressure. Secrieru et al. (2020) simulated the flow pattern using the CFD approach. The semi implicit method implemented for pressure linked equations was applied for the pressure-velocity coupling. The concrete flow behavior was simulated by the single-fluid approach. It was found that the

simulated results were in good agreement with those derived from full-scale rheological tests before and after pumping.

In recent decade large-scale constructions, as well as large-scale concrete pumping practice, have taken place more rapidly in China than other countries. In China a large number of ultra-high buildings above 300m have been built or are being built, which have greatly promoted the advancement of the theory and technology of large-scale concrete pumping. Over the recent decade the technology of high strength, high flow and low viscosity self-compacting concrete has developed rapidly. This section provides six typical ultra-high pumping construction projects in China as examples to introduce the development of high strength self-compacting concrete ultra-high pumping construction technology in China. The details of these engineering examples are shown in Table 3 and Table 4 (Chen et al. 2016; Gu 2009; Li et al. 2016; Ran et al. 2011; Yu et al. 2011; Zhang et al. 2017).

Table 3. Examples of ultra-high pumped concrete engineering in China.

| Name | Structural height (m) | Layer number | Floor area ($m^2$) | Maximum strength grade of concrete | Pumping height (m) |
|---|---|---|---|---|---|
| International Finance Centre | 420 | 88 | 200000 | C90 | 392 |
| KingKey Financial Center | 442 | 98 | 602402 | C120 | 422 |
| Guangzhou International Finance Centre | 440 | 103 | 450000 | C90/C60 | 168/432 |
| Tianjin 117 building | 597 | 117 | 1960000 | C60 | 621 |
| Shanghai World Financial Center | 492 | 101 | 381600 | C60 | 492 |
| CITIC Tower | 528 | 108 | 437000 | C70 | 528 |

Table 4. Concrete proportioning of the ultra-high pumped concrete engineering ($kg/m^3$).

| Name | Portland cement | Fly ash | Silica fume | Sand | Gravel | Water | Water reducer | Slump flow (mm) |
|---|---|---|---|---|---|---|---|---|
| International Finance Centre | 370 | 180 | 35 | 600 | 1000 | 152 | 2.9 | 700 |
| KingKey Financial Center | 500 | 170 | 80 | 700 | 1000 | 130 | 26.0 | 650 |
| Guangzhou International Finance Centre | 430 | 145 | 40 | 729 | 1000 | 130 | 16.0 | 600 |
| Tianjin 117 building | 297 | 143 | 33 | 850 | 850 | 160 | 8.8 | 650 |
| Shanghai World Financial Center | 440 | 110 |  | 800 | 870 | 175 | 7.2 | 650 |
| CITIC Tower | 360 | 180 | 40 | 760 | 850 | 160 | 6.6 | 700 |

The first Guinness World Records concerning Chinese concrete industry was created by the construction engineering of Tianjin 117, and the high-performance concrete with C60 was pumped to the height of 621m (Ngo et al. 2011). The experimental database used for simulating the ultra-high pumping was established, which aimed to solve the technical problems in real engineering. The superplasticizer developed in China has contributed significantly to solving the problems of large loss of workability, high viscosity in high strength concrete, dispersing easily in low strength concrete, and so on.

## 8. Conclusions

1) The flow state of pumped concrete in horizontal pipe comprises friction flow and viscous flow. CVC moves mainly by friction flow in the pipe, while SCC and HFC move concurrently by friction flow and viscous flow due to the low yield stress.
2) Viscous flow includes three parts: lubrication layer, block zone and shear zone. Lubrication layer, consisting of water, cementitious materials, and fine sand with diameter smaller than 0.25 mm, plays a dominant role in the pumping process. It is meaningful in practice to characterize the pumpability by measuring the properties of lubrication layer. The shear zone has a great influence on the pumping performance of the fresh concrete, but that the studies regarding the influencing mechanism of shear zone on the fresh concrete pumpability are far from sufficient.
3) It is not reliable for the conventional theories and models to describe the pumping of modern concrete, e.g. SCC and HFC. The particle diffusive models, in combination with special rheological model, can be used only to predict the flow rate. Kaplan's model is applicable for CVC and SCC, but it cannot explain the changes in the air content and slump/slump flow of the fresh concrete before and after pumping.
4) Simulation experiment is considered a comprehensive, effective and direct method to evaluate the concrete pumpability. Coaxial cylinder tribometer and slipper can quantify the pumpability and can be used in field tests.
5) The pumpability of modern concrete is affected by concrete composition, workability, thixotropy, pressure, shear behavior, temperature and other factors. Understanding the tribology of lubrication layer, along with the effects of these factors on the concrete rheology, is helpful to capture the pumping mechanism of modern concrete.

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## Conflicts of Interest

The authors declare no conflict of interest.

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