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Experimental Observation on Variation of Rheological Properties during Concrete Pumping

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Abstract

Workability of concrete varies during pumping. Even though concrete satisfies the required workability before pumping, it often does not satisfy the required standard after pumping. Moreover, serious problem could happen such as segregation and blockage. In this study, the rheological properties of concrete change during pumping from the pressure distribution over the pipe length was investigated. The rheological properties and the pressures measured from seven different real-scale pumping tests with 116 m to 1000 m long pipelines and 24 MPa to 100 MPa concrete were analyzed. As a result, it was found that the rheological properties vary gradually along the pipeline, and could abruptly change inside the pump. The variation of rheological properties during pumping seems to be attributed in part to the increase of water absorption in aggregates under high pressure and the additional mixing effect, namely, intensive shearing under high pressure inside pump.

Keywords: concrete pumping, rheological property, pressure, shearing, workability

1 Introduction

The workability and rheological properties of concrete are changed during pumping (Choi et al. 2016a; Feys et al. 2016; Ko et al. 2008, 2010; Kwon et al. 2013; Kwon et al. 2016; Secrieru et al. 2018). The rheological properties of concrete generally change gradually over time, but the changes in rheological properties due to pumping are very large in comparison. Especially, in the case of a large construction such as a high-rise building, the pressure and shearing due to pumping are so significant that the change of the rheological properties is also great. Even satisfying the quality control standard before pumping (i.e. slump or slump flow), workability after pumping may significantly change and often does not satisfy the standard. Moreover, Pipe blockages or segregation could occur during pumping.

As for the causes of changes in rheological properties during pumping, the following hypotheses has been presented: (1) more dispersion of coagulated cement particles due to shear and normal stress induced by pipe flow and pumping pressure (Ouchi and Sakue 2008; Sugamata et al. 2000), (2) thixotropy of plug zone or no-shearing zone in pipe flow of pumped concrete (Alekseev 1952; Kaplan et al. 2005a, b; Tanigawa et al. 1991; Tattersall and Banfill 1983; Watanabe et al. 2007), (3) temperature rise due to friction between concrete and internal surface of pipe (Beitzel and Beitzel 2008; Ji and Seo 2006; Petit et al. 2008), (4) increase in water absorption of aggregates under high pressure (Choi et al. 2016b; Ko et al. 2010), (5) changes in molecular chain structure of chemical admixture (Ko et al. 2008), and (6) decrease in air content (Du and Folliard 2005; Dyer 1991; Hover 1989; Vosahlik et al. 2018). However, the hypotheses are still insufficient to explain all the phenomena observed in the real pumping.

The previous studies (Feys et al. 2016; Ko et al. 2008, 2010; Kwon et al. 2013; Secrieru et al. 2018) have reported on change in slump (or slump flow) and rheological properties before and after pumping. However, there have not

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yet been any reports on how these changes occur during pumping (i.e. do the changes occur gradually the pipe length or do they occur rapidly in the front part of the pipeline near the pump).

In this paper, the test data such as rheological properties, pressure distributions over pipeline, slump or slump flow, temperature, and air content were collected from seven real-scale pumping tests, which were performed with the pipeline lengths of 116 m to 1000 m and the concrete of 24 MPa to 100 MPa. An analysis for the test data was conducted to explain the observed change before and after pumping and to investigate how the rheological properties vary along the pipe length. Discussion was also made for the mechanism of the variation in rheological properties due to pumping.

2 Experimental Program

2.1 General

To observe the changes in rheological properties of concrete during pumping, the test data were collected from seven real-scale pumping tests. The three of them were performed previously (Choi et al. 2014; Choi 2013; Jang et al. 2018; Jang 2018; Kim et al. 2018; Kwon et al. 2013; Park et al. 2010), and the other four tests are newly introduced in this study.

Table 1 is a list of the seven real-scale pumping tests. In the first column of Table 1, T1 to T7 designates the pumping tests, and S24 to S100 refer to the concrete strength. T2-S80HV and T2-S80LV respectively designate high viscosity and low viscosity versions of the concrete with the same strength of 80 MPa. In the test T6, four different pipe lengths from 200 to 1000 m were used. The names of L200, L400, L600, and L1000 refer to the respective pipe lengths of 200 m, 400 m, 600 m, and 1000 m. The items measured in the tests include the pipe pressure and the rheological properties of concrete, slump, slump flow, temperature, and air content before and after pumping.

The test T7 (548 m) was designed to observe the changes in rheological properties caused by a high-pressure pump (Kwon et al. 2013; Park et al. 2010). At a position 3.6 m far from the pump, the pipe was disassembled, and the concrete was extracted to measure the rheological properties and compare them to the rheological properties before pumping.

2.2 Materials

The total 15 different mixtures used in the pumping test, and their design strengths range from 24 to 100 MPa. The 24 MPa, 27 MPa, and 30 MPa normal-strength concretes have a slump range of 150 mm to 240 mm. The 50 MPa, 60 MPa, 80 MPa, and 100 MPa high-strength concretes have a slump flow range of 600 mm to 700 mm. Table 2 shows the mix proportions of concrete used in the T1, T2, T3, and T5 pumping tests. Coarse aggregates with a maximum size of 25 mm were used for the all concrete mixtures. OPC (Ordinary

Table 1 Test program.

Designation of test	Testing year and site	Pipe length (m)	Design strength (MPa)	Measurement items
T1-S60	2018 Myongji Univ. South Korea	116	60	Pipe pressure Slump or slump flow Rheological property Temperature Air content
T2-S60 T2-S80HV T2-S80LV T2-S100	2017 Eumseong South Korea	389	60 80 80 100	
T3-S24	2017 Eumseong South Korea	514	24	
T4-S24 T4-S27 T4-S30 T4-S80	2016 Myongji Univ. South Korea	337	24 27 30 80	
T5-S100	2016 Eumseong South Korea	540	100	
T6-L200-S50 T6-L400-S50 T6-L600-S50 T6-L1000-S50	2012 Mokpo South Korea	200 400 600 1000	50	
T7-S30 T7-S50 T7-S80	2010 Yongin South Korea	548 (3.6 m discharge)	30 50 80	

Table 2 Mix proportions of concrete for pumping tests.

