The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Prediction on pipe flow of pumped concrete

*Myoungsung Choi[1)], Youngjin Kim[2)], Yongjic Kim[2)] and Yuseung Kim[3)]

[1)] *Dept. of Safety Engineering, Dongguk University-Gyeongju, 123 Dongdae-ro, Gyeongju, Gyeongbuk, South Korea*
[2)] *Daewoo Institute of Construction Technology, Suwon, South Korea.*
[3)] *KTMG Inc., Seoul, South Korea*
[1)] *mschoi@dongguk.ac.kr*

ABSTRACT

When concrete is being transported through a pipe, the lubrication layer is formed at the interface between concrete and the pipe wall and is the major factor facilitating concrete pumping. A possible mechanism that contributes to the formation of the layer is the shear-induced particle migration. In this study, the pipe flow of pumped concrete was numerically simulated based on its mechanism and compared with 170 m full-scale pumping test. It was found that the irregular shape of the concrete particles, especially sand and gravel, greatly influences the pipe flow of pumped concrete. The flow rate and the velocity profile calculated based on the consideration of the particle shape effects by using intrinsic viscosity factor for the real sand and gravel exhibit a good agreement to the results of full scale pumping tests.

Keywords: pumping, shear-induced particle migration, lubrication layer

1. INTRODUCTION

Concrete pumping was first introduced in the 1930s and has since become the most extensively used approach to place concrete. Pumping allows concrete to reach normally inaccessible areas of the construction sites, while, at the same time, increasing the speed of delivery. Also, as the increase in demand for super structures such as high-rise buildings continues to grow, the optimization and development of prediction methods for concrete pumping is becoming a crucial issue for the concrete industry. However, there has not been an extensive reporting of research on pumping which, indeed, has been largely limited to a few thesis and papers. The major obstacle on conducting research on pumping is that it is no small undertaking, requiring concrete

---

[1)] Assistant Professor
[2)] Chief Research Fellow, Senior Researcher, respectively.

truck and pipes, combined with a large amount of material and instrumentation. Thus, developing realistic and simple measurements techniques and predictions tools remains a challenge that is of paramount importance for the concrete industry.

Clearly, as concrete pumping involves the flow of a complex fluid under pressure in a pipe, predicting its flow requires detailed knowledge of the rheological properties of concrete. 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, geometry of the pumping circuit, a lubrication layer formed between the bulk concrete and the pipe wall, pressure, and flow rate. Interestingly, ACI terminology does not include a definition of pumpability, although the term is often used in practice to describe the ability of a concrete to be pumped. This paper will attempt to provide ideas on what are the dominant factors to predict the pipe flow of pumped concrete and how to characterize them.

2. FLOW IN A PIPE

In the case of concrete, the pumping of aggregates may result in segregation as shown in Figure 1. As a result, the flow of a granular material with yield stress in a pipe will result in three layers: lubrication layer, shearing layer and plug layer. The plug layer depends on the yield stress, the shearing layer is governed by the viscosity and yield stress and lubrication layer is characterized by the tribology. The composition of each layer is difficult to know as it is impossible to extract material from each layer or to visually observe the various regions. The lubrication layer contains mainly cement paste and maybe very small sand particles [1-3], while the middle section contains coarse aggregates. Also, the diameter of the plug layer or the thickness of the lubrication layer is unknown. Thus, the characterization of each layer is paramount to understand the flow of the concrete in a pipe as well as to predict whether a concrete would be pumpable.

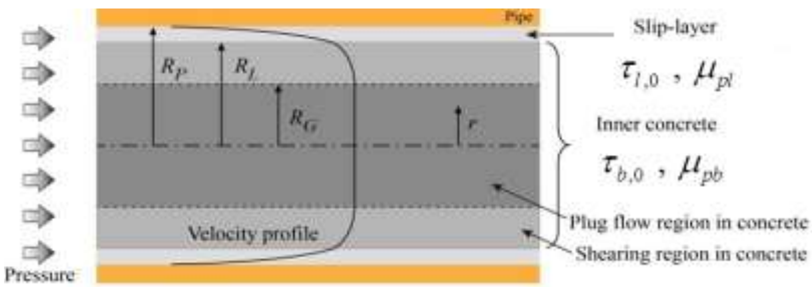

Figure 1: Profile of flow of concrete in a pipe [2]

