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Scientific paper

Effect of the Mineral Admixtures on Pipe Flow of Pumped Concrete

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Abstract

The objective of this study is to investigate the effect of the mineral admixtures on pipe flow of pumped concrete through analyzing the properties of lubrication layer playing a dominant role to facilitate concrete pumping. Concrete mixtures incorporating blast furnace slag (BFS), fly ash (FA) and silica fume (SF) were selected with three different replacement ratios for each case and pumped through 170 m circuit. The rheological properties were measured before pumping and the thickness of lubrication layer was also experimentally observed with a special sensor, ultrasonic velocity profiler (UVP). An analytical equation considering the effect of the layer was adopted to calculate the thickness of the layer and to compare with full scale pumping results. The lubrication layer of BFS and FA indicated almost constant value regardless of replacement ratios but varied with SF mixtures. The concrete incorporating BFS or 5% SF represented satisfactory improvement of pumping efficiency.

1. Introduction

Concrete pumping was firstly introduced in the 1930s and has become the most extensively used approach to transport concrete. Pumping enables concrete to reach normally inaccessible places of structure while, at the same time, increasing the speed of delivery. Also, as the increase in demand for super structures such as high-rise buildings and super structures continues to grow, the technical challenges associated with pumping concrete to the top levels of these structures become critical issues.

Recently, as mineral admixtures have been widely used in concrete mixtures due to several advantages such as improving material properties and environmental benefit like reducing cement usage, the understanding about pumping performance due to mineral admixtures is becoming an important need for the concrete construction industry to ensure successful concrete pumping.

There are several studies to investigate the effect of mineral admixtures on fluidity and material properties of cementitious materials (Cyr *et al.* 2000; Ferraris *et al.* 2001; Ferraris and De Larrard 1998; Ferraris 1999; Nehdi *et al.* 1998; Park *et al.* 2005; Tattersall and Banfill 1983; Tattersall 1991; Zhang and Han 2000) and indicated that Blast Furnace Slag (BFS) and Fly Ash (FA) could contribute to increase flowability and densify microstructures and develop higher mechanical properties due to their latent hydraulic properties and pozzolanic reaction (Ferraris *et al.* 2001; Park *et al.* 2005; Tattersall

and Banfill 1983; Tattersall 1991). The Silica Fume (SF), having very fine particle size, works as a densifying additive for cementitious materials and also affects on flowability of fresh concrete (Nehdi *et al.* 1998; Park *et al.* 2005; Zhang and Han 2000). Namely, mineral admixtures have an effect on flow properties of cementitious material, which could lead to influence on the performance of the pipe flow of pumped concrete.

Recent studies (Choi *et al.* 2013a; Choi *et al.* 2013b; Kaplan *et al.* 2005) have indicated that the lubrication layer plays a crucial role to govern concrete pumping. Kaplan *et al.* (2005) demonstrated that the lubrication layer is a major factor in facilitating concrete pumping, because the layer has a significantly lower viscosity and yield stress than concrete. Choi *et al.* (2013a, 2013b) noted that the lubrication layer behaves similarly as the constitutive mortar of the pumping concrete and direct measurement for the velocity of lubrication layer was performed to estimate the concrete pumping pressure. Kwon *et al.* (2013a, 2013b) deduced correlation between properties of lubrication layer measured by tribometer and flow rates in concrete pumping. A possible mechanism that explains the formation of lubrication layer is shear-induced particle migration (Choi *et al.* 2013b; Ingber *et al.* 2009; Phillips *et al.* 1992). When concrete is being pumped, a redistribution of particles occurs near the wall of the pipe due to the gradient of the shear stress. The concrete pumping can therefore be considered in most cases as the shearing of an annular layer that is a few millimeters thick and has much lower viscosity than the concrete itself. Therefore, in order to investigate the effect of the mineral admixtures on concrete pumping, it is necessary to figure out the properties of lubrication layer such as the thickness and the rheological properties according to the mineral admixtures.