Mix.	W/B (%)	S/a (%)	Unit weight (kg/m^3)							AD1 (%B)	AD2 (%B)
			W	OPC	SP*	SF	FA	S	G		
T1-S60	24.3	45.1	160	526	132	–	–	688	858	1.2	–
T2-S60	29.0	45.0	179	419	185	12.0	–	698	863	1.2	–
T2-S80HV	22.0	40.0	172	507	234	39.0	–	569	863	2.0	–
T2-S80LV	22.0	40.0	172	507	234	39.0	–	569	863	–	1.3
T2-S100	19.9	38.0	167	521	252	67.0	–	522	861	2.5	–
T3-S24	52.2	49.4	175	218	67.0	–	50.0	870	909	0.6	–
T5-S100	22.0	45.0	160	545	–	109	73.0	662	861	1.1	–

*SP** slag powder.

Portland Cement) with a specific gravity of 3.15 was used for cement. Slag powder, silica fume, and fly ash, with specific gravity of 2.90, 2.20, and 2.23, respectively, were used as mineral admixtures. As for the chemical admixture, a polycarboxylate high-range water-reducing admixture (HRWRA) was used. HRWRA for low viscosity concrete was used for the T2-S80LV mixture. The mix proportions of concrete used in tests T4, T6, and T7 can be found in the existing literatures (Choi et al. 2014; Choi 2013; Jang et al. 2018; Jang 2018; Kim et al. 2018; Kwon et al. 2013; Park et al. 2010).

2.3 Pumping Circuit

Figure 1 shows the installation of pipelines for the pumping tests T1, T2, T3, and T5. The location of the pressure sensors are also shown in Fig. 1. The diameter of the pipes used in the pumping tests was 127 mm (5 in.). A large-capacity piston pump with a maximum pressure of 250 bar was used in all the tests.

2.4 Test Method

As shown in Table 1, the test items included slump, slump flow, rheological properties, temperature, and air content. The slump and slump flow test were carried out in accordance with ASTM C143 (ASTM 2015). The rheological properties of concrete were measured using a portable rheometer (Kim et al. 2018). The temperature was measured by immersing the thermometer directly in the concrete. The air content test was carried out in accordance with ASTM C173 (ASTM 2016). The pressure inside the pipe was monitored in real time using the pre-installed pressure sensors.

3 Test Results and Analysis on Changes in Rheological Properties During Pumping

3.1 Test Results

3.1.1 Slump and Slump Flow

Table 3 shows the test data measured before and after pumping. Figures 2, 3, 4, 5 show diagrams of the results for each test item. In Table 3 and Figs. 2, 3, 4, 5, the "−1" and "−2" behind the test names designate the order of the ready-mixed concrete truck. In the T2-S100 test, the rheological properties could not be measured due to concrete segregation after pumping. In the T5-S100-2 test, the rheological properties could not be measured after pumping because a pipe blockage occurred.

Figure 2 shows the slump and slump flow. In the case of normal-strength concrete, the slump decreased after pumping except the case T3-S24. In the cases of T4-S24-1 and T4-S24-2, the workability was almost maintained during pumping, slump reductions of 5 mm and 10 mm, respectively. The slump of T4-S30 was 50 mm after pumping that is 64% lower than the slump of 140 mm before pumping, resulting in very poor workability. T3-S24's slump increased by 33% from 150 mm before pumping to 200 mm after pumping. 5 out of the 14 high-strength concretes experienced an increase in slump flow after pumping. In one of these, T2-S100, the slump flow increased from 700 mm before pumping to 805 mm after pumping, but segregation was observed. T2-S80LV-1 experienced about 24% increase in slump flow from 485 mm before pumping to 600 mm after pumping. In the test T6, which performed pumping tests with pipe lengths from 200 to 1000 m, the slump flow was significantly reduced in all mixtures. The slump flow of all concrete mixtures used in test T6 was measured to greater than 550 mm before pumping, but decreased to less than 250 mm after pumping and performance of self-consolidating concrete was lost.

In T7-S30, T7-S50, and T7-S80, which collected the concrete from a position 3.6 m from the pump during the experiments and tested it, the slump and slump flow both tended to increase. This can be seen as proof that the rheological properties of concrete can be changed by the pump itself.