3. ANALYTICAL APPROACH TO PREDICT THE PUMPABILITY

The analytical method for the pumpability of concrete could be obtained from previous studies [2, 4]. When pump pressure is applied to the pipe, the shear stress inside the pipe was induced so that it created a shear rate both in the lubrication layer and in the concrete. The shear rate within the lubrication layer can be written as follows:

$$\dot{\gamma} = \frac{\tau(r) - \tau_{l,0}}{\mu_{pl}} \qquad (1)$$

where $\dot{\gamma}$ is the shear rate inside the lubrication layer and μ_{pl} and $\tau_{l,0}$ are the viscosity and the yield stress of the lubrication layer. The difference between R_p and R_L in Figure 1 is the thickness of the lubrication layer. The same idea, that the thickness of the lubrication layer should be considered in calculating the flow rate, has been adopted in the existing research [1, 2, 4]. The shear rate of the inner 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,

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

where R_G is the radius at which the shear rate starts, 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.

$$\dot{\gamma} = \frac{\tau(r) - \tau_{b,0}}{\mu_{pb}} \qquad (3)$$

The inner region where has a lower yield stress than the concrete has zero shear rate.

$$\dot{\gamma} = 0 \qquad (4)$$

The velocity is the integral of the shear rates from the wall to any position in the radial direction and the flow rates are the integral of the velocity over the radius,

$$\begin{aligned} Q &= \int_{R_L}^{R_p} 2\pi r U_s dr + \int_{R_G}^{R_L} 2\pi r U_{p1} dr + \int_{0}^{R_G} 2\pi r U_{p2} dr \\ &= 3600\frac{\pi}{24\mu_{pl}\mu_{pb}}[3\mu_{pb}\Delta P(R_p{}^4 - R_L{}^4) - 8\tau_{l,0}\mu_{pb}(R_p{}^3 - R_L{}^3) \\ &\quad + 3\mu_{pl}\Delta P(R_L{}^4 - R_G{}^4) - 8\tau_{b,0}\mu_{pl}(R_L{}^3 - R_G{}^3)] \qquad (5) \end{aligned}$$

where Q is the flow rate (m3/h). The flow rate that characterizes pumpability can be analytically determined using rheological properties of the each region with prescribed pumping pressure.

4. DYNAMIC SEGREGATION

The dynamic segregation plays an important role in characterizing concrete pumpability. When concrete is being pumped, three types of dynamic segregation can be considered: a particle migration, a particle movement to forward and bleeding. Although all types of dynamic segregation can affect the pumpability of concrete, in the present study, to focus on the characterization of lubrication layer which is the primary goal, particle migration phenomena was mainly investigated. There are several conjectured mechanisms that could lead to the formation of the lubrication layer and investigated by experimental test methods. Firstly, the pumpability has been qualitatively estimated through bleeding tests, which indicate that bleeding water or free water may be concentrated near the pipe wall and this assists the formation of the lubrication layer. Secondly, the pipe wall prevents the uniform distribution of the solid particles, which results in a phenomenon called the wall effect. 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, which explains that particles in suspension migrate across the streamlines from a region with a higher shear rate to a region with a lower shear rate. Particle migration should be a function of the particle concentration. In the pipe flow of pumped concrete, the shear stress is the highest at the pipe wall and linearly decreases as the position moves to the center of the pipe. The inhomogeneous distribution of the particle concentration leads to spatially varying rheological properties in the suspension because the higher shear stress near the wall moves the particles of concrete, sand, and gravel toward the center of the pipe, and the lubrication layer near the wall is the region where the viscosity and yield stress become much lower.

In this study, the shear-induced particle migration was considered as a major possible mechanism that contributes to the formation of the lubrication layer. Leighton et al. [5, 6] 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. [7] adapted the scaling arguments of Leighton et al. [5, 6] 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. [7], 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 governing equation of the shear-induced particle migration for the Poiseuille flow was as follows,

$$\frac{\partial \phi}{\partial t} + \frac{\partial (u_z \phi)}{\partial z} = \nabla \cdot \left\{ a^2 K_c \phi \nabla \left(\phi \frac{\partial u_z}{\partial r} \right) + K_\eta \phi^2 a^2 \frac{\partial u_z}{\partial r} \frac{\nabla \eta}{\eta} \right\} \qquad (6)$$

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.

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. (6). 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. (6). As a result, the concentration of the particle 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 rheological properties. Through the analysis of the shear-induced particle migration which is one type of the dynamic segregations, the formation of lubrication layer can be simulated and its layer properties could be determined.

5. NUMERICAL APPROACH TO PREDICT PUMPABILITY

For the prediction of pipe flow of pumped concrete, a numerical simulation using computational fluid dynamics could be used to solve complex flow problems. This would allow the prediction of the pumpability of concrete depending on its rheological properties and the pumping circuit. The computational modeling techniques found in the literature may be divided into three categories [8, 9]: 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 [10] 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. [11] also simulated the 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 and sand and the granular phase is particle flow consisting of coarse aggregate. Mori and Tanigawa [10] also used the viscoplastic suspension element method (VSEM) to simulate the concrete flow in various tests with this method. Moreover, as stated in previous section, the shear-induced particle migration analysis which is used to illustrate the formation of lubrication layer is also included in this approach.

In the third method, the concrete flow by nature is dominated by granular media. Chu et al. [12] 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 [13] and Petersson [14] also adopted this method in order to simulate the SCC flow during L-box and slump flow tests, and J-ring and L-box tests. These three different types of approaches could be used to simulate the concrete flow in a pipe.

6. DISCUSSION ON RESEARCH NEEDS

The pumping of concrete is a critical issue in construction site. From this study, the authors tried to provide paramount factors in predicting the concrete pumping and some ideas on how to characterize the pumpability. The following major conclusions are drawn.

1. It could be found that pumpability is governed mainly by the lubrication layer and dynamic segregation. The lubrication layer which is formed between the pipe and the concrete plays a dominant role to facilitate the pumping of concrete and dynamic segregation determines the flow condition in the pipe.
2. Regarding the dynamic segregation, the shear-induced particle migration was considered as a major possible mechanism that contributes to the formation of the lubrication layer.
3. The analytical prediction based on assumption of the three layers in a pipe was obtained for predicting flow rate or pumping pressure.
4. The numerical simulation approaches to solve complex flow problems to predict the pipe flow of pumped concrete were demonstrated.

REFERENCES

[1] Choi M., Roussel N., Kim Y., Kim J., “Lubrication layer properties during concrete pumping” Cement and concrete Research 2012
[2] Choi M., “Prediction of Concrete Pumping Performance based on the Evaluation of Lubrication Layer Properties” , Ph. D. Thesis Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST) 2012
[3] Rio, O., Rodriguez A., Nabulsi S., Alvarez, M., “Pumping Quality Control Method Based on Online Concrete Pumpability Assessment” ACI Materials Journal, 108 #4, August 2011
[4] Kwon S.H., Park C.K., Jeong J. H., Jo S. D., Lee S.H., “Prediction of concrete pumping: Part I – Development of New Tribometer for Analysis of Lubricating Layer” , ACI Mat. J., V.110 #6, pp. 647-655, 2013
[5] Leighton D., Acrivos A., “The shear-induced self-diffusion in concentrated suspensions”, Journal of Fluid Mech.181 (1987) 415-439
[6] Leighton D., Acrivos A., “Measurement of shear-induced self-diffusion in concentrated suspensions of Spheres”, Journal of Fluid Mech.177 (1987) 109-131.
[7] Phillips R.J., Armstrong R.C., Brown R.A., Graham A.L., Abbot J.R., “A constitutive equation for concentrated suspensions that accounts for shear-induced particle migration”, Phys. Fluids 4 (1992) 30-40.
[8] Roueesl N., Geiker M.R., Dufour F., Thrane L.N., Szabo P., “Computational modeling of concrete flow: General overview”. Cement and Concrete Research 37

(2007) 1298-1307.
[9] Gram A., Silfwerbrand J., "Numerical simulation of fresh SCC flow: applications". Materials and Structures 44 (2011) 805-813.
[10] Mori H., Tanigawa Y., "Simulation methods for fluidity of fresh Concrete". Memoirs of the School of Engineering, Nagoya University 44 (1992) 71-133.
[11] Thrane L.N. et al, "Simulation of the test method "L-Box" for self-compacting concrete". Annual Trans. of the Nordic Rheology Society, Reykjavik, Iceland, 12 (2004) 47-54.
[12] Chu H., Machida A., Suzuki N., "Experimental investigation and DEM simulation of filling capacity of fresh concrete". Transactions of the Japan Concrete Institute 16 (1996) 9-14.
[13] Petersson Ö., Hakami H., "Simulation of SCC - laboratory experiments and numerical modeling of slump flow and L-box tests". Proc. of the 2nd Int. RILEM Symp. on SCC, Tokyo, (2001) pp 79-88.
[14] Petersson Ö. "Simulation of self - compacting concrete - laboratory experiments and numerical modeling of testing methods". Proc. of the 3rd Int. Symp. on SCC, Reykjavik, Iceland, (2003) pp 202-207.