The objective of this study is therefore to investigate the effect of mineral admixtures on performance of con-

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crete pumping through analyzing the properties of lubrication layer. The performance of concrete pumping incorporating BFS, FA and SF were experimentally investigated. For each mineral admixture, three different replacement ratios that are widely used in construction site are selected. Concrete mix having 50 MPa compressive strength was selected and was being pumped into 170 m full scale pumping circuit. The rheological properties of concrete and the lubrication layer were measured before pumping according to the replacement ratios of each mineral admixture. The thickness of lubrication layer was experimentally measured using a special sensor known as an ultrasonic velocity profiler (Choi *et al.* 2013a, 2013b). An analytical equation developed by previous study (Choi *et al.* 2014) to calculate the concrete flow rates considering the properties of the lubrication layer was adopted and compared with experimental results of a 170 m full scale pumping test. From a full scale test and analytical comparison, the manner in which the rheological properties of the concrete and the lubrication layer as well as the thickness of the layer according to the mineral admixtures, which lead to determine the pipe flow of pumped concrete, were quantitatively analyzed.

2. Analytical method of pumped concrete

The analytical equation developed by previous study (Choi *et al.* 2014) which calculates the concrete flow rate and required pressure was adopted to compare with experimental results of full scale pumping test. Here, to adapt the equation, the two premise, the pressure drop is high enough to make the concrete flow and the lubrication layer is fully sheared were assumed. **Fig. 1** illustrated the schematic velocity profile in the pipe flow of pumped concrete and more detail information like derivation processes could be found in early paper (Choi *et al.* 2014).

$$Q = \int_{R_L}^{R_p} 2\pi r U_s dr + \int_{R_G}^{R_L} 2\pi r U_{p1} dr + \int_0^{R_G} 2\pi r U_{p2} dr$$

$$= \frac{\pi}{24\mu_{pl}\mu_{pb}} \left[3\mu_{pb} \frac{\Delta P}{L_{pipe}} (R_p^4 - R_L^4) - 8\tau_{l,0} \mu_{pb} (R_p^3 - R_L^3) \right] \quad (1)$$

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

Fig. 1 Schematic velocity profile of pumped concrete in the pipe [6].

Here, Q is the flow rate. $\tau_{l,0}$ and μ_{pl} are respectively the yield stress and the plastic viscosity of the lubrication layer and $\tau_{b,0}$ and μ_{pb} the yield stress and the plastic viscosity of concrete, respectively. R_p is the radius of the pipe and R_L is the distance from the center of the pipe to the lubrication layer. L_{pipe} is the length of pipe. The difference between R_p and R_L is the thickness of the lubrication layer. In addition, the size of the shearing region could be determined as following relation $R_G = 2\tau_{b,0} (L_{pipe} / P_{inlet})$, where R_G is the radius at which the shear rate starts and P_{inlet} is the inlet pressure to move the materials for L_{pipe} .

3. Experimental program

3.1 Concrete mixes

In order to figure out the effect of mineral admixtures on concrete pumping, one compressive strength having 50 MPa and three types of mineral admixtures, BFS, FA and SF were selected. The cement was CEM I 52.5 N with a density of 3150kg/m³ having 3,150 cm²/g. The sand was natural river sand with a density of 2590kg/m³ and a fineness modulus of 2.81. The sand particles size ranged from 0.08 to 5 mm with a water absorption capacity of 2.43%. The coarse aggregate with 20 mm maximum size was a limestone aggregate material with a water absorption capacity of 0.8% and a density of 2610kg/m³. Three types of mineral admixtures, BFS with 3,950 cm²/g, FA with 3,060 cm²/g and SF with 200,000cm²/g were selected. The chemical compositions of cement and mineral admixtures used are given in **Table 1**. Concrete mixes designed as unary, binary blends with replacing cement with mineral admixtures in the study are shown in **Table 2**. A polycarboxylate-based HRWRA containing viscosity agent was constantly used for each mineral admixture, marked as % HRWRA, meaning the percentage of the admixture relative to the binder content (in mass).

To carry out 170 m long full scale pumping tests, concrete produced by a ready-mix concrete company was used and detail mixing procedures were as follows: sand and coarse aggregate were mixed for 15 seconds and then all other raw materials were added for 15 seconds, and water and HRWRA were added during two minutes of mixing process. The total duration for mixing is two and half minutes.