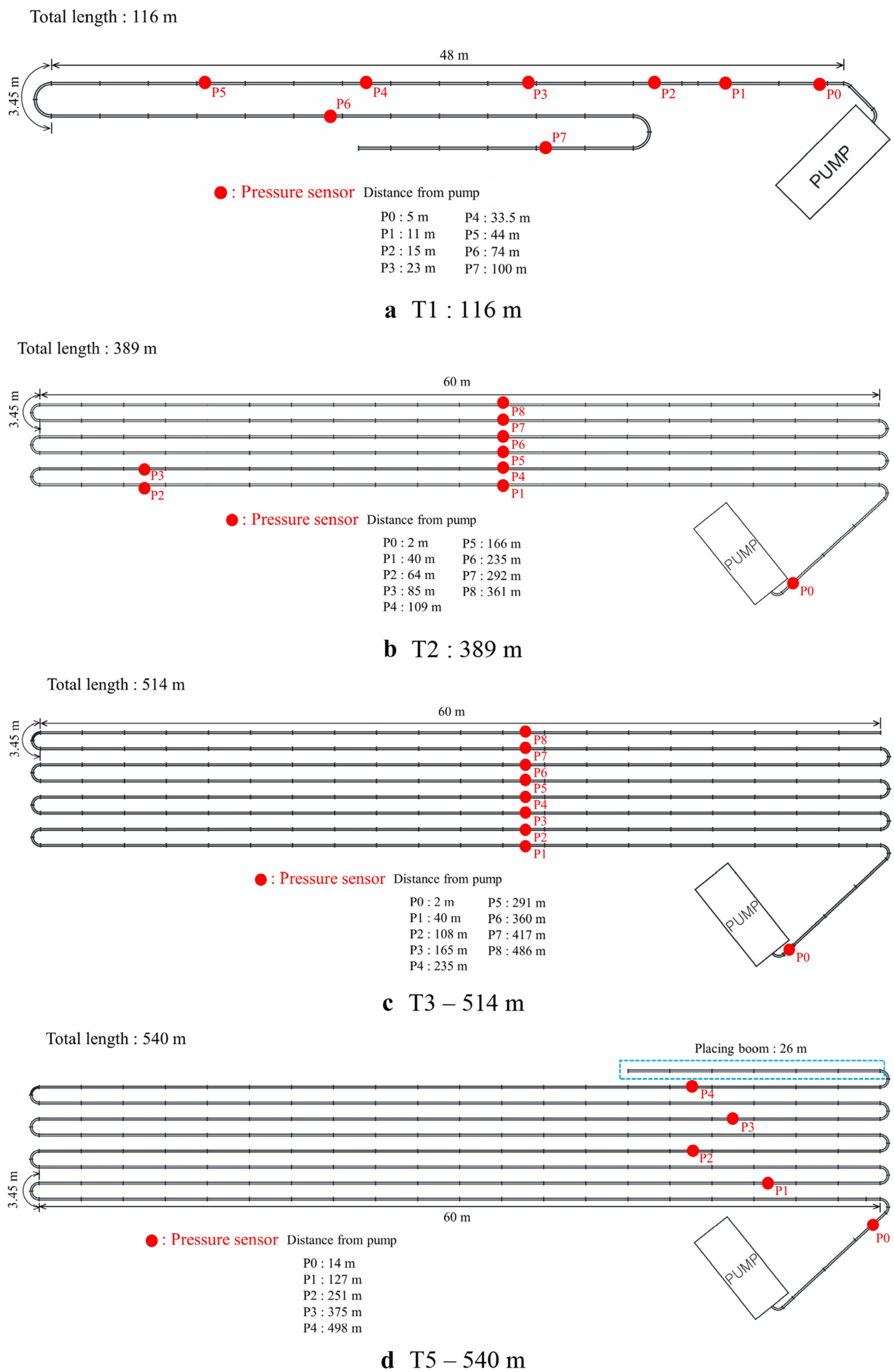

Fig. 1 Pipeline used in full-scale pumping tests.

Table 3 Measurements before and after pumping in the real-scale pumping tests.

Designation of test	Slump or slump flow (mm)		Viscosity (Pa s)		Yield stress (Pa)		Air content (%)		Temperature (°C)	
	Before	After	Before	After	Before	After	Before	After	Before	After
T1-S60-1	590	500	122	68.1	0.1	78.5	2.3	8.0	24.8	26.2
T1-S60-2	500	540	68.1	38.9	78.5	86.5	8.0	9.0	26.2	28.1
T2-S60	605	535	162	44.8	15.3	92.8	4.3	5.3	20.2	20.1
T2-S80HV	610	700	117	31.7	0.1	46.5	3.0	–	21.9	22.3
T2-S80LV-1	485	600	73.9	41.9	96.0	28.4	3.3	2.5	20.8	22.5
T2-S80LV-2	600	500	41.9	37.3	28.4	92.7	2.5	3.0	22.5	22.8
T2-S100	700	805	142	–	0.1	–	2.9	–	20.2	18.6
T3-S24	150	200	105	4.0	274	379	4.5	2.6	22.3	22.0
T4-S24-1	235	230	63.3	31.6	89.8	215	6.4	3.5	18.3	20.8
T4-S24-2	245	235	46.9	31.4	126	105	5.0	3.8	18.2	20.8
T4-S27	230	190	78.7	26.9	61.0	515	6.0	–	18.2	23.1
T4-S30	140	50	83.8	116	505	1361	5.0	4.5	19.1	25.3
T4-S80	585	440	63.5	18.3	20.6	203	–	–	16.8	11.2
T5-S100-1	695	730	229	132	0.1	0.1	1.3	1.8	19.7	23.0
T5-S100-2	680	–	371	–	0.1	–	2.4	–	19.9	–
T6-L200-S50	620	205	134	70.5	0.1	351	8.8	9.5	24.5	26.9
T6-L400-S50	580	190	208	61.1	0.1	848	2.2	7.2	20.1	25.8
T6-L600-S50	680	205	105	78.4	0.1	422	3.4	–	20.3	27.2
T6-L1000-S50	670	240	112	40.3	0.1	248	2.9	3.9	23.9	25.2
T7-S30	190	220	50.5	35.8	413	425	4.8	3.1	15.1	16.4
T7-S50	540	590	57.8	40.6	43.5	32.2	3.9	3.2	18.0	18.0
T7-S80	480	590	72.9	56.9	65.6	10.6	1.8	1.4	21.7	20.4

