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A new method to estimate rheological properties of lubricating layer for prediction of concrete pumping

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Abstract. The most crucial factor determining the pumping performance of concrete is the characteristics of the lubricating layer formed between the pipe wall and the inner concrete. Thus, it is important to accurately identify the rheological properties of the lubricating layer to predict the pumping of concrete. In this study, a new method is proposed for measuring the rheological properties of the lubricating layer with improved convenience. To verify the new method, a pumping test was conducted with 337 m-long horizontal piping. The rheological properties of the lubricating layer were assessed by a previously verified method and the new method proposed in this study for a total of four concrete mixtures with design strength ranging from 27 MPa to 60 MPa. The correlation between the existing method and the new method in relation to the viscosity of the lubricating layer was determined, and it was possible to predict the pumping performance with an accuracy of about 88.5% using the viscosity of the lubricating layer obtained from this correlation.

Keywords: lubricating layer; pumping; rheological property; prediction; pumpability

1. Introduction

The concrete placement method by pumping is applied in most construction sites, as concrete can be placed more easily and quickly in comparison with other methods using a bucket, conveyor, or cart among others. With the increasing demand for large-scale construction work for skyscrapers and long bridges, for example, there have recently been many studies conducted on the prediction of concrete pumping. In order to predict concrete pumping, it is important to first understand the mechanism of the flow inside the piping such as lubrication layer formation and velocity distribution in the pipe and to analyze the material to be pumped. When concrete is pumped, a lubricating layer forms between the pipe wall and the inner concrete. According to the preceding studies on concrete pumping (Alekseev 1952, Browne and Bamforth 1977, Choi *et al.*

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2012, Ede 1957, Jacobsen *et al*. 2009, Kaplan *et al*. 2005, Kwon *et al*. 2013a, b, Kwon *et al*. 2016, Morinaga 1973, Sakuta *et al*. 1989, Secrieru *et al*. 2017), the characteristics of the lubricating layer are the most important factors in determining pumping performance.

The lubricating layer has a significantly smaller viscosity compared to concrete and exists in a thin layer with a thickness of several millimeters across the entire pipe section (Alekseev 1952, Kwon *et al*. 2013a, b, Choi *et al*. 2012, Kwon *et al*. 2016, Le *et al*. 2015, Jo *et al*. 2011, Choi 2013, Choi *et al*. 2014a). Most of the pumping velocity appears in this thin lubricating layer (kwon *et al*. 2013b). Accordingly, the viscosity of the lubricating layer, which is directly related to the friction resistance at the pipe wall, is the most crucial factor in determining the pumping performance.

The methods for assessing the rheological properties of the lubricating layer that have been developed thus far (Kaplan *et al*. 2015, Kwon *et al*. 2013a, Choi 2013, Chapdelaine 2007, Ngo *et al*. 2010, Feys *et al*. 2014, Feys *et al*. 2015) involve positioning a cylindrical rotary shaft in a concrete container filled with concrete and assessing the rheological properties of the lubricating layer using the torque measured while rotating the shaft at a designated rotational speed. The flow layer formed between the sides of the cylinder and the concrete during cylinder rotation is regarded as the lubricating layer. A variety of equipment for measuring the rheological properties of the lubricating layer have been developed (Kaplan *et al*. 2005, Kwon *et al*. 2013a, Chapdelaine 2007, Ngo *et al*. 2010, Feys *et al*. 2014, Mechtcherine *et al*. 2014). Kaplan *et al*. (2005) have developed a tribometer that can measure the rheological properties of the lubricating layer by modifying BTRheom (De Larrard *et al*. 1997), a rheometer for concrete. They also presented a method of predicting concrete pumping by using the rheological properties of the lubricating layer measured with this equipment. Since then, various types of tribometers have been developed by Chapdelaine (2007), Ngo *et al*. (2010), Kwon *et al*. (2013a), and Feys *et al*. (2014) by improving the estimation method and supplementation the related problems. Kwon *et al*. (2013a, b), particular, proposed a prediction method of concrete pumping using the rheological properties of the lubricated layer measured with the developed tribometer. The accuracy of this prediction method has been verified through a comparison of the results of the 350 m and 548 m full-scale pumping tests (Kwon *et al*. 2013b). Choi (2013), on the other hand, determined that the rheological properties of the lubricating layer are similar to those of the mortar through a numerical analysis, which took into consideration the shear-induced particle migration (Jo *et al*. 2011, Choi 2013, Phillips *et al*. 1992, Choi *et al*. 2013), which is the formation mechanism of the lubricating layer. The rheological properties of the mortar extracted through a wet screening of concrete with a 5 mm sieve were considered as the rheological properties of the lubricating layer.

The aim of this study was to propose a new method of assessing the rheological properties of the lubricating layer. The existing methods of assessing the rheological properties of the lubricating layer that have been previously developed (Kaplan *et al*. 2005, Kwon *et al*. 2013a, Chapdelaine 2007, Ngo *et al*. 2010, Feys *et al*. 2014, Mechtcherine *et al*. 2014) have drawbacks in that the equipment used is large and that the test procedure is complicated, as the test has to be carried out twice by filling in concrete at different heights or the mortar must be extracted. Also, some of the methods have not yet been validated by full-scale pumping tests or field applications. Considering the situation of construction sites, where the rotations of concrete supplying vehicles and vehicles on standby occur quickly, it is deemed that the methods requiring two measurements using large equipment are impractical, as they are time-consuming and complicated. For this reason, this study was conducted to propose a new method of assessing the rheological properties of the lubricating layer more easily and quickly in the field through small-scale and simplified tests. The new method was verified through a full-scale pumping test with 337 m-long horizontal pipeline. The pumping test was carried out using four types of concrete mixtures with design strength ranging from 27 MPa to 60 MPa. The rheological properties of the lubricating layer were then measured by the previously verified method (Kwon *et al*. 2013a) and the new method proposed in this study. The correlation was determined by comparing the viscosity measurements obtained from the two measurement methods, based on which a viscosity estimation method was proposed for the new measurement method. Concrete pumping was then predicted using the estimated viscosity, and validation was performed, based on a comparison with the results of the full-scale pumping test.