Table 1 Chemical compositions of raw materials used in the study (wt.%).

Chemical compositions	OPC* ¹	BFS* ²	FA* ³	SF* ⁴
Al ₂ O ₃	4.19	14.55	23.66	1.30
SiO ₂	17.76	29.98	49.83	92.00
Fe ₂ O ₃	3.24	0.50	9.03	2.40
CaO	67.16	45.92	8.77	-
MgO	2.26	4.90	1.83	0.40
TiO ₂	0.23	0.73	1.62	-
K ₂ O	1.21	0.60	1.97	1.20
Na ₂ O	0.09	0.21	0.72	0.10
SO ₃	2.99	-	0.96	-
Loss on ignition	0.84	-	2.88	-

*¹ OPC: Ordinary Portland Cement, *² BFS: Blast Furnace Slag, *³ FA: Fly Ash, *⁴ SF: Silica Fume.

Table 2 Mix designs.

Blended types	Notation	W/B	OPC	Mineral Admixtures			HRWRA*
				BFS	FA	SF	
Unary	UO	0.33	100	-	-	-	0.75
	BFS40		60	40	-	-	
Binary	BFS50		50	50	-	-	
	BFS60		40	60	-	-	
	FA10		90	-	10	-	
	FA20		80	-	20	-	
	FA30		70	-	30	-	
	SF5		95	-	-	5	
	SF10		90	-	-	10	
	SF20		80	-	-	20	

* HRWRA: High Range Water Reducing Admixture

3.2 Rheological measurements

From experimental and numerical studies (Choi *et al.* 2013a, 2013b), Choi *et al.* found out and verified that the rheological properties of the lubrication layer are identical to those of the constitutive mortar extracted from the concrete. So, the rheological properties, plastic viscosity and yield stress, of the constitutive mortar obtained by wet-screened from the fresh mix were measured with a coaxial cylinder type mortar rheometer (Brookfield 2006b) and the measured values were regarded as the rheological properties of the lubrication layer. Simultaneously, the rheological properties of the concrete mix were measured with the coaxial cylinder type concrete rheometer (ConTec 2010) and the measured values were regarded as the rheological properties of the concrete region in the pipe flow of the pumped concrete.

The information of rheometer apparatus was as follow. In case of mortar rheometer, 0.5 L of mortar is filled in container which consists of 8 mm smooth type bob and 36 mm serrated type container. The height of the spindle is 60 mm. The maximum rotational speed used is 4.2 rev/s, which corresponds to approximately 60 s⁻¹ shear rate. For the concrete rheometer, the radii of the serrated type inner cylinder and outer cylinder are 100 mm and 145 mm, respectively. The height of the inner cylinder is 98 mm. To avoid slippage between the tested concrete and the steel surface during rotation, both the inner and outer cylinders are especially equipped with ribs. The maximum rotational speed used is 0.6 rev/s, which corresponds to approximately 10 s⁻¹

shear rate.

All tests were performed at an age of 15 minutes after cement is contacted with water. The test procedures were as follow; initiated with 30seconds high-speed shearing to eliminate any thixotropy and/or structural breakdown artifacts (Roussel 2006; Roussel 2005) and then shear rate was increased with 10 stepwise steps up to targeted maximum shear rate and back to 0 shear rate with another 10 stepwise steps. At each step, 2 seconds transient time and 3 seconds sampling time were used to get a steady state. Using Bingham model, the slope of the down curve was used to calculate the plastic viscosity, while the intercept at zero shear rate was used to calculate the yield stress. More information and details as regards the measuring and data transformation procedures for the each rheometer can be found in the literature (Brookfield 2006a; Feys *et al.* 2007; Wallevik 2010).

3.3 Pumping circuit

For the full scale pumping test, 170 m long horizontal circuit having eight 180° and three 90° bends with a diameter of 0.7 m was installed (Cf. Fig. 2). The diameter of pipe was 125 mm and its thickness was 7.7 mm. The concrete pump used was a high pressure piston pump and a piston side cylinder was used to get a high pressure pumping capacity (Choi *et al.* 2013a). The filling rate of the pump cylinder, which measures the degree of filling in the cylinder per stroke and directly affects the flow rate, was calibrated with 1 m³ reservoirs connected to a linear variable differential transformer

Fig. 2 Overview of the 170 m full-scale test setup.

(LVDT) and found to be around 85% filling rate for tested pump (Choi *et al.* 2013a). The circuit was equipped with 11 pressure gauges and the detailed locations of the gauges are shown in Fig. 3.

3.4 Ultrasonic velocity profiler (UVP)

In this study, to investigate the thickness variation of the lubrication layer according to the mineral admixtures, the actual velocity profile near the wall of the pipe was experimentally measured with a special sensor known as an ultrasonic velocity profiler (UVP) (Choi *et al.* 2013a, 2013b). The detailed specifications of the sensor including its principle of measurement, the installation of the ultrasonic probe and some limitations can be found in earlier studies (Choi *et al.* 2013a, 2013b; Met-flow 2002).

Fig. 3 Schematic ground plan of the pumping circuits and the location of the pressure gauges for 170 m full-scale circuit. (The values indicate the distance from the beginning of the circuit)

4. Results and discussion

4.1 Rheology

The rheological properties of concrete and constitutive mortar representing the material properties of the concrete region and the lubrication layer, respectively, were measured using the concrete and mortar rheometers. The results of rheological measurement are summarized in Table 3 with slump flow of concrete and illustrated in Fig. 4-6. As shown in Fig. 4-6, the plastic viscosity and yield stress of the concrete and the constitutive mortar are varied depending on the types and replacement ratios of mineral admixtures. When taking a look at Fig. 4, the yield stress and plastic viscosity of constitutive mortar and concrete are gradually decreasing in this region tested as the replacement ratios of BFS are increasing

Table 3 Rheological properties of the constitutive mortar and concrete.

Mineral Admixture	Notation	Item	Plastic viscosity (Pa·s)	Yield stress (Pa)	Slump flow (mm)
-	UO	Constitutive mortar	2.0	10.0	600
		Concrete	30.0	80.0	
BFS	BSF40	Constitutive mortar	1.7	7.0	630
		Concrete	25.0	60.0	
	BSF50	Constitutive mortar	1.5	5.0	650
		Concrete	23.0	50.0	
	BSF60	Constitutive mortar	1.4	4.0	660
		Concrete	20.0	45.0	
FA	FA10	Constitutive mortar	2.0	12.0	600
		Concrete	30.0	80.0	
	FA20	Constitutive mortar	2.3	13.0	600
		Concrete	33.0	85.0	
	FA30	Constitutive mortar	2.5	15.0	570
		Concrete	35.0	100.0	
SF	SF5	Constitutive mortar	1.2	5.0	650
		Concrete	20.0	50.0	
	SF10	Constitutive mortar	3.0	20.0	570
		Concrete	40.0	100.0	
	SF20	Constitutive mortar	4.0	50.0	520
		Concrete	55.0	150.0

Fig. 4 Effect of replacement ratios of BFS on the rheological properties of constitutive mortar and concrete. (The measured data are calculated from 3 repeat tests, i.e., one standard deviation. Here, the standard deviations are 0.2 and 0.5 for plastic viscosity and yield stress of constitutive mortar and 1.5 and 2.0 for plastic viscosity and yield stress of concrete, respectively.)

Fig. 5 Effect of replacement ratios of FA on the rheological properties of constitutive mortar and concrete. (The measured data are calculated from 3 repeat tests, i.e., one standard deviation. Here, the standard deviations are 0.2 and 0.6 for plastic viscosity and yield stress of constitutive mortar and 1.7 and 5.0 for plastic viscosity and yield stress of concrete, respectively.)

and rheological properties of mixes having BFS are smaller than the mix without BFS. It could be noted that BFS acts as a good flowability aid in this system. The BFS particles fill into the spaces made by larger particles of mortar and concrete and decrease frictional forces of matrix, resulting in contributing to increase flowability in this system. When examining mixes having FA shown in Fig. 5, the yield stress and plastic viscosity slightly increase as the replacement ratios of FA increase. The FA, from a theoretical point of view, should improve flowability as the spherical shape of FA reduces the frictional force among the angular particles, as called ball bearing effect (Termkhajornkit *et al.* 2001). However, there is a critical factor making worse flowability. The unburned carbon in FA is known to adsorb SP, which lead to worse workability of matrix (Akgerman and Zardkoohi 1996). The FA used in this study

contains about 2.88 wt.% unburned carbon which actively adsorbs SP, resulting in reducing effect of SP on better flowability of materials. So, in case of FA mixes tested, the effect of unburned carbon is more governing factor than the ball bearing effect. Regarding mixes having SF, the yield stress and plastic viscosity are decreasing at 5 % replacement but steeply increasing as the SF is over 10% replacement. Based on these rheological test results for SF mixes, it could be demonstrated that the ball bearing effect due to the spherical shape of SF could be governing the flowability of matrix at 5 % replacement, but above that like 10 % and 20 % replacement cases, due to high specific surface area of very fine particles of SF, average particle size $0.1 \mu\text{m}$, the particles of SF become chemically highly reactive and easy to adsorb SP molecules which end up multi-layers (Cyr *et al.* 2000; Kucharska and Moczko 1994). As the

Fig. 6 Effect of replacement ratios of SF on the rheological properties of constitutive mortar and concrete. (The measured data are calculated from 3 repeat tests, i.e., one standard deviation. Here, the standard deviations are 0.2 and 1.5 for plastic viscosity and yield stress of constitutive mortar and 2.0 and 6.0 for plastic viscosity and yield stress of concrete, respectively.)

replacements with SF are exceeded 5 %, the quantity of SP in the system substantially decreases because much adsorption of SP into the SF was occurred, which lead to steeply increase of the yield stress and plastic viscosity at 10 % and 20 % replacements.

4.2 Thickness of the lubrication layer

For the reliable verification, in this study, the thickness of the lubrication layer was determined by two methods, i.e. an analytical method developed by earlier study (Choi *et al.* 2014) and an experimental method. With the measured rheological properties for each region, i.e. concrete region and lubrication layer, the thickness of the lubrication layer which accurately fits the measured flow rates of the pumped concrete could be analytically calculated using Eq. (2). In order to calculate the thickness using Eq. (2), the experimentally measured initial pressure was substituted along with the measured rheological properties, after which the thickness of the lubrication layer corresponding to the measured flow rate was calculated. The calculation results according to the types and replacement ratios of each mineral admixture are listed in Table 4. The calculation results of BFS and FA mixes, although there is a little discrepancy due to the experimental conditions, the average thickness of the lubrication layer has roughly around 2 mm regardless of replacement ratios. However, when examining SF cases shown in Fig. 6, the results are altered depending on the replacement ratios. At 5 % of SF replacement, the thickness of lubrication layer is getting thinner around 1.5 mm on average. On the other hand, as the % of SF replacement is increasing above 5 %, the thickness of lubrication layer is getting thicker, i.e. around 3 mm and 4 mm for the 10% and 20 % of replacements, respectively. In other words, unlike the cases of BFS and FA, the thicknesses of lubrication layer incorporating SF mixes are varied depending on replacement ratios.

To verify the analytical results, the axial velocities experimentally measured by means of UVP are compared in Fig. 7, where the normalized velocity is defined as the relative velocity to its own maximum velocity depending on the mix types and replacements ratios of mineral admixtures. As shown in Fig. 7, a significant change in the slope is visible within a limited zone, which represents the lubrication layer and shear rates, approximately the slope of the velocity profiles, concentrated in this layer for all tested cases. The concentration thickness, i.e. the thickness of the lubrication layer, has a nearly identical profile for mixes having BFS and FA, with nearly 2 mm, which is roughly agreed with analytical results. Moreover, in case of SF mixes, the measured thicknesses have changed depending on the replacement ratios, i.e. become smaller at 5% of replacement and become larger above 10 % of replacement, which is also

Fig. 7 Experimental results for the thickness of the lubrication layer using the UVP.

Table 4 Calculation results for the thickness of the lubrication layer.