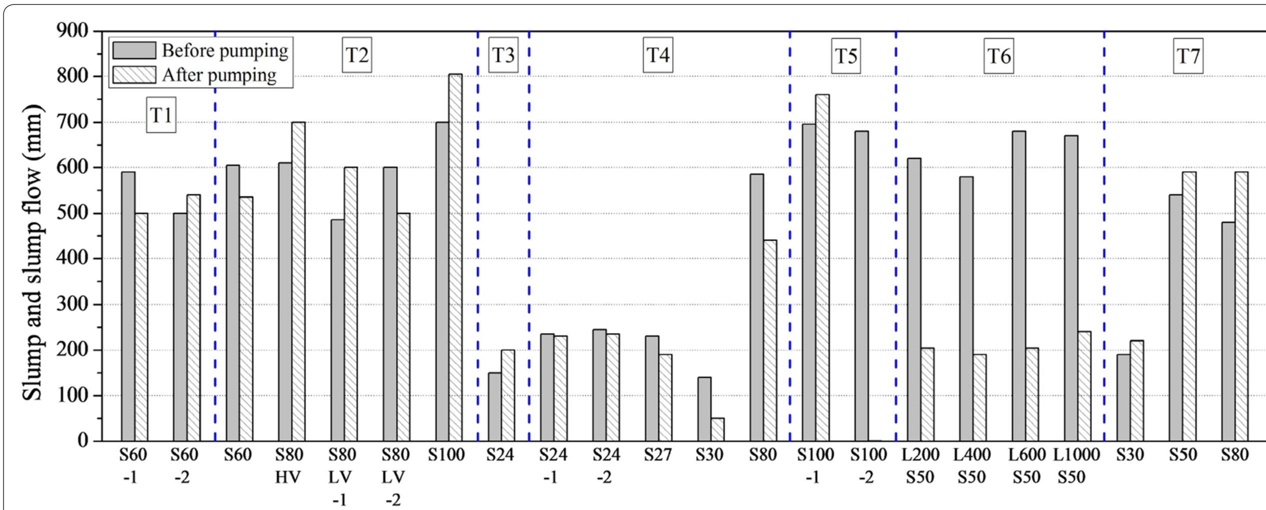

Fig. 2 Results of slump and slump flow from the real-scale pumping tests.

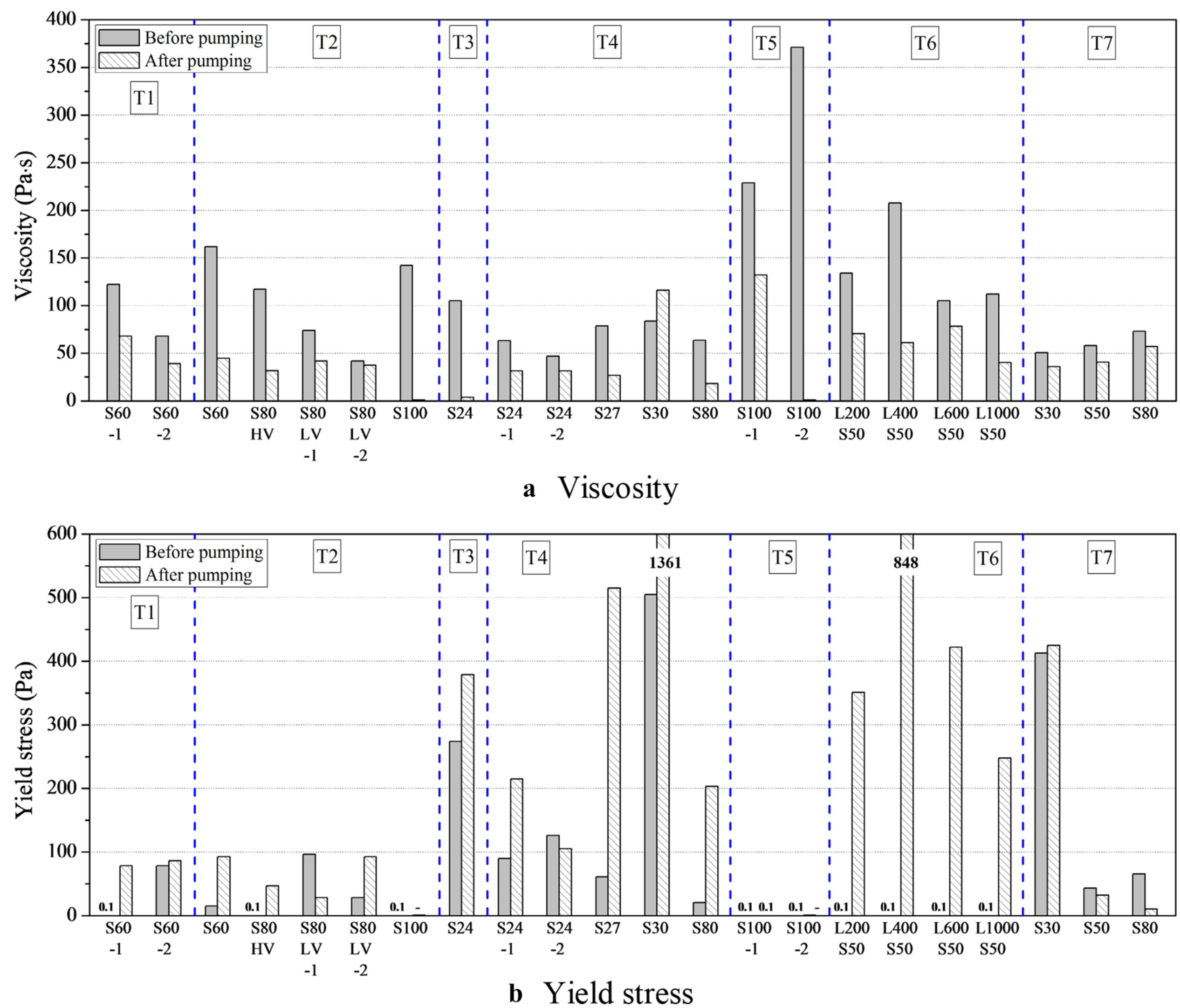

Fig. 3 Results of rheological property from the real-scale pumping tests.

3.1.2 Rheological Properties

Figure 3 shows the measurements on the concrete viscosity and yield stress. There was a general trend in which most viscosity decreased and most yield stress increased after pumping. There were cases like T2-S80LV-1 and T4-S24-2 in which the viscosity and yield stress decreased together, as well as a case like T4-S30, in which the viscosity and yield stress increased together. Of all the pumping tests, there was only one case where the viscosity increased, making it a very rare phenomenon. The T2-S80-LV-1 mixture, in which the viscosity and yield stress both decreased, experienced an increase in slump flow after pumping, while the T4-S24-2 mixture showed almost no change in slump before and after pumping. As for the T4-S30 mixture, in which the concrete viscosity and yield stress both increased, the slump results were 140 mm before pumping and 50 mm after pumping, and the workability became very poor. The T4-S30's yield stress was 505 Pa before pumping and 1361 Pa after pumping, increasing by around 856 Pa. The overall range of viscosity reduction was from around 11 to 97%. The range in the yield stress increase was from around 8 Pa to 856 Pa.

In test T7, the viscosity and yield stress both tended to decrease. However, in the case of the T7-S30 mixture, the yield stress was 413 Pa before pumping and 425 Pa directly after passing through the pump, meaning it stayed almost constant.

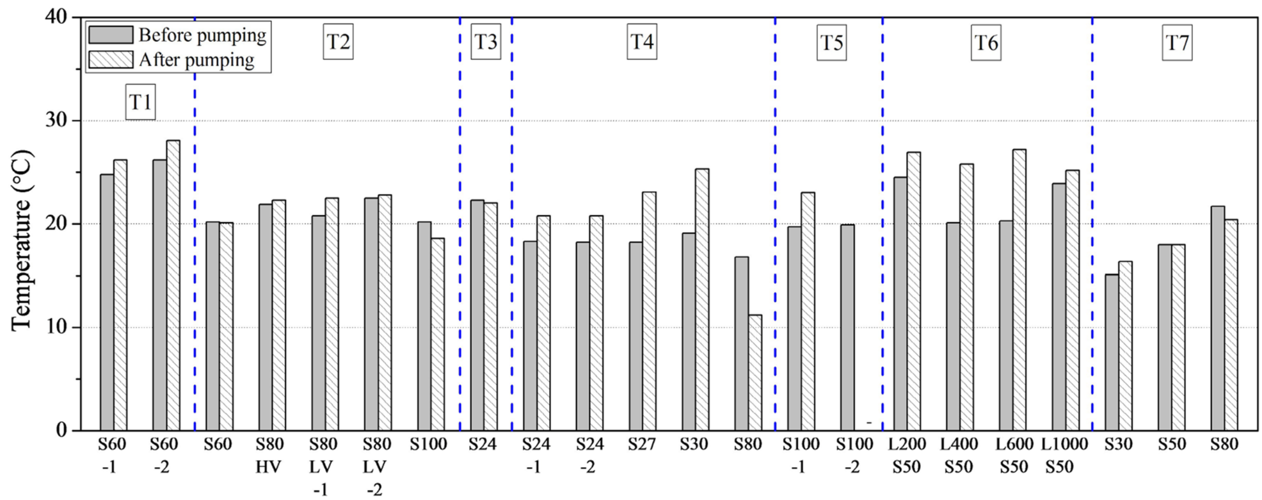

Fig. 4 Results of temperature from the real-scale pumping tests.

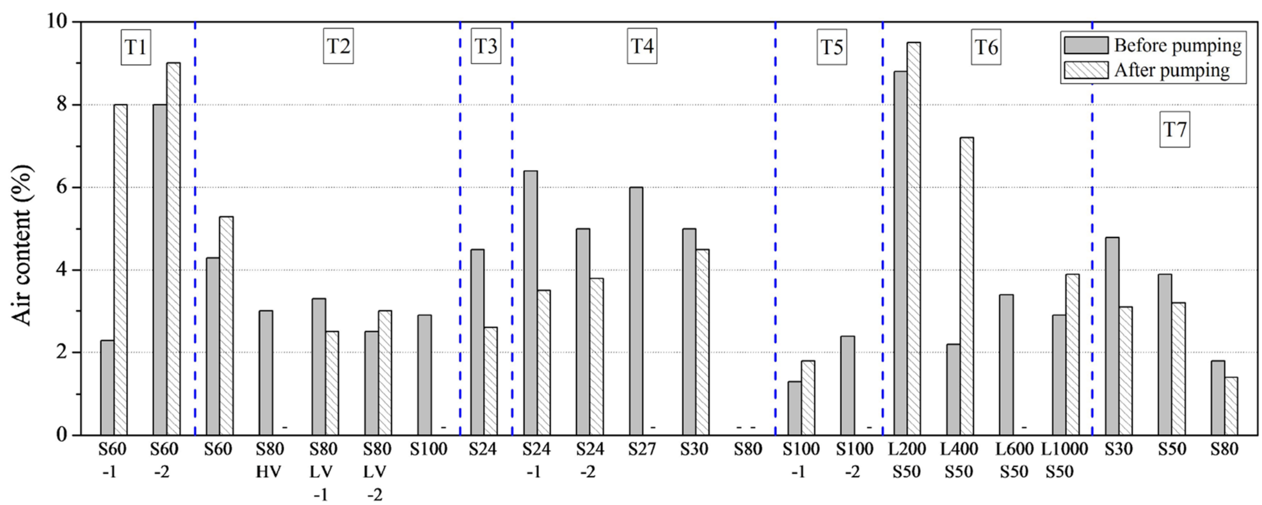

Fig. 5 Results of air content from the real-scale pumping tests.

3.1.3 Temperature

As shown in Fig. 4, the temperatures tended to rise after pumping. The range of temperature increase after pumping was from 0.3 to 6.9 °C. For some mixtures, there were also cases where the temperature decreased. In particular, T4-S80 experienced a decrease of 5.6 °C, going from 16.8 °C before pumping to 11.2 °C after pumping. This is considered to be an effect of the outdoor air temperature in the winter.

3.1.4 Air Content

Figure 5 shows the air content of the concrete measured in before and after pumping. There was no consistent trend for variation of air content. In the T1, T2, T5, and T6 tests, the air content tended to increase after pumping. In the T3 and T4 tests, the air content tended to decrease after pumping. In the T7 test, the air content decreased in all cases.

3.2 Analysis on Changes in Rheological Properties During Pumping

According to research on pumping predictions by Jang et al. (2018) and Kwon et al. (2013), when rheological properties of the slip-layer and the inner concrete are kept at constant levels during pumping, the pressure distribution over the pipe length decreases linearly. According to the results of the parametric studies conducted in the previous studies (Jang et al. 2018; Kim et al. 2018), the viscosity of slip-layer has the greatest effect in pumping. Therefore, if when the rheological properties of slip-layer are kept at a constant level and the rheological properties of inner concrete change, linearity of the pressure distribution over the pipe length is expected to be maintained without change. However, if the rheological properties of the inner concrete and the slip-layer change simultaneously, the pressure distribution over the pipe length occurs non-linearly.

Figure 6 shows the pressure distribution and the pressure gradient over the pipe length. It can be divided into cases where the pressure distribution over the pipe length decreases linearly according to changes in the rheological properties during pumping, and cases where it decreases nonlinearly.

This paper aims to analyze data on pressure within the pipe that is measured by performing pumping tests in order to understand how the rheological properties of concrete change. First, the 19 mixtures that the pumping tests were performed on were divided into cases where the pressure gradient over the pipe length remained almost constant, cases where it decreased, and cases where it increased. As shown in Table 4, of the 19 mixtures, there were 9 cases where the pressure gradient over the pipe length stayed almost constant, 8 where it decreased, and 2 where it increased.

Figure 7 shows the pressure distribution and pressure gradient measured in T6-L600-S50 which is a case where the pressure decreased linearly over the pipe length. There was a difference in the magnitude of the pressure gradient in each test, but overall it remained almost constant. As it can be seen in Tables 3 and 4, in case of the pressure gradient over the pipe length remained almost constant, the change of rheological properties shows a general tendency: decrease in viscosity and yield stress, slump loss. As was reported in a previous study (Jang et al. 2018; Kwon et al. 2013), it can be seen that the rheological properties of the slip layer remain constant, and the rheological properties of the inner concrete change in such a case.

Table 4 Classification of pressure gradient change over the pipe length.

Pressure gradient	Test
Constant	T2-S80LV-2 T3-S24 T4-S24-1 T4-S24-2 T4-S27 T4-S80 T6-L200-S50 T6-L400-S50 T6-L600-S50
Decrease	T1-S60-1 T1-S60-2 T2-S60 T2-S80HV T2-S80LV-1 T2-S100 T5-S100-1 T6-L1000-S50
Increase	T4-S30 T5-S100-2 (blockage)

Figures 8, 9 shows the test results for cases where the pressure gradient over the pipe length decreased. In the T1 and T2 tests, the pressure gradient decreased rapidly until around 1/4 of the overall pipe length, and afterward there was almost no change in the gradient (Fig. 8b and d). This means that the rheological properties of concrete changed quickly in the front part of the pipeline near the pump, and afterward they changed gradually. In the case of T5-S100 and T6-L1000-S50, the pressure

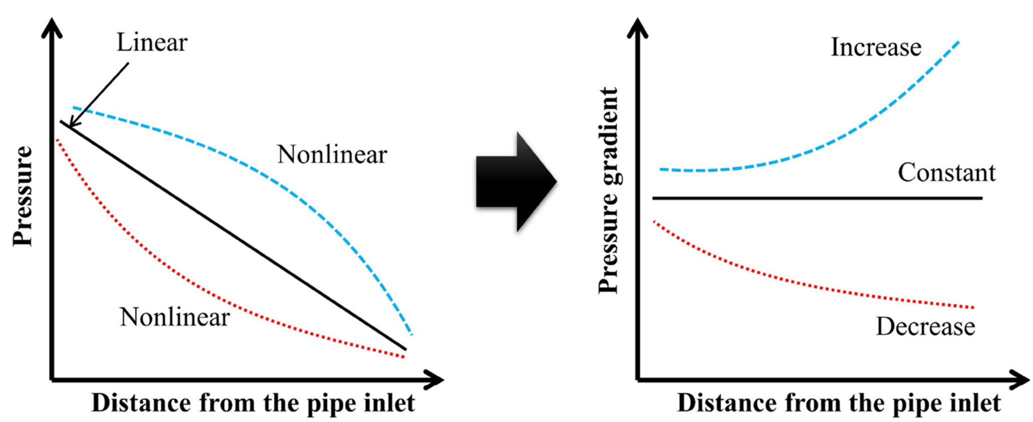

Fig. 6 Relationship between the pressure and the pressure gradient over the pipe length.

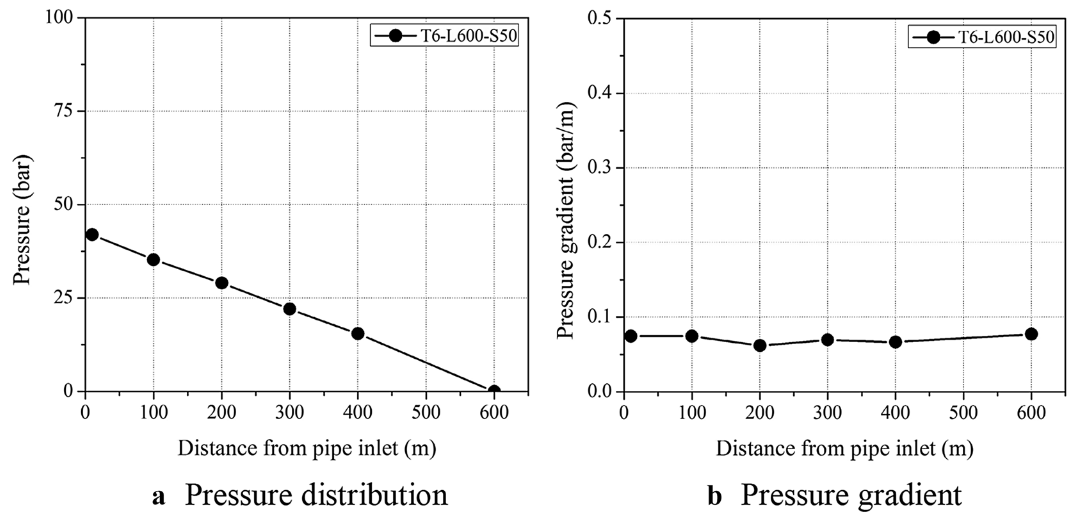

Fig. 7 Results of pressure and pressure gradient over the pipe length—constant slope.

gradient gradually decreased over the pipe length. In these cases, the rheological properties of the concrete in the pumping process are expected to change gradually. As can be seen in Table 3, when the pressure gradient decreased, the viscosity tends to decrease, and the yield stress tends to increase, in most cases. However, cases like T2-S80LV-1 and T5-S100-1 where the yield stress decreased or did not change were also confirmed. From the test results on the pressure gradient and the slump flow, it can be seen that all of the cases where the workability improved (i.e. when the slump flow increased after pumping), belonged among the cases where the pressure gradient decreased. For the T2-S100 test where segregation after pumping occurred, it was found that the pressure gradient decreased by about four times from 0.43 to 0.1 (Fig. 8d). The rheological properties of concrete could not be measured due to segregation, but considering the decrease in pressure gradient, it is expected that the decrease in viscosity was fairly large.

Figure 10 shows the test results for T4-S30, which is a case in which the pressure gradient increased over the pipe length. It was confirmed that the pressure gradient increased after the middle part of the overall pipe length. From the results on the rheological properties of the concrete in T4-S30, it can be seen that the viscosity and yield stress both increased after pumping (Table 3). Among all the pumping tests, T4-S30 is the only case where the concrete viscosity increased.

Figure 11 shows the test results for T5-S100-2, which is a case where pipe blockage occurred during pumping. From Fig. 11b, which shows the changes in pressure gradient over the pipe length, it can be seen that there were almost no changes in pressure gradient, and then there was abruptly increased at around 400 m position. The rheological properties of concrete discharged after pumping could not be measured, but it is considered to be due to the change of rheological properties during pumping. The slump flow before pumping was very large at 680 mm, and even though there was a decrease in slump flow during pumping (an increase in yield stress), it was not enough to cause blockage. Rather, there seems to be a high possibility of blockage due to segregation caused by the rapid decrease in viscosity (increase in slump flow). The results of opening the blocked part of the pipe and observing the state of the concrete showed that almost only cement paste was escaping from the outlet direction pipe (Fig. 11c).

4 Discussion on the Variation in Rheological Properties Due to Pumping

4.1 Slump Loss

According to the test results from the existing researches (Feys et al. 2016; Ko et al. 2008, 2010; Secrieru et al. 2018) and this study, the slump and slump flow generally tended to decrease after pumping. As the hypotheses on the cause of slump loss during pumping, a decrease in the effective amount of superplasticizer due to more dispersion of coagulated cement particles (Ouchi and Sakue 2008; Sugamata et al. 2000), thixotropy of plug flow (Alekseev 1952; Kaplan et al. 2005a, b; Tanigawa et al. 1991; Tattersall and Banfill 1983; Watanabe et al. 2007), temperature rise due to friction (Beitzel and Beitzel 2008; Ji and Seo 2006; Petit et al. 2008), increase in the water absorption of aggregate under high pressure (ko et al. 2010; Choi et al. 2016b), changes in the molecular chain structure of superplasticizer (Ko et al. 2008),

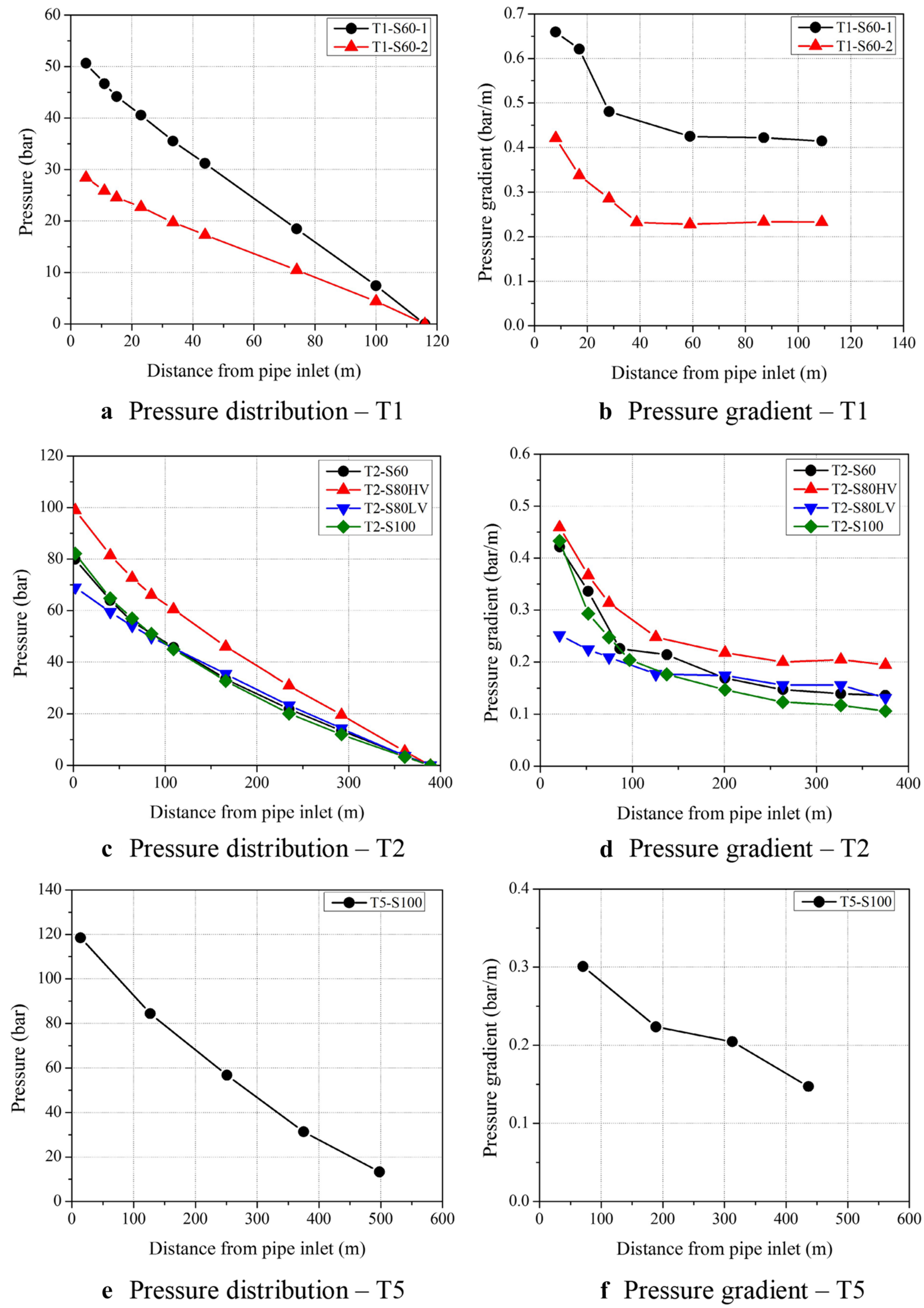

Fig. 8 Results of pressure and pressure gradient over the pipe length—decrease slope.

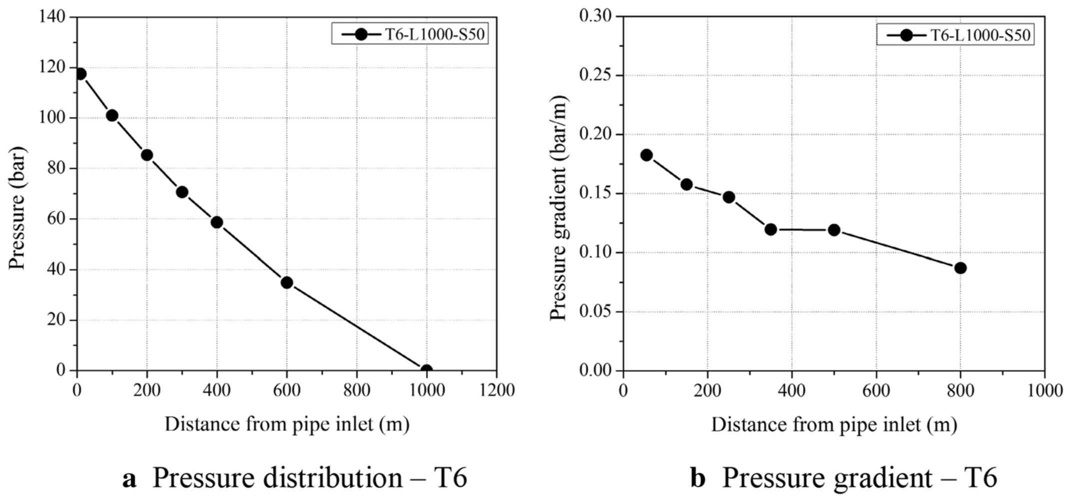

Fig. 9 Results of pressure and pressure gradient over the pipe length—decrease slope.

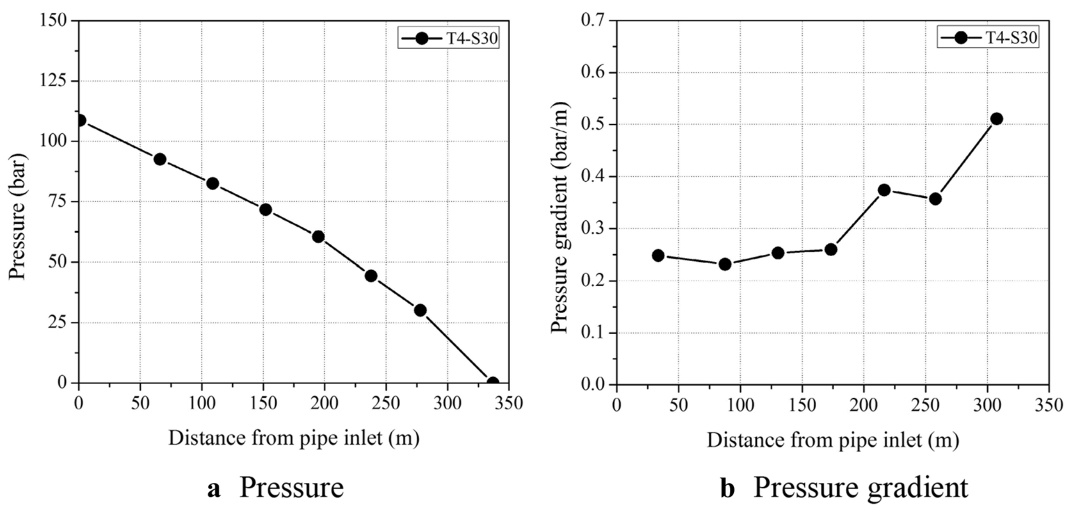

Fig. 10 Results of pressure and pressure gradient over the pipe length—increase slope.

and decrease in air content (Du and Folliard 2005; Dyer 1991; Hover 1989; Vosahlik et al. 2018), were presented. Of these, the hypothesis that there is a decrease in the effective amount of superplasticizer faces conflicting results from other researchers (Kim et al. 2017; Yim et al. 2016) and requires more detailed verification. