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Evaluation of Pumping Characteristics of High Strength Concrete using Continuous Pumping System

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Abstract

In the construction of tall-building, concrete pumping influences the success of the project. In order to establish pumping technology for high speed construction of tall building, study for quantitative evaluation of flow characteristics and pumpability should be conducted. So in this study, the characteristics including the inner pipe pressure, rheological properties of concrete and mortar through the continuous pumping test were evaluated. Then we analyzed the relations between rheological properties and pumpability. In the result of test, there are high correlations between the rheological characteristics which represented by yield stress and plastic viscosity and pressure loss with pipe length. Also, we estimated pressure loss according to conditions of concrete mix and pumping through the evaluation of inner pipe friction.

Keywords : concrete pumping, rheology, bingham model

1. Introduction

Concrete pumping technology has become an essential element for high–speed construction, and use of high–performance pump has also increased[1]. The evaluation and prediction of pumpability has become more and more important, and many studies related to characteristics of materials and the mechanisms of pumps have been conducted to improve pumpability[1,2]. Pumpability is often affected by the characteristics of fresh concrete[3,4]. However, the slump test, which has been used to evaluate the consistency of existing concrete, is no longer sufficient to evaluate the pumpability of the high–fluid and high–strength concrete which has recently been developed. Therefore, the necessity for a method based on Rheology characteristics is increasing for quantitative and reasonable evaluation of concrete' fluidity[5]. Since complicated factors affect concrete when the fresh concrete is passing through a pumping pipe, it is essential to use the Rheology approach to evaluate and predict pumpability in regard to fluidity, viscosity, resistant of slip and segregation[2,3]. It is difficult to perform an experiment to evaluate the concrete pumpability, so there is almost no case of conducted experimental study which have evaluated Rheology characteristics and their effect on pumpability[4,5]. In this research, change in characteristics of Rheology according to pumping is measured by assuming concrete as Bingham fluid, and comparing the correlation between pumping characteristic and Rheology properties. The purpose of this research is

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to establish a fundamental resource for predicting pumpability. Particularly, a 50m short-length pumping system which can continuously pump concrete was established for this study, to compare it with the results of vertical pumping on an actual construction site or the long span horizontal pumping test.

2. Pumpability and Concrete Rheology

The most direct indicator to determine concrete pumping performance is the maximum pumping load to need to pour the amount of concrete required. Fundamentally, it is very important to select optimum pump equipment, and it is essential to consider losses and operational efficiency that might occur from installation of equipment and pipe.

As a way to calculate the pumping load of concrete pumps, Bernoulli's equation on pipe fluidity is suggested by many companies with high-pressure pumps. However, unlike situations where targeting Newton fluid, it is not appropriate to adapt this equation because concrete is in liquid-solid form. The equation from Architectural Institute of Japan (Equation1) is the most common pumping load calculation. In other words, it is a function of the length of pipe for pumping concrete, pumping height, and concrete density where pressure loss occurs due to friction between the tube wall and concrete while the concrete is flowing in the pipe. Thus, pumping load (P) of the pump can be calculated in advance by considering the pressure gradient, which changes depending on the flow characteristics of the concrete[2].

$$P = K(L + 3B + 2T + 2F) + 0.01 \times W \times H \quad (1)$$

where, P : pumping load applied to pump(N/㎟)

K : pressure loss coefficient(N/㎟/m)

L : length of straight pipe(m)

B : vent pipe length(m)

T : length of the tapered pipe(m)

F : length of wrinkle pipe(m)

W : unit mass of fresh concrete(t/㎥)

H : pumping height(m)

On the other hand, pumping pressure loss of concrete is closely related to pumping speed or discharge per hour, which can be significantly changed by the mixing condition of the concrete. Therefore, it is very important to understand the characteristics of fresh concrete to evaluate pumpability. In the past, slump flow of concrete, initial speed of L type flow, time to reach 50cm of slump flow were evaluation method generally used to understand pumpability of concrete. During the past 10 years, experiments to assess pumpability using a correlation between the result of concrete consistency measurements and pressure loss have actively been progressed. As new kinds of concrete, such as high-strength and high-fluidity concrete, are widely used, viscosity and friction resistance of concrete, which determine flow characteristics in pipe, have significantly altered. Therefore, in terms of pipe flow, attempt that want to evaluate pumpability of concrete are increasing. When pumping high-strength and high-fluidity concrete, especially, slip that occurs in concrete and inside the tube walls makes friction resistance. Such friction resistance becomes a critical element for predicting pressure loss[2,3]. Generally, pipe flow of concrete can be explained by movement of Bingham fluid, and as rheology indicator, yield stress and plastic viscosity as rheology constants are obtained by Equation (2).

$$\tau = \mu\dot{\gamma} + \tau_0 \quad (2)$$

where, τ : shear stress(Pa)

τ_0 : yield stress(Pa)

μ : plastic viscosity(Pa · s)
$\dot{\gamma}$: shear rate(1/s)

Rheology characteristics of concrete can be evaluated by an experiment that uses test devices, such as a 2-point test device and a rotational viscometer. As shown in Figure 1, plastic viscosity can be expressed as a slope between shear stress and shear rate. Yield stress means shear stress that starts to deform[6,7].

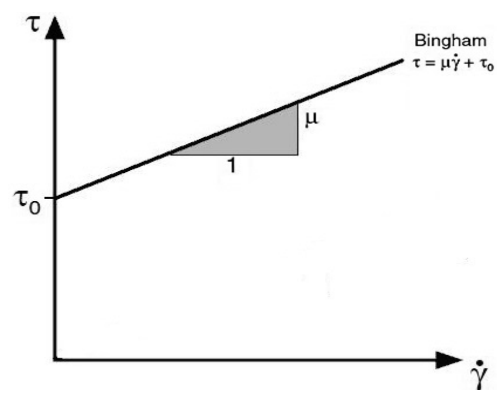

Figure 1. Flow curve for Bingham fluids

In the viewpoint of rheology, concrete, mortar, and cement paste represent different forms of suspension characteristics. Fresh concrete can be divided as matrix and particulate matter; the properties fluidity is often influenced by matrix viscosity and aggregate volume[9,10]. Therefore, to understand the rheology characteristics of concrete, it is necessary to compare and review the rheology characteristics of matrix and concrete, including the influence of the cement, the various kinds of admixture and binder However, there are no standard methods to identify the rheology characteristics of fresh concrete and mortar. Moreover, the variances of the measurement results about yield stress and plastic viscosity are different depending on different researchers and measuring devices. Thus, it is advisable to analyze the correlation between pump ability and the rheology characteristics of concrete through a relative comparison of measured samples and experimental conditions using the same test device[11].

3. Experiment

3.1 Experimental Factors and Level

To find the influence of concrete fluidity on pumping pressure, compressive strength and flow test values of concrete were set as experimental factors for the mixing condition, and pumping speed and pumping elapsed time were set as factors for the pumping condition. Specifically, as it is expected that the changes in the amount of chemical admixture and binder used have the biggest influence on the concrete viscosity, 4 levels of concrete compressive strength (40MPa, 60MPa, 80MPa and 100MPa) were determined with each strength level having several target slump values. In the case of 40MPa, 210mm slump and 600mm of target slump level, in case of 60MPa, 500, 600, and 700mm of target slump level and in case of 80, 100MPa, 700mm of target slump level have been determined. Three pumping frequency levels of 5, 10 and 15 times per minute, were selected as the pumping condition. In addition, in sequentially circulating pumping, pumping frequency was set as about 10 times per minute and conducted for 25 minutes.

Table 1. Experimental factors

Factor		Level
Concrete Mix Proportion	Compressive strength (MPa)	40, 60, 80, 100
	Slump (mm) Slump flow (mm)	210, 400, 500, 600, 700
Pumping Condition	Speed level	1, 2, 3
	Continuous pumping time (min)	10, 25

3.2 Materials and Mix Proportion

Tables 2~4 show the physical properties of the materials used. In addition, as indicated in Table 5, AE Water reducing admixtures were used. Different kinds and amounts of admixture were used in accordance with expected concrete strength and target flow value. As Table 5 shows, the totals of 7 concrete mix designs were classified based on target strength. The evaluation of the difference in slump and flow is only adapted for a 60 MPa concrete mix design.

Table 2. Physical properties of cement and admixture

		OPC	BFS	FA
Fineness(㎠/g)		3326	4530	3229
Density(g/㎤)		3.14	2.88	2.22
Ignition loss (%)			1.23	3.80
Compressive strength	3day	31.8	-	-
	7day	41.8		
	28day	56.7		

Table 3. Physical properties of aggregate

	Fine aggregate	Coarse Aggregate
Density(g/㎤)	2.60	2.64
Absorption ratio (%)	0.99	0.57
Amount passing through 0.08mm sieve (%)	0.92	0.41
Fineness modulus	2.59	6.64

Table 4. Physical properties of chemical admixture

	Density (g/㎤)	pH	Viscosity (Pa·s)	Solid Content (%)	Application mix
AD1	1.05	6.01	57.4	23.2	40MPa (Slump 210)
AD2	1.05	6.08	58.1	22.4	40MPa (Flow 600)
AD3	1.04	6.27	48.5	19.5	60MPa
AD4	1.06	6.11	67.0	24.2	80MPa
AD5	1.07	6.10	96.0	30.0	100MPa

Table 5. Mix proportion of concrete

Strength (flow)	W/C	S/a	Mix proportion(kg/m^3)							AD (%)
			W	OPC	BFS	FA	SF	S	G	
40(210)	35.6	46.5	160	315	90	45		793	920	0.85
40(600)	35.1	45.5	165	329	94	47	-	762	920	1.05
60(500)	26.6	44.5	165	434	124	62	-	687	864	1.05
60(600)	26.6	44.5	165	434	124	62	-	687	864	1.20
60(700)	26.6	44.5	165	434	124	62	-	687	864	1.35
80(700)	22.0	43.5	165	503	188	-	60	618	809	2.20
100(700)	19.1	43.0	165	553	225	-	86	564	754	2.50

3.3 Experiment Methods

3.3.1 Physical Properties of Fresh Concrete

This is an experiment to determine the changes in characteristics of fresh concrete before and after pumping. An evaluation before pumping was conducted was made right after mixing in the batch plant. The evaluation for after pumping was conducted after mixing for 25minute in the mixing truck and continuous pumping for first 10minutes continuously. Furthermore, in order to compare changes in properties of concrete caused by pumping, a test on the physical property was also conducted on the fresh concrete that was in the container for an hour without pumping.

Figure 2. Consistency test of fresh concrete

3.3.2 Evaluation of Rheology Characteristic

As Figure 3 indicates, the Brookfield company' s DV-III Rheometer is used in the concrete Rheology characteristic test. The mortar used in the test was taken from the concrete before and after pumping by extracting coarse aggregate by sieving. Shear stress and shear rate was calculated by torque of spindle which was measured by gradually increasing the spindle rotational speed in a sequence of 50, 100, 200, 250rpm and then decreasing [12,13].

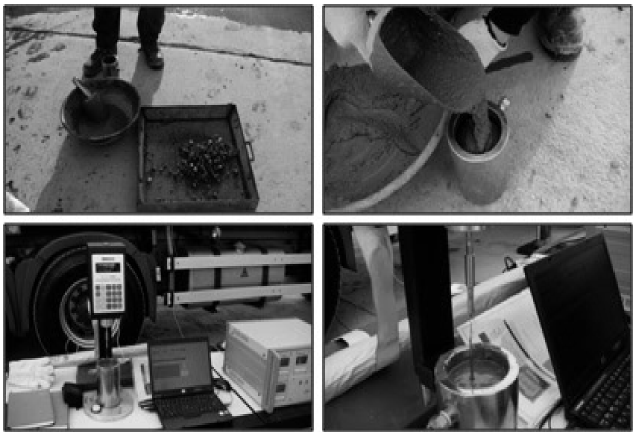

Figure 3. Rheology test for mortar separated from concrete

3.3.3 Pumping and Pressure Measurement

In the pumping test, a pipe for high-pressure pumping with 125mm diameter was used and a short-length pumping system was consisted of 38m straight pipe in length and a 4m 90-degree bent pipe. As shown in Figure 4, the short-length pumping system is operated by making repeat pumping cycles of concrete inserted into the hopper of the concrete pump and then concrete is circulated in the repeat pumping system. Pumping pressure was measured by main pressure of pump cylinder and pressure sensor located at 3m (P1), 6.6m (P2), 39m (P3) respectively. The pressure sensor is a steel diaphragm type as shown in Figure 5, and pressure value is measured when concrete inside a pipe pressurizing pressure tap on the sense. The electronic signal measured from the sensor was converted by data acquisition system and saved simultaneously in the database.

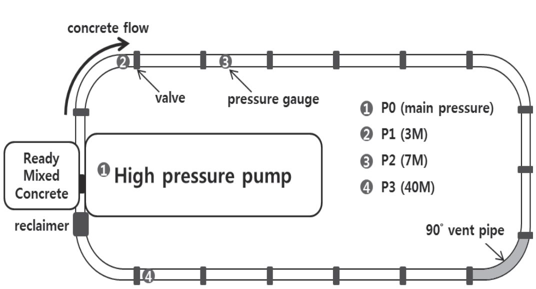

Figure 4. Set-up for pumping test

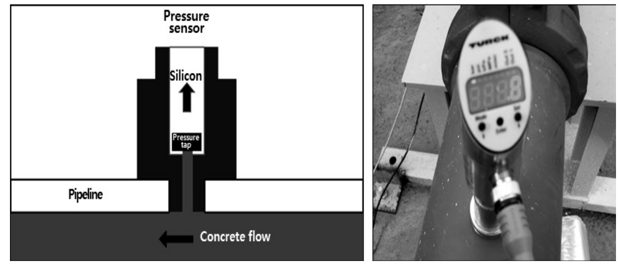

Figure 5. Pressure sensor

4. Experiment Results and Analysis

4.1 Change of Properties before/after Pumping

Table 6 indicates the amount of time required to reach 500mm of slump flow and L type flow before and after pumping classified by mix. It is generally known that there is a tendency for decreasing consistency characteristics of slump flow and L type flow as viscosity of concrete after pumping decreases compared to before pumping. In this experiment, as shown in Figure 6, there was a similar tendency with the existing studies in the test result of slump flow and L type flow[3]. In most concrete mix conditions, test values after pumping showed a tendency to decrease. It had the same result in the test after on hour without pumping. On the other hand, visual degree of segregation was much severe because of the reduction of viscosity after pumping. Therefore, to obtain construction quality of high-strength and high fluidity concrete after pumping, review and prediction in advance before pumping is required.

Table 6. Results of flow arrivals

Concrete Mix	Slump Flow 500㎜ Arrivals		L-Flow 500㎜ Arrivals	
	Before Pumping	After Pumping	Before Pumping	After Pumping
20-40-600	8.8	6.8	8.6	7.3
20-60-500	9.2	6.4	6.1	5.8
20-60-600	5	5.2	6.1	3.3
20-60-700	5.2	4	4.6	2
20-80-700	6.3	4.5	4.8	2.7
20-100-700	13.8	4.9	13	5.6

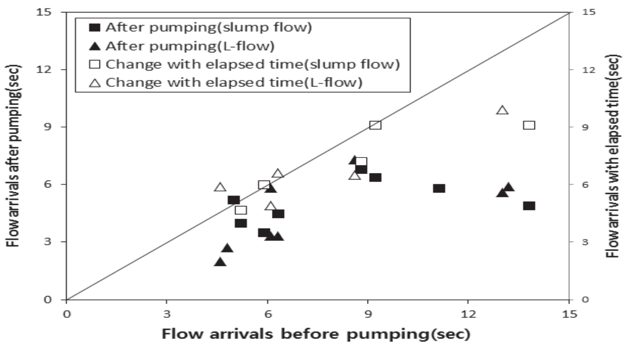

Figure 6. Flow arrivals according to pumping and elapsed time

4.2 Rheology Characteristics of Mortar

Figure 7 shows the test results of plastic viscosity and yield stress of mortar according to concrete mixing conditions. Generally, the higher strength concrete, shows a higher rate of plastic viscosity and yield stress and in the case of 60MPa which has the same compressive strength, the higher slump flow shows a lower value of plastic viscosity and yield stress. On the other hand, in 40 MPa mix conditions, plastic viscosity and yield stress of slump flow 600mm increased much more than at slump flow 210mm as the result of using a different kind of admixture to satiate the target slump flow. As a result of measuring rheology characteristics of mortar before/after pumping and one hour after without pumping, Figure 8, 9 shows the general tendency of decrease in plastic viscosity and yield stress after pumping. According to the existing research, this is caused by a structural change between the pastes by internal pressure and friction when pumping of concrete occurs and this change causes viscosity degradation[6].

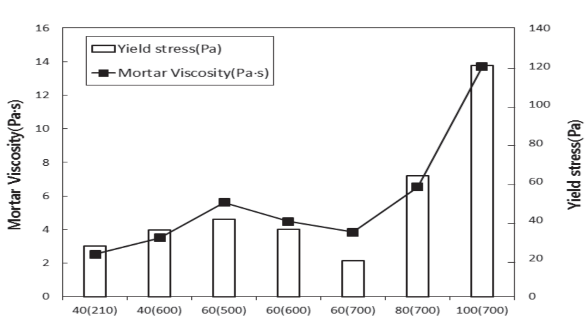

Figure 7. Rheology characteristics according to mix condition

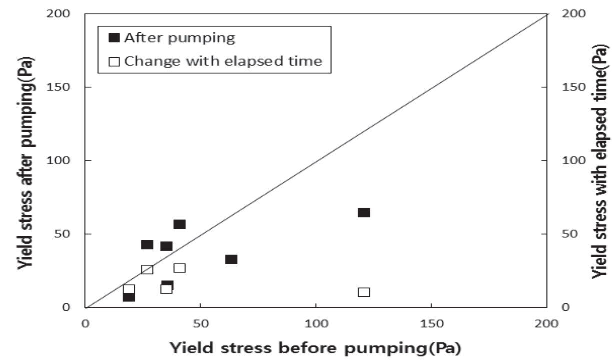

Figure 8. Yield stress according to pumping and elapsed time

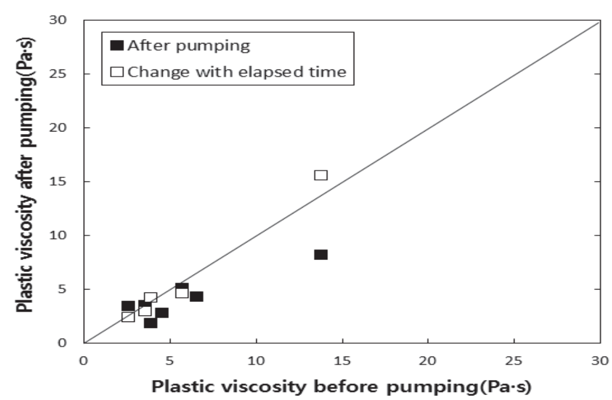

Figure 9. Plastic viscosity according to pumping and elapsed time

4.3 Concrete Compressive Strength Experiment

Figure 10 indicates the experiment results for concrete compressive strength before/after pumping. On 28 days, the measurement of concrete compressive strength before/after pumping exceeded designed compressive strength, and the rate of compressive strength after pumping was 5～10% higher which meant there was no problem with compressive strength. There was variation on the rate of compressive strength before/after pumping, but generally, the result after pumping was 3～5% higher, which means that internal concrete unit quantity of water was decreased by pumping, and consolidation effected by pumping pressure which caused the elaboration of internal organization[14].

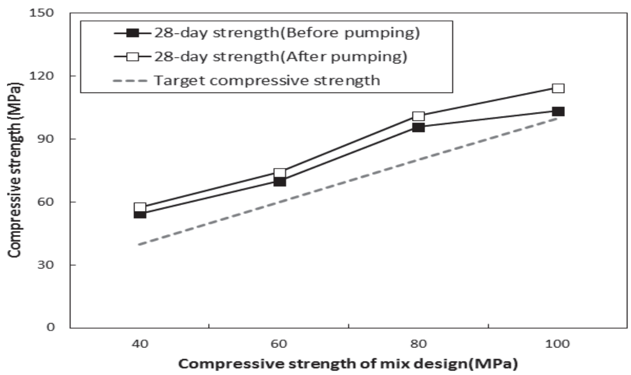

Figure 10. Concrete compressive strength due to the pumping

4.4 Characteristics of Pumping Pressure in Pipe

Table 7 shows main pressure, average stroke time of pump cylinder and pumping frequency per hour with mix condition of concrete and pumping condition. Moreover, Figure 11 shows the result of positional pressure measurement in the case of different pumping speeds and repeated continuous pumping. In this figure, per elapsed time, pressure change tendency of 3 level pumping speeds from left, and continuous pumping can be known. The positional pressure means the average value of the highest pressure measured by every stroke, and stroke time is the average time per one time pumping by measuring the time for 15~20 pumping which means the time from the start of one pulsation to the next pulsation.

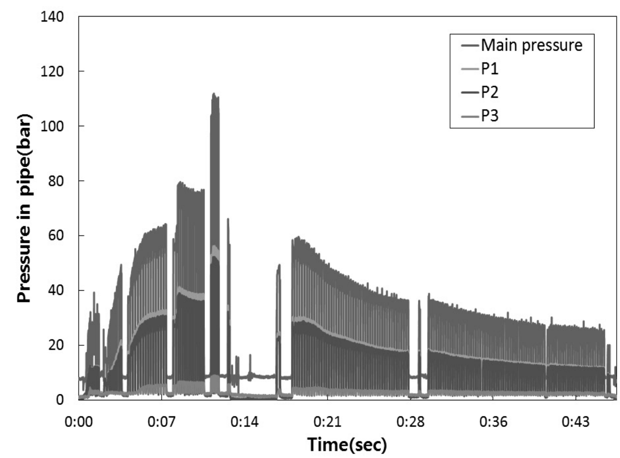

Figure 11. Results of inner pipe pressure by each pumping method

4.4.1 Change Pressure by Mixing Condition

Figure 12 indicates the result of the positional pumping pressure measurement with compressive strength in case of continuous pumping. Generally, the higher level of strength showed higher pumping

Table 7. Results of continuous pumping system test

Mix proportion of concrete	Pumping method	Average of maximum pressure (bar)				Stroke time (sec)	Number of discharge/hour	ΔP/L (Pa/cm)
		Main pressure	P1	P2	P3			
20-40-600	Level1	17.84	3.78	3.74	2.08	13.42	268.26	52
	Level2	66.11	16.21	14.96	3.71	5.69	632.69	379
	Level3	109.50	26.30	24.42	5.51	3.42	1052.63	630
	Rotation1	54.27	13.84	12.85	2.70	6.14	586.32	338
	Rotation2	49.30	12.47	11.35	2.39	6.33	568.72	305
20-60-700	Level1	54.50	16.80	15.63	4.43	7.53	478.09	375
	Level2	74.83	22.20	20.84	5.51	5.94	606.06	506
	Level3	47.49	14.42	13.68	3.77	8.97	401.34	323
	Rotation1	39.52	12.24	11.77	2.99	9.76	368.85	280
	Rotation2	28.60	8.15	7.96	2.38	7.03	512.09	175
20-80-700	Level1	56.34	18.02	16.84	3.23	10.88	330.88	448
	Level2	73.01	23.73	22.25	4.66	9.10	395.60	578
	Level3	76.59	24.54	23.72	3.17	7.60	473.68	648
	Rotation1	47.27	15.99	15.33	3.50	13.66	263.54	379
	Rotation2	33.78	11.42	11.06	2.67	12.79	281.47	265
20-100-700	Level1	54.58	27.21	25.05	4.28	13.09	275.02	695
	Level2	62.89	32.18	29.95	5.77	12.09	297.77	800
	Level3	96.77	48.69	45.30	7.88	8.48	424.53	1237
	Rotation1	65.18	33.62	31.47	4.97	11.29	318.87	868
	Rotation2	37.24	18.21	17.21	3.46	11.00	327.27	447

pressure because viscosity of concrete goes higher and high pressure is required in case of pumping according to the lower ratio of water-cement and increase of volume of powder.

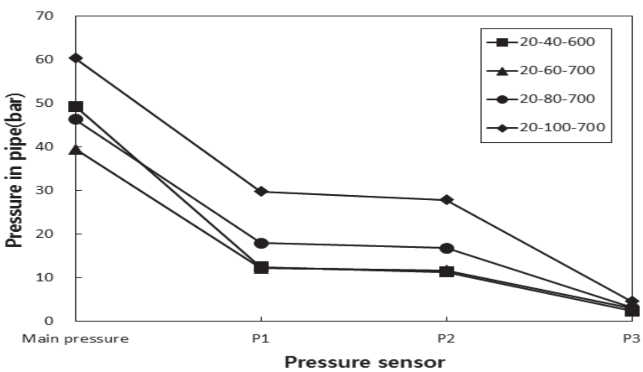

Figure 12. Pressure of inner pipeline at each pressure sensor

4.4.2 Change Pressure by Pumping Condition

Figure 13 is the graph showing pressure loss change according to the pumping speed which shows the volume of pumping per hour in the horizontal pipe. According to the speed increase, in every mixing condition, pressure loss (or pressure gradient) per unit length increased, and when the level of strength increased, the pressure loss per unit length also increased.

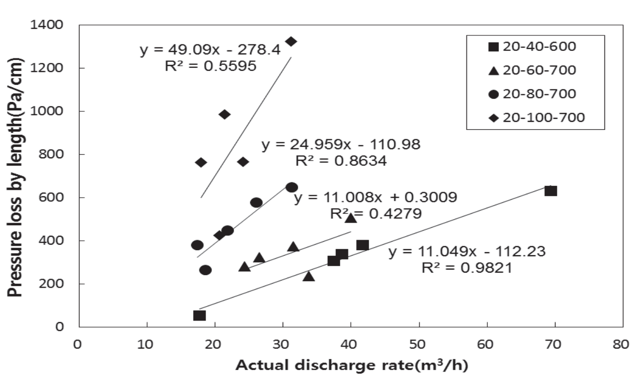

Figure 13. Relation between pressure loss and actual discharge rate

4.4.3 Corelation between Rheology and Pressure

Figures 14 and 15 represent the relationship between yield stress and plastic viscosity and pressure loss per unit length of mortar. Generally, when the measurement results increases, pressure loss also increases; this shows a high correlation which means there is a direct relationship between frictional resistance which occurs in the movement of concrete with high yield stress and plastic viscosity subjected to pressure in the pipe.

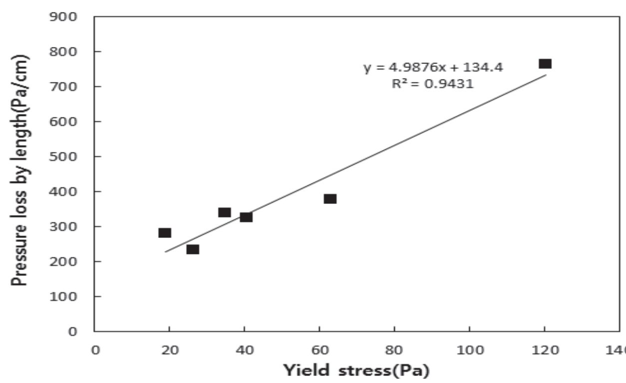

Figure 14. Pressure loss per pipe length by mortar yield stress

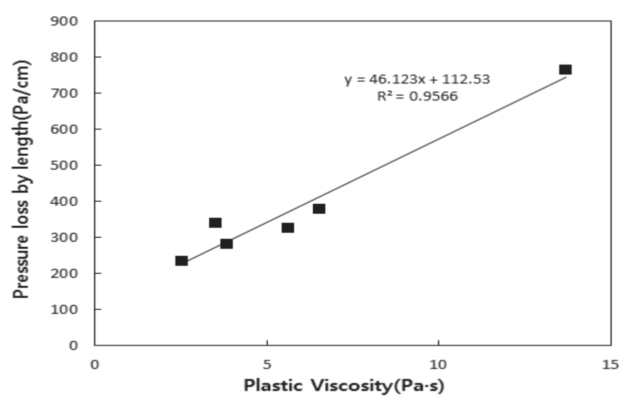

Figure 15. Pressure loss per pipe length by mortar viscosity

5. Conclusion

Through the continuous study on the characteristics of inner pipe pressure and rheology properties of high-strength and high-fluidity concrete utilizing continuous pumping, it is concluded that:

1) The consistency characteristics of fresh concrete such as slump flow and L frame flow tests tended to decrease before and after pumping. Because of

the reduction of viscosity, the time reaching 500mm seems to be reduced after pumping. Therefore, the possibility of concrete segregation will be increased when pouring concrete into the form.

2) Yield stress and plastic viscosity, which is a rheology indicator of mortar, increased with higher concrete strength and it seemed to be reduced generally after pumping.
3) The research represents that when a higher strength of concrete was used, main pressure increased. Moreover, with increased pumping speed, the inner pipe pressure loss increased and when high strength concrete was used, the loss of inner pipe pressure increased because of the increase of viscosity in high-strength concrete.
4) There was a very high correlation between loss of inner pipe pressure and the rheology characteristic. Therefore, it can be said that there is a direct relationship between yield stress and plastic viscosity.

Acknowledgement

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