2. Parametric study on effect of rheological properties on pumpability

2.1 General

Generally, the rheological properties of concrete and the lubricating layer are described with the Bingham fluid model (Tattersall and Banfill 1983), which is expressed in viscosity and yield stress as shown in Eq. (1). Bingham fluid refers to a fluid that behaves like a solid at stress levels below the yield stress and behaves like a liquid at stress levels above the yield stress.

$$\tau = \tau_0 + \dot{\gamma}\mu \tag{1}$$

Where, τ is the shear stress (Pa), τ_0 is the yield stress of fluid (Pa), $\dot{\gamma}$ is the shear rate (1/s), and μ is the viscosity of fluid (Pa·s).

In order to predict the pumping of concrete, it is very important to accurately measure the rheological properties of the concrete and lubricating layer. Of particular note, since the viscosity of the lubricating layer is directly related to the pumping performance, the pumping estimates including the pumping pressure, flow rate, and pumpable distance can vary significantly depending on the viscosity measurement results of the lubricating layer.

In this study, a parametric study was carried out to quantitatively determine the effects of the viscosity and yield stress of the concrete and lubricating layer on pumping performance under the same pumping conditions (pumping pressure, pipe diameter, and pipe length). The range of each parameter was selected based on the measurement data of the rheological properties of the concrete and lubricating layer measured in prior studies (Kwon *et al*. 2013b, Choi 2013, Jeong *et al*. 2016, Choi *et al*. 2014b). The rheological properties of the concrete and lubricating layer that were considered in the parametric study are shown in Table 1. For concrete, the range considered was from 50 Pa·s to 300 Pa·s for viscosity and from 0.1 Pa to 300 Pa for yield stress. In the case of the lubricating layer, the rage considered was from 1 Pa·s to 10 Pa·s for viscosity and from 0.1 Pa to 100 Pa for yield stress. As for the reference values of viscosity and yield stress, they were set at 150 Pa·s and 50 Pa, respectively, for concrete, and at 5 Pa·s and 50 Pa, respectively, for the lubricating layer.

Table 1 Range of rheological properties of concrete and lubricating layer for parametric study

	Concrete		Lubricating layer	
	Viscosity (Pa·s)	Yield stress (Pa)	Viscosity (Pa·s)	Yield stress (Pa)
Range	50 ~ 300	0.1 ~ 300	1 ~ 10	0.1 ~ 100
Reference value	150	50	5	50

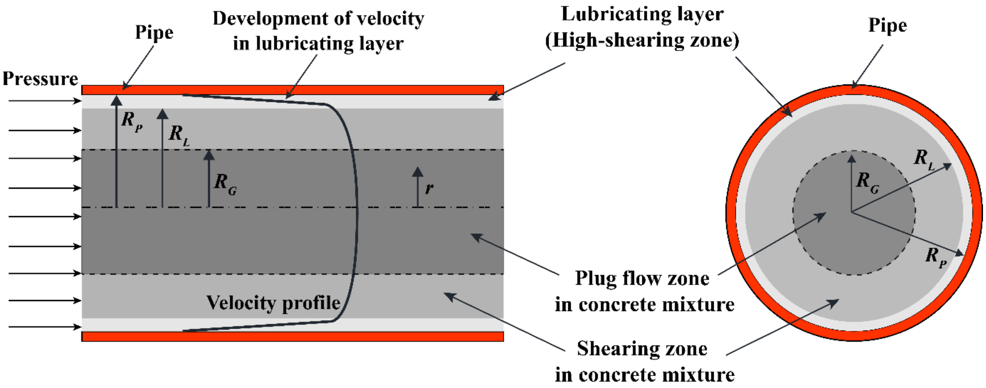


Fig. 1 Velocity profile of concrete in the pipe during pumping (Kwon *et al*. 2013b)

2.2 Calculation method of flow rate

For the pumping performance, the flow rate in relation to the given conditions (pumping pressure, pipe length and diameter, rheological properties of concrete and lubricating layer) were calculated and compared. A previously verified pumping prediction method (Kwon *et al*. 2013b) was used to calculate the flow rate. Fig. 1 shows the flow zones and velocity distribution in the pipe section during concrete pumping. The flow rate per unit hour can be calculated by integrating the velocities of the lubricating layer in the pipe section, the shearing flow layer of the inner concrete, and the plug flow layer (Tattersall and Banfill 1983), and the following Eq. (2) is used for the calculation (Kwon *et al*. 2013b).

$$Q = 3600\frac{\pi}{24\mu_L\mu_C}\left[3\mu_C\Delta P\left({R_P}^4 - {R_L}^4\right) - 8\tau_L\mu_C\left({R_P}^3 - {R_L}^3\right)\right. \\ \left. +3\mu_L\Delta P\left({R_L}^4 - {R_G}^4\right) - 8\tau_C\mu_L\left({R_L}^3 - {R_G}^3\right)\right] \tag{2}$$

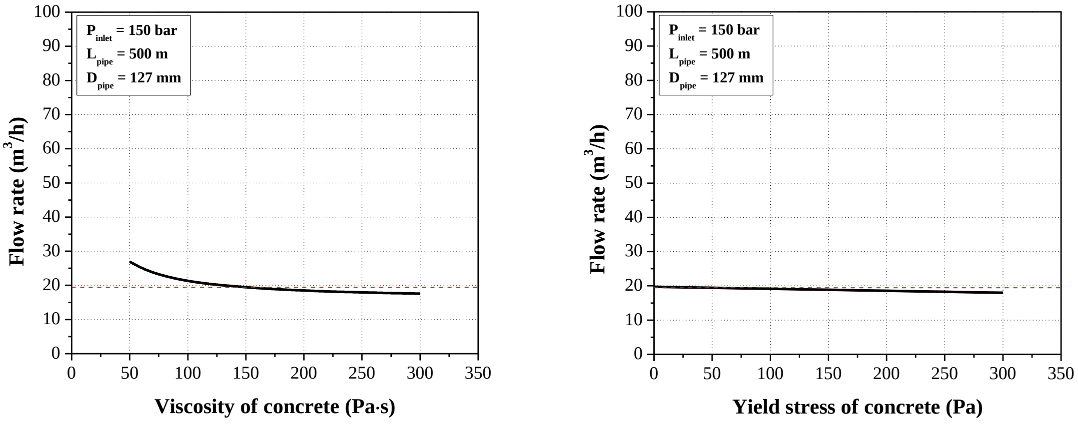
Where, Q is the flow rate (m^3/h), R_P is the radius of pipe (m), R_L is the distance from the center of the pipe to the lubricating layer (m), R_G is the radius at which the shear rate starts (m), ΔP is the pressure per unit length (Pa/m), τ_C and μ_C are the yield stress (Pa) and the viscosity (Pa·s) of the concrete, respectively. τ_L and μ_L are the yield stress (Pa) and the viscosity (Pa·s) of the lubricating layer, respectively. The difference between R_P and R_L is the thickness of the lubricating layer. In the pumping prediction method developed by Kwon *et al*. (2013b), the thickness of the lubricating layer was assumed to be 2 mm, and the calculation was performed with the same assumption in this study.

The pumping conditions considered in the calculation of the flow rate were kept identical as follows: inlet pressure of 150 bar, horizontal pipe length of 500 m, and pipe diameter of 127 mm. Of the four parameters, i.e., the viscosity and yield stress of the concrete and lubricating layer, only one parameter was varied, while the other three were kept the same, to calculate the flow rate, and the same calculation method was applied for all of the four parameters.

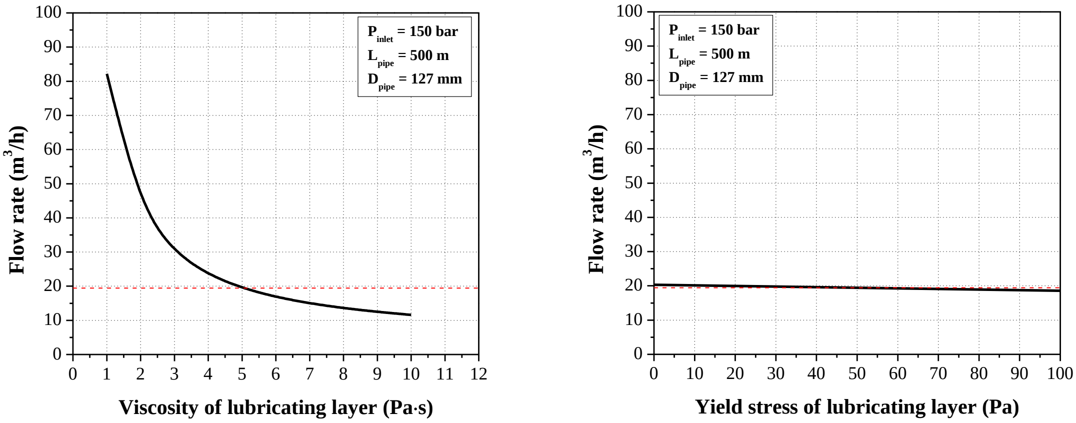
2.3 Results of parametric study

The results of calculating the flow rate for each parameter are shown in Fig. 2. The flow rate, calculated as reference values of rheological properties of the concrete and lubricating layer, was 19.4 m^3/h, and it is shown as a dotted line in Fig. 2. When the viscosity of the concrete is changed from 50 Pa·s to 300 Pa·s, the flow rate was calculated to have changed from 26.6 m^3/h to 17.6 m^3/h, with a variation range of about 9.3 m^3/h (Fig. 2 (a)). When the yield stress of concrete was changed from 0.1 Pa to 300 Pa, the flow rate was calculated to have changed from 19.7 m^3/h to 18.0 m^3/h, with the variation range being about 1.7 m^3/h (Fig. 2 (b)). The changes in the flow rate resulting from the changes in the yield stress of the concrete were only marginal compared to the changes in the flow rate resulting from the changes in the viscosity. When the viscosity of the lubricating layer was changed from 1 Pa·s to 10 Pa·s, the flow rate was calculated to have changed from 82.2 m^3/h to 11.6 m^3/h, with the variation range being about 70.6 m^3/h (Fig. 2(c)). It was confirmed that the decrease in the flow rate was very large when the viscosity of the lubricating layer was changed from 1 Pa·s to 3 Pa·s, while the amount of decrease in the flow rate gradually became smaller when the viscosity exceeded 3 Pa·s. When the yield stress of the lubricating layer was changed from 0.1 Pa to 100 Pa, the flow rate was calculated to have changed from 20.3 m^3/h to 18.6 m^3/h, and the variation range was approximately 1.7 m^3/h (Fig. 2 (d)).

An analysis of the results of calculating the flow rate according to the changes in the



(a) Viscosity of concrete (b) Yield stress of concrete



(c) Viscosity of lubricating layer (d) Yield stress of lubricating layer

Fig. 2 Results of parametric study to the effect of rheological properties on pumpability rheological properties of the concrete and lubricating layer showed that the viscosity of the lubricating layer exerted the greatest influence on the pumping performance of the concrete. The second most influential factor was found to be the viscosity of the concrete. In comparison with viscosity, the yield stress of the concrete and lubricating layer was found to have significantly smaller effects on pumping performance.

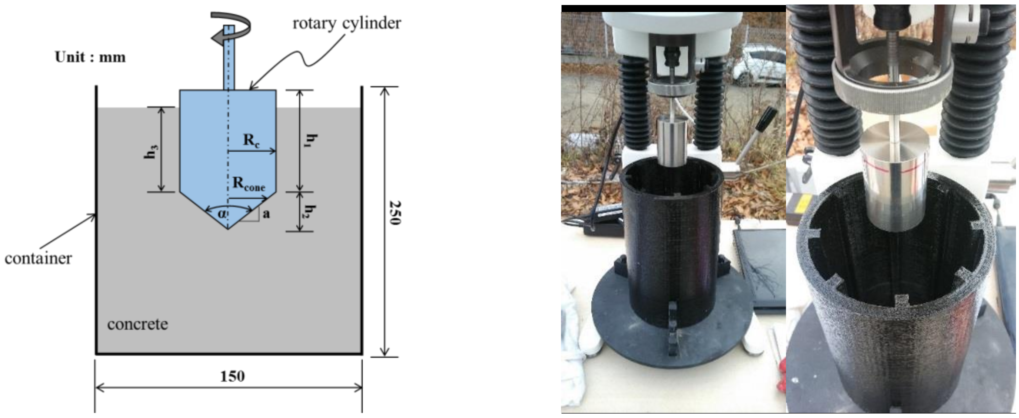
The parametric study reaffirmed that the viscosity of the lubricating layer is the most important factor governing the pumping performance of concrete. This shows that an accurate understanding of the rheological properties of the lubricating layer is very important when it comes to pumping prediction.

3. A new method to measure rheological properties of lubricating layer

3.1 Equipment and test method

Some of the measuring equipment that have been developed for measuring the rheological properties of the lubricating layer are modifications of the equipment for measuring the rheological properties of concrete. Also, the testing process for measuring the rheological properties of the lubricating layer is not simple, as it requires the concrete to be filled to different heights for two different measurements or the extraction of mortar. Thus, the aim of this study was to propose a new method of estimating the rheological properties with just a single measurement, without any intermediate processes, using a small amount of concrete with a portable device.

The new method attempted in this study is basically similar to the existing methods of assessing the rheological properties of the lubricating layer (Kaplan *et al*. 2015, Kwon *et al*. 2013a, Choi 2013, Chapdelaine 2007, Ngo *et al*. 2010, Feys *et al*. 2014). The method involves inducing the formation of a lubricating layer by rotating a smooth cylindrical rotary shaft as a means to create an environment similar to the actual pipe wall and measuring the generated torque to calculate the rheological properties of the lubricating layer. An RST-rheometer (AMETEK Brookfield) is used as the measurement equipment in this method. Fig. 3 shows the dimensions



(a) Dimension of rotary cylinder and container

(b) Rotary cylinder installed in the RST-rheometer

Fig. 3 Dimension and rotary cylinder installed in the RST-rheometer

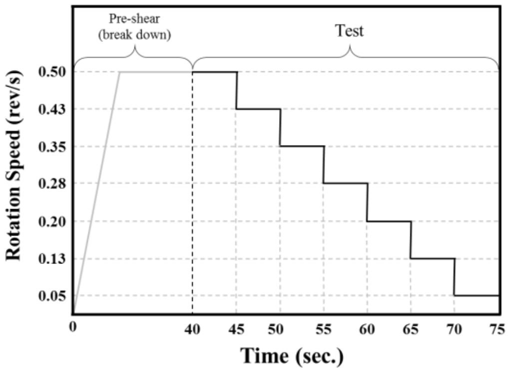


Fig. 4 Setting of rotation speed for flow curve test

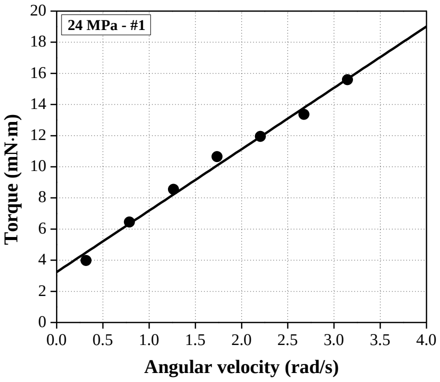


Fig. 5 measured torque-angular velocity relationship

of the rotary cylinder and container, which were used to estimate the rheological properties of the lubricating layer, and the RST-rheometer set up for the test. The diameter and height of the container were 150 mm and 250 mm, respectively. Eight ribs were set up at regular intervals to prevent slipping of concrete at the container wall. The bottom of the rotary cylinder was a cone type with a pointy end. The height of the side (h_1) of the rotary cylinder was 68.5 mm, the height of the cone (h_2) was 13.8 mm, the angle (α) was 120°, and the radius (R_c) was 23.9 mm. In the test, the rotary cylinder was not completely immersed in the concrete, and the concrete was filled to the extent where the cylinder side was immersed to h_3 (60 mm), as shown in Fig. 3(a).

Fig. 4 shows the rotational speed set to measure the rheological properties of the lubricating layer. Pre-shearing was performed for 40 seconds at 0.5 rev/s to remove thixotropy (Tattersall and Banfill 1983). Then, the rotational speed was changed from 0.5 rev/s to 0.05 rev/s in 7 steps, and the rotations were performed for 5 seconds for each step, while taking measurements of the corresponding torque. Fig. 5 shows the torque-angular velocity relationship measured using the RST-rheometer, and the viscosity and yield stress of the lubricating layer were calculated based on this relationship.

3.2 Determination of rheological properties of lubricating layer

In case the viscosity and yield stress of the lubricating layer are constant, the relationship between the torque and angular velocity can be expressed in the Reiner-Riwlin equation (Tattersall and Banfill 1983), shown as Eq. (3).

$$\Omega = \frac{\Gamma_{tot}}{4\pi h\mu_L}\left[\frac{1}{{R_1}^2}-\frac{1}{{R_2}^2}\right]-\frac{\tau_L}{\mu_L}\ln\left(\frac{R_2}{R_1}\right) \tag{3}$$

Where, Ω is the angular velocity (rad/s), Γ_{tot} is the total torque applied to the concrete (N·m), h is the height to which the concrete is filled (m), and R_1 is the radius of the inner cylinder (m). R_2 is the radius of the outer cylinder (m), which is calculated by adding the thickness of the lubricating layer to the radius of the inner cylinder. τ_L and μ_L are the yield stress (Pa) and viscosity (Pa·s) of the lubricating layer.

The rotary cylinder of the RST-rheometer has a cone-type bottom, unlike the conventional tribometer (Kaplan *et al*. 2005, Chapdelaine 2007, Ngo *et al*, 2010, Kwon *et al*. 2013a). Thus, the torque value obtained from RST-rheometer is the sum of the torque generated on the side of the cylinder and at the cone-shaped part, as shown in Eq. (4).

$$\Gamma_{tot} = \Gamma_{cylinder} + \Gamma_{cone} \tag{4}$$

Where, $\Gamma_{cylinder}$ is the torque (N·m) acting on the side of the rotary cylinder, which is a straight section, and Γ_{cone} is the torque (N·m) acting on the incline section.

The torque acting on the side of the rotary cylinder, i.e., the straight section, can be calculated easily using Eq. (5) (Kwon *et al*. 2013a). Here, the shear flow is assumed to occur only in the lubricating layer.

$$\Gamma_{cylinder} = 2\pi {R_c}^2 \tau_L h_3 \tag{5}$$

Where, R_c is the radius of the rotary cylinder (m), and h_3 is the height of the side of the rotary cylinder immersed in concrete (m), which was 0.06 m, as mentioned above.

The radius from the center of the cylinder in the cone section to the incline section is a function of the height h_2 of the cone shown in Fig. 3(a). When the torque at the cone area re-expressed using Eq. (3), it can be expressed as Eq. (6).

$$\Gamma_{cone} = \int_0^{h_2} 2\pi {R_{cone}}^2 \left[\frac{2\Omega}{{R_{cone}}^2(1/{R_{cone}}^2 - 1/({R_{cone}}^2 + T_L)^2)}\mu_L + \tau_L\right]\sqrt{1 + (1/a)^2}\,dh \tag{6}$$

$$R_{cone} = h/a \qquad (0 \le h \le h_2) \tag{7}$$

Where, Γ_{cone} is the torque acting on the incline section (N·m), R_{cone} is the radius of the incline section (m), which changes from 0 to h_2, a is the slope of the incline, and T_L is the thickness of the lubricating layer (m), assumed to be 2 mm, as was the case for the tribometer developed by Kwon *et al*. (2013a).

The torque-angular velocity relationship that can be obtained from the RST-rheometer, shown in Fig. 5, is the value of the rotary force determined by adding the results of Eq. (5) and Eq. (6), which makes it difficult to calculate the rheological properties of the lubricating layer separately for the straight section and the incline section of the rotary cylinder. Thus, the viscosity and yield stress of the lubricating layer that can be measured were substituted into Eq. (5) and Eq. (6), and the intercept (Γ_0) and slope (k) were determined from the torque-angular velocity relationship. The relationship between the viscosity of the lubricating layer and k and the relationship between the yield stress of the lubricating layer and Γ_0, determined through the above process, are shown in Eq. (8) and Eq. (9).

$$\mu_L = 2.98 \times 10^3 \cdot k \tag{8}$$

$$\tau_L = 3.86 \times 10^3 \cdot \Gamma_0 + 0.3 \times 10^{-3} \tag{9}$$

Where, k is the slope of torque-angular velocity relationship, Γ_0 is the intercept of torque-angular velocity relationship.

4. Experimental program

4.1 Materials

Table 2 Mix proportions for 337 m pipeline pumping tests

Mix.	W/B (%)	S/a (%)	Unit weight (kg/m^3)							AD (%B)	AE (%B)
			W	OPC	FA	SP*	SF	S	G		
S27	44.7	49.6	168	263	38	75	-	884	900	0.90	0.31
S30	40.2	47.6	165	287	41	82	-	828	910	0.85	0.28
S40	35.1	43.9	165	282	47	141	-	751	961	1.00	0.18
S60	29.6	42.1	160	297	54	162	27	696	958	1.10	0.24

*SP : slag powder

Table 3 Pump specifications

Item	Content
Output (m^3/h)	72
Delivery cylinder (Φ mm)	180
Delivery cylinder stroke (mm)	2100
Strokes / minute	22
Engine (kW)	470
Hopper capacity (L)	Approx. 600
Weight (kg)	11000

As for the concrete used in the pumping test, a total of four types of concrete mixes with design strength ranging from 27 MPa to 60 MPa were used. The mix proportions for the concrete used in the test are shown in Table 2. In the Table 2, S27, S30, S40 and S60 mean concrete strengths of 27 MPa, 30 MPa, 40 MPa and 60 MPa, respectively. Coarse aggregates with a maximum size of 25 mm were used for the mixing of general strength concrete with design strengths of 27 MPa and 30 MPa, while 20 mm aggregates were used for high-strength concrete with design strength of 40 MPa and 60 MPa. The cement that was used was Portland cement type I, with specific gravity of 3.15. Fly ash, slag powder, and silica fume, with specific gravity of 2.20, 2.90, and 2.20, respectively, were used as mineral admixtures. As for the chemical admixtures, an air entraining agent and a polycarboxylate high-range water-reducing admixture were used. A total of 75 m^3 of concrete was used in the pumping test, with 30 m^3 of concrete used for the mix design with design strength of 27 MPa, 25 m^3 of concrete for the 30 MPa mix design, and 10 m^3 of concrete for the 40 MPa and 60 MPa mix designs.

4.2 Pumping circuit

For the pumping test, a horizontal piping line with a length of 304 m and a placing boom with a length of 33 m were set up to install a pumping circuit with a total length of 337 m. The diameter of the installed pipe was 127 mm (5 inches). Fig. 6 shows the layout of the pumping test site. As for the concrete pump, a large-capacity piston pump that can transport not only ordinary concrete but also high-viscosity concrete such as high-strength concrete was used. The specifications of the pump used in the pumping test are shown in Table 3. Pressure sensors were installed at eight locations in total to measure the pressure during pumping. The sensors were installed at the hydraulic cylinder and at 1 m, 66 m, 109 m, 152 m, 195 m, 238 m and 278 m from the pump inlet. The locations of the pressure sensors are indicated with dots in Fig. 6.

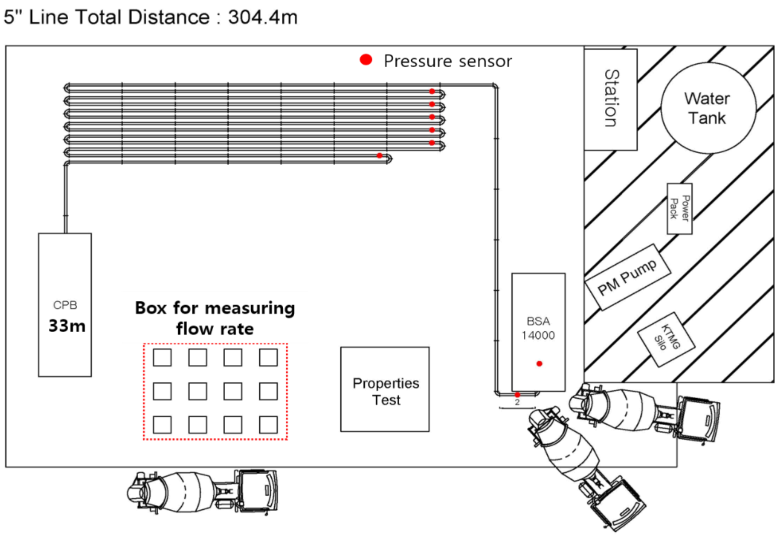


Fig. 6 Layout of 337 m horizontal pipeline for pumping test

Fig. 7 The whole view of pumping test site

4.3 Test method

Pumping was proceeded after receiving concrete from the hopper of the pump from the ready-mixed concrete truck arriving at the experiment site. The pumping test site is shown in Fig. 7. Concrete was discharged to the flow rate measurement box and the waste disposal vehicle using a placing boom set up in the discharge section. The pressure inside the pipe was monitored in real time using the pre-installed pressure sensors. A 1.0 m×1.0 m×1.2 m box was fabricated and placed near the discharge section for the purpose of measuring the flow rate. The flow rate was calculated by measuring the speed at which the flow rate measurement box was filled with concrete using a timer. Fig. 8 shows the pressure sensors installed in the pipe and the process of measuring the flow rate. The amount of concrete used in the test was 75 m^3 in total, and this is identical to the amount carried by fifteen ready-mixed concrete trucks, which can carry 5 m^3 each. A material test was carried out in the tent shown on the right side of Fig. 7. The rheological properties of the concrete


(a) Installation of pressure sensor (b) measurement of flow rate

Fig. 8 Measurement of pressure and flow rate


(a) Tribometer (b) RST-rheometer

Fig. 9 Measurement of rheological properties of lubricating layer

and the lubricating layer were measured. The rheological properties of the concrete were measured using a rheometer for concrete (Koehler *et al*. 2006), while the rheological properties of the lubricating layer were measured using two types of equipment: a previously verified tribometer (Kwon *et al*. 2013a) and a RST-rheometer used for the first time in this study. Fig. 9 shows the tribometer and the RST-rheometer set up to measure the rheological properties of the lubricating layer.

5. Results and discussion

5.1 Rheological properties of concrete and lubricating layer

Table 4 shows the results of measuring the rheological properties of the concrete mixes used in the pumping test. Even with the identical concrete mixes, there were slight differences in the measurement results across the batches. It was expected that the higher the design strength, the

Table 4 Results of rheological properties of concrete and lubricating layer – pumping test

Mix.	Truck No.	Concrete		Lubricating layer			
				Tribometer		RST-Rheometer	
		Viscosity (Pa·s)	Yield stress (Pa)	Viscosity (Pa·s)	Yield stress (Pa)	Viscosity (Pa·s)	Yield stress (Pa)
S27	1	91.4	117	1.77	30.0	1.20	13.9
	2	119	103	1.96	30.6	1.35	12.6
	3	85.5	144	1.94	16.0	1.41	15.4
	4	78.7	61.0	2.08	0.10	1.16	14.0
	5	64.9	76.0	2.15	20.2	1.08	8.76
	6	80.5	152	1.70	35.1	1.21	13.8
S30	1	71.3	340	2.08	26. 6	1.62	16.7
	2	83.8	505	2.56	79.4	2.17	9.58
	3	98.3	89.0	1.56	43.6	1.12	7.99
	4	90.0	83.7	1.62	20.5	1.18	9.39
	5	92.2	171	1.89	20.4	1.28	6.71
S40	1	87.3	67.7	3.00	9.90	2.20	12.4
	2	39.8	155	2.30	15.3	1.69	14.7
S60	1	50.1	129	2.30	11.4	2.14	17.5
	2	58.6	39.0	2.92	0.10	2.33	11.9

higher the viscosity of the concrete would be, due to a lower W/B, but no particular trends were observed. In order to improve the pumping performance, efforts were made in the mix design process to lower the viscosity of the concrete by adequately adjusting the amount of the mineral and chemical admixtures. The yield stress of concrete also showed no special trends in relation to strength.

As for the viscosity of the lubricating layer measured using the tribometer and RST-rheometer, the viscosity measured using the RST-rheometer was about 30% lower overall. According to the results of previous studies, in which the rheological properties of same concrete mixture were measured using various types of equipment for a comparison (Ferraris and Brower 2001), the values of the rheological properties obtained by each equipment were different. This is deemed to be due to the fact that the size of each equipment and the method of estimating the rheological properties of concrete differed.

The reason for the difference in the viscosity values measured by the tribometer and the RST-rheometer is that the test was conducted at the same rotational speed, despite the differences in the size of the equipment used. For the tribometer, the size and rotational speed of the rotary cylinder that can generate the same shear rate as in the pipe during actual pumping were considered in the development process. The radius of the rotary cylinder of the tribometer is 65 mm, and in this case, in order to simulate the shear rate at the actual pipe wall during concrete pumping, the test must be carried out at a rotational speed of 3.14 rad/s. As for the RST-rheometer, the radius of the rotary cylinder is 23.9 mm, and in order to generate the same shear rate as the tribometer, the test must be conducted at a rotational speed of about 7.94 rad/s. However, due to the specifications of the equipment, it is difficult to carry out experiments at a rotational speed of 7.94 rad/s.

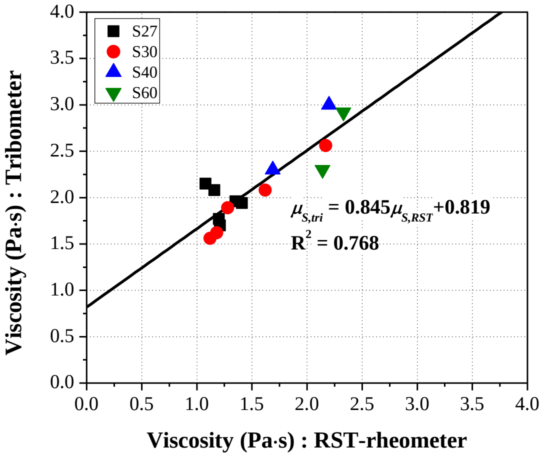


Fig. 10 Relationship between the viscosities measure from tribometer and RST-rheometer

Accordingly, the test was carried out at the same rotational speed, and then an attempt was made to reduce the difference in the measurements by correcting the viscosity measured using the RST-rheometer based on the viscosity measured by the tribometer.

The reason for making the correction based on the viscosity measurement obtained from the tribometer is that the accuracy of the tribometer has already been verified through full-scale pumping tests (Kwon *et al.* 2013b). Plus, the results of measuring the rheological properties of thirty-two types of concrete mixtures for high-rise buildings reported by Jeong *et al.* (2016) show that the relationships between the viscosities of the concrete mixes and the viscosities of the lubricating layers were all linear. The fact that the same tendency was shown when the same equipment was used means that the measurement method of the equipment and the measurement values have small fluctuations. Thus, it was deemed reasonable to make corrections based on the viscosity measurements obtained from the tribometer.

Fig. 10 shows a comparison of the results of measuring the viscosity of the lubricating layer using the tribometer and the RST-rheometer. While there were slight differences in the absolute values, the R-squared value was found to be highly correlated at 0.768. The viscosity measured by the tribometer and the RST-rheometer showed a linear relationship, and as a result of performing linear fitting, a relationship shown in Eq. (10) was determined.

$$\mu_{S,tri} = 0.845\mu_{S,RST} + 0.819 \tag{10}$$

Where, $\mu_{S,tri}$ and $\mu_{S,RST}$ are the viscosity (Pa·s) of lubricating layer measured by tribometer and RST-rheometer, respectively.

In the case of the yield stress of the lubricating layer, no particular relationship was observed between the tribometer and the RST-rheometer. In addition, the yield stress of the lubricating layer was neglected as it had a negligible effect on the pumping performance compared to viscosity, as previously noted.

5.2 Prediction of flow rates

To verify the new method of measuring the rheological properties of the lubricating layer, pumping was predicted using the measurements of the rheological properties of the concrete and lubricating layer from the pumping test. The measured and calculated flow rates were compared. For the pumping prediction, the previously verified prediction method (Kwon *et al.* 2013b) was used, and Eq. (2) was used to calculate the flow rate. The thickness of the lubricating layer was assumed to be 2 mm for all cases when calculating the flow rate. Table 5 shows a summary of the pressures and flow rates measured in the pumping test, and the flow rates calculated using the measurements of the rheological properties of the lubricating layer obtained using the tribometer and the RST-rheometer. Since the viscosities of the lubricating layers measured using the RST-rheometer were about 30% smaller than the viscosities measured using the tribometer, the flow rate calculated based on the rheological properties of the lubricating layer measured using the RST-rheometer were found to be larger.

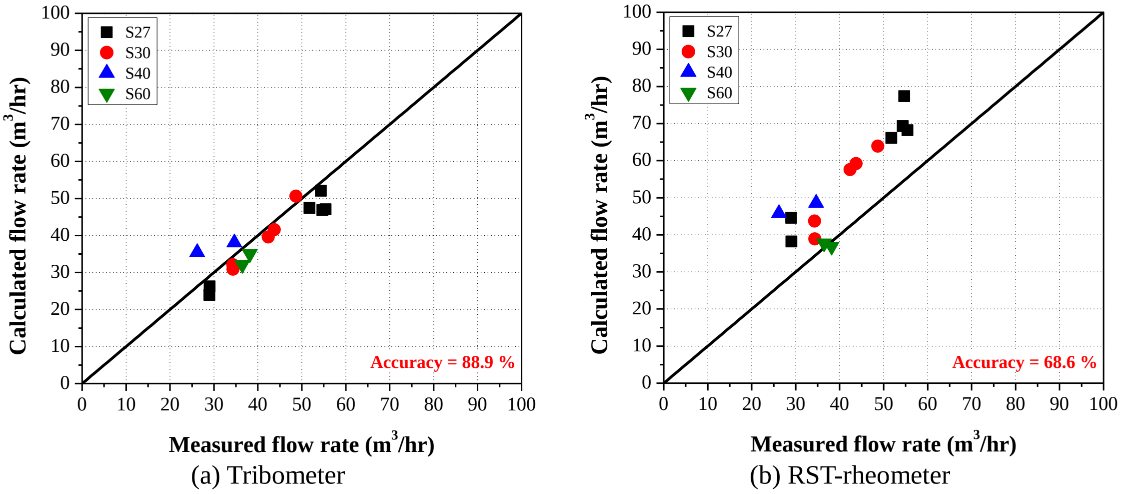
For the verification of the pumping prediction results, Eq. (11) was used to calculate the accuracy.

$$Accuracy\ (\%) = \left(1 - \frac{1}{n}\sum_{i=1}^{n}\frac{|Q_{measured} - Q_{calculated}|}{|Q_{measured}|}\right) \times 100 \tag{11}$$

Where, n is the number of pumping tests, $Q_{measured}$ is the measured flow rates (m^3/h), $Q_{calculated}$ is the calculated flow rates (m^3/h). Fig. 11 shows a comparison of the flow rates that were predicted using the rheological properties of the lubricating layer measured by the tribometer and RST-rheometer and the measured flow rates. The accuracy of the pumping prediction made based on the rheological properties of the lubricating layer measured by the tribometer was very high at 88.9%. In contrast, the accuracy of the pumping prediction made based on the RST-rheometer was 68.6%, which was lower than that of the tribometer. Fig. 11(b) shows that the data are skewed to one side, as the calculated flow rates were large overall.

Table 5 Measured and calculated flow rates

Mix.	Truck No.	Inlet pressure (bar)	Measured flow rate (m^3/h)	Calculated flow rate (m^3/h)	
				Tribometer	RST-Rheometer
S27	1	94.1	55.4	47.1	68.2
	2	60.6	29.0	26.2	38.2
	3	110	54.3	52.1	69.3
	4	101	54.7	46.9	77.4
	5	54.5	29.0	23.9	44.6
	6	91.6	51.7	47.4	66.1
S30	1	117	48.7	50.6	63.9
	2	98.8	34.3	30.9	38.9
	3	76.5	43.7	41.6	59.2
	4	59.5	34.3	32.1	43.7
	5	84.6	42.4	39.6	57.6
S40	1	107	26.2	35.4	45.8
	2	83.1	34.7	38.1	48.6
S60	1	79.3	38.2	35.0	36.8
	2	85.4	36.5	32.1	37.7



(a) Tribometer (b) RST-rheometer

Fig. 11 Comparison between measured and calculated flow rates

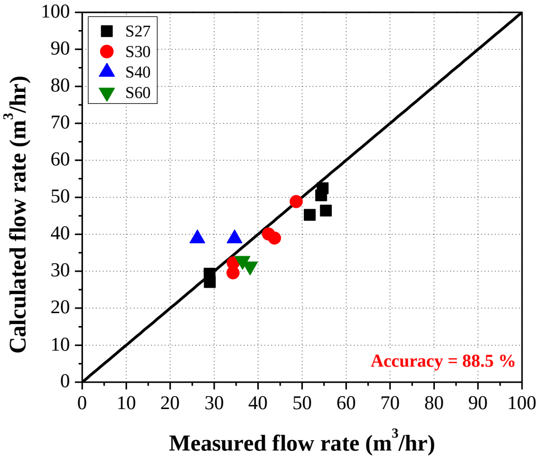


Fig. 12 Comparison between measured and calculated flow rates after viscosity correction of lubricating layer measured by RST-rheometer

Using the relationship of the viscosities of the lubricating layer measured by the two previously analyzed devices, the flow rates were recalculated by correcting the viscosity measurements from RST-rheometer. Fig. 12 shows the results of recalculating the flow rates by correcting the viscosity measurements from the RST-rheometer using Eq. (10). In case of correcting the viscosity of the lubricating layer using Eq. (10), the accuracy of the pumping prediction was improved to 88.5%. Thus, it is proposed that when pumping is predicted by measuring the rheological properties of the lubricating layer using the RST-rheometer, which is the new method attempted in this study, the viscosity be corrected using Eq. (10) for the pumping prediction.

Based on the above experimental results, the applicability of the newly proposed method for measuring the rheological properties of the lubricating layer was verified. Considering the field situation of construction sites, where the rotations of concrete supplying vehicles and vehicles on standby occur quickly, due to the nature of the pumping process that requires continuous

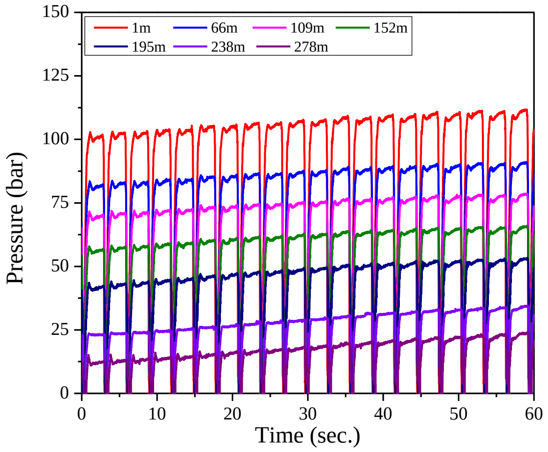


Fig. 13 Pressure pulsed of hydraulic cylinder and inner pipe

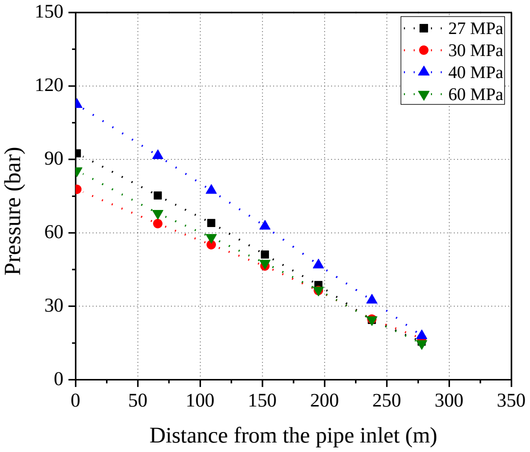


Fig. 14 pressure drop over the pipe length

placement of concrete, the new method proposed in this study is deemed to have high utility, as it involves a test that is simpler and less time-consuming than the existing method (Kwon *et al.* 2013a).

5.3 Pressure drop over the pipe length

As shown in Fig. 6, the pressure was measured at eight locations during the pumping test. The measurements were taken at the hydraulic cylinder, and at 1 m, 66 m, 109 m, 152 m, 195 m, 238 m and 278 m from the pump inlet. Fig. 13 shows the time history of the pipe pressure measured during the pumping test on the concrete mixes with design strength of 27 MPa. Due to the cylinder stroke of the concrete pump, the pressure waveform showed a pulse shape, and the average value of the pressure waveform was used for the pumping prediction.

Fig. 14 shows an average of the pressure levels measured across the length of the pipe. Although the slope of the pressure drop was different for each mix design, it was confirmed that the pressure drop with respect to length was linear, regardless of the design strength of the concrete. Generally, if the friction on the wall is constant in the flow of the fluid in the pipe, the relationship between the pipe length and the pressure drop is linear. In other words, the slope of the pressure drop is kept constant. The friction on the wall that occurs as the concrete flows inside the pipe is directly related to the viscosity of the lubricating layer. Thus, the fact that the slope of the pressure drop was constant means that the viscosity of the lubricating layer was maintained and did not change during pumping. Previous studies on concrete pumping (Kwon *et al.* 2013b, Choi *et al.* 2012) have reported that the rheological properties of the lubricating layer remain unchanged during pumping, and this was also confirmed, based on the relationship of the pipe length and pressure drop found in the pumping test performed in this study.

6. Conclusions

In this study, a new method for measuring the rheological properties of the lubricating layer was proposed. A pumping test of 337 m horizontal pipeline was carried out for four types of concrete mixes in total, and the new method was validated by comparing the flow rates calculated under the same pumping conditions as the test and the flow rates measured in the pumping test. The main conclusions are summarized as follows:

- A new method for assessing the rheological properties of the lubricating layer using RST-rheometer was proposed. The rheological properties of the lubricating layer were measured by using a tribometer (Kwon *et al*. 2013a) that has been previously verified and a RST-rheometer newly proposed in this study on fifteen concrete mixtures in total. An analysis of the viscosity measurements of the lubricating layer from the two aforementioned devices showed that the viscosities measured by the RST-rheometer were about 30% lower overall than the viscosities measured by the tribometer. Although there were slight differences in the absolute values, a high correlation was found between the viscosity values measured using the two methods. As the viscosity and yield stress measurements vary across the equipment used to measure rheological properties (Ferraris and Brower 2001), it is proposed that the pumping be predicted using the viscosity values corrected based on the correlation determined in this study, instead of using the viscosity values estimated using the RST-rheometer as they are.
- The flow rate was predicted using the values of the rheological properties of the lubricating layer measured using the tribometer (kwon *et al*. 2013a) that has been previously verified and the RST-rheometer that was newly applied in this study. For the purpose of verifying the predicted results, the predicted flow rate was compared with the flow rate measurements from the actual pumping test. The predictions of the flow rate made based on the values of the rheological properties of the lubricating layer measured using the tribometer and the RST-rheometer were found to have an accuracy of 88.9% and 68.6%, respectively.
- Using the correlation of viscosity proposed in this study, the viscosity was recalculated after correcting the viscosity measurements from the RST-rheometer, and this improved the accuracy of the pumping prediction to 88.5%. Thus, the applicability of the newly proposed method for measuring the rheological properties of the lubricating layer was verified. Also, it is expected that the method will be highly useful, as it presents advantages in that the experimental method is simpler and the time consumed for the test is shorter compared to its counterpart.
- A parametric study was conducted to identify the effect of the rheological properties of concrete and the lubricating layer on pumping performance. It was found that the viscosity of the lubricating layer had the biggest effect on the pumping performance, and this was followed by the viscosity of the concrete. It was also found that the yield stress of the concrete and lubricating layer had a very small effect on the pumping performance compared to viscosity.
- The results of analyzing the data on the pressure drop at various distances obtained from the 337 m horizontal pipe pumping test carried out in this study showed that the slope of the pressure drop was linear, regardless of the design strength of the concrete. A linear slope of the pressure drop in the pipe flow means that the pipe friction is constant, and from this, it can be inferred that the viscosity of the lubricating layer remains constant without any changes during concrete pumping.

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