Mixes		Measured results		Calculation results
Mineral Admixture	Notation	Inlet pressure per unit length (Pa/m)	Flow rate (m ³ /h)	Lubrication layer thickness (mm)
-	UO	15,882	29	2.00
		18,824	35	2.10
		20,588	40	2.00
		24,118	48	2.30
		25,882	52	2.30
BFS	BFS40	14,118	28	1.80
		17,647	35	1.80
		20,000	42	1.90
		22,353	48	1.90
		25,294	53	2.00
	BFS50	12,941	28	1.70
		15,882	35	1.70
		18,824	42	1.70
		21,765	48	1.70
		23,529	53	1.70
	BFS60	11,765	28	1.80
		14,706	35	1.80
		17,059	42	1.80
		20,000	48	1.70
		21,765	53	1.70
FA	FA10	16,471	28	1.90
		20,588	35	1.80
		22,941	42	2.00
		25,294	48	2.10
		27,059	53	2.20
	FA20	18,824	28	1.80
		22,941	35	1.90
		25,294	42	2.10
		27,647	48	2.20
		29,412	53	2.35
	FA30	20,588	28	1.80
		25,294	35	1.80
		27,059	42	2.10
		29,412	48	2.30
		31,176	53	2.50
SF	SF5	10,588	28	1.40
		14,706	35	1.50
		16,471	42	1.60
		19,412	48	1.40
		21,765	53	1.80
	SF10	20,588	28	2.40
		22,941	35	2.80
		25,882	42	3.00
		28,235	48	3.20
		29,412	53	3.50
	SF20	22,353	28	3.50
		25,882	35	3.80
		28,824	42	4.20
		32,941	48	4.20
		35,294	53	4.20

in good agreement with the analytically calculated results. Along with analytical calculation, through the experimental measurement using UVP, it could be worth noted that the thickness of the lubrication layer for BFS and FA mixes used in this study almost have a constant value regardless of the replacement ratios but for the SF it tends to be varied depending on the replacement ratios. It would however be worth noting that the ideal velocity profile of lubrication layer should be parabolic increase pattern up to the boundary of bulk layer as shown in Fig. 1, however, due to the limitation of ultrasonic technique (e.g. scattering of echoed ultrasound energy as depth increase), the measured profile does not clearly represent such a trend.

4.3 Pipe flow of pumped concrete depending on the mineral admixtures

To investigate the effect of the mineral admixtures on the pipe flow of pumped concrete, the measured inlet pressures depending on the flow rate according to replacement ratios for each mineral admixture are illustrated in Fig. 8 for the 170 m full-scale, in which the inlet pressures are calculated using a linear extrapolation process with 11 designated position pressure gauges, as shown in Fig. 3. The results illustrated that for BFS mixes, the pressures required to obtain the same flow rate are decreasing as the replacement ratios are increasing, indicating that as the BFS usages are increasing, the efficiency for concrete pumping is improving. However, when taking a look at the results of FA mixes, it shows opposite results, which means as the replacement ratios of FA are increasing, the pressures required to obtain the same flow rate are increasing. In other words, the usage of FA in concrete mix could create adverse effect on pipe flow on pumped concrete. As expected through the results of rheological properties, in case of SF mixes, the results are changing depending on replacement ratios. The required pressures become lower at 5% of replacement, but turn to higher at 10% and 20% of replacements, which have same tendency with rheological properties. Moreover, as shown in Fig. 8, the degree of pressure variation depending on the % of replacement ratios of SF mixes is bigger than that of the other two mix cases, which means through the changes of the SF replacement ratio, the performance of concrete pumping could be easily altered.

The measured pressures show a nearly linear relationship with the flow rate regardless of types of mineral admixtures, with an extrapolated ordinate at the origin in the investigated regime being nearly equal to zero. This indicates, in this regime and in the pumping conditions tested, that the pumping pressure does not appear to be affected by shear thickening or shear thinning (Cyr *et al.* 2000; Feys *et al.* 2008; Lachemi *et al.* 2004; Roussel *et al.* 2010) or by any pressure dependency of the rheological parameters of the pumped materials (Curcio and Deangelis 1998; Mansoutre *et al.* 1999).

With these experimental results, the required pres-

Fig. 8 Effect of replacement ratios of mineral admixtures on pressure-flow rate relationship in 170m full-scale test. (The measured data are calculated from 3 repeat tests, i.e., one standard deviation.)

Fig. 9 Pump pressure per unit length of pipe required to secure a flow rate of 35 m³/h according to the types and replacement ratios of mineral admixtures. (The measured data are calculated from 3 repeat tests, i.e., one standard deviation.)

tures per unit length are illustrated in **Fig. 9** under the 35 m³/h flow rate condition depending on the replacement ratios of mineral admixtures. When examining the required pressures according to replacement ratios, the concrete mixes incorporating BFS60 or SF5 have the lowest pressure per unit length, which means that these two cases provide the best efficiency for pipe flow of pumped concrete. On the other hand, the concrete mixes incorporating FA30 and SF20 have the highest pressure values, which implies when using these mixes it needs careful precaution considering the capacity of pump and the required duration of construction.

Through these experimental and analytical comparisons, it can therefore be concluded that the pipe flow of pumped concrete is obviously affected by the mineral admixtures and it could be one of the dominant factors to determine concrete pumping. The usage of BFS and SF having 5% replacement could increase efficiency of concrete pumping, but the mixes incorporating FA and SF above 10% replacement can have adverse effect, which means decreasing efficiency of concrete pumping.

5. Concluding remarks

In order to investigate the effect of the mineral admixtures incorporating BFS, FA and SF on pipe flow of pumped concrete, the rheological properties of the concrete region and the lubrication layer inside of pipe were experimentally measured, while the thickness of the lubrication layer playing a crucial role governing concrete pumping was analytically and experimentally determined. A 170 m full scale pumping test was conducted to figure out the actual performance of concrete pumping and the following major conclusions are drawn.

(1) In terms of the rheological properties, the plastic viscosity and yield stress of the concrete region and the lubrication layer of pumped concrete in the pipe are varied obviously depending on the types

and replacement ratios of mineral admixtures. Concrete mixtures incorporating BFS tend to decrease the rheological properties as the replacement ratios are increasing under the condition tested in this study. On the other hand, as the replacement ratios of FA mixes are increasing, rheological properties are increasing. In case of SF mixes, the results initially decreasing at 5 % replacement but turning into increase at above 10 % replacement. These variations of the rheological properties according to types and replacement ratios of mineral admixtures are the paramount factors affecting on the pipe flow of pumped concrete.

- (2) In order to determine the thickness of the lubrication layer, in this study, two methods, an analytical method and an experimental method, were used. From those two methods, it found that the average thickness of the lubrication layer of concrete mixtures having BFS and FA was roughly 2 mm regardless of replacement ratios. However, the results of SF mixes are different depending on the replacement ratios, *i.e.* getting smaller around 1.5 mm at 5% of replacement and getting larger around 3 mm to 4 mm at 10 % and 20 % of replacement, respectively.
- (3) With the measured rheological properties, the thickness of the lubrication layer which accurately fits the experimentally measured flow rates was analytically calculated. It was found that the results are in good agreement with the actual experimental results as measured by a UVP, which implies that the measured rheological properties of the concrete and the constitutive mortar are verified to represent the actual materials properties of pumped concrete in the pipe and the thickness of the lubrication layer determined by analytical and experimental methods provide a precise value to simulate actual concrete pumping.
- (4) The pressures required to obtain same flow rate were investigated depending on the types and replacement ratios of mineral admixtures. Concrete incorporating BFS and SF having 5% replacement could increase efficiency of concrete pumping but those of FA and SF above 10% replacement can have adverse effect under the condition tested in this study. Therefore, it could be concluded that the pipe flow of pumped concrete is obviously affected by the types and replacement ratio of mineral admixtures, so that sufficient consideration is needed to determine the mix design and pumping setup for constructing high rise buildings and super structures, for which normally demand extreme pumping condition.
- (5) From a practical point of view, the information of lubrication layer play a crucial role to govern concrete pumping. However, it is practically difficult to determine those information. Therefore, along with previous studies, from this study, the informa-

tion of lubrication layer such as rheological properties and thickness could be effectively utilized to predict concrete pumping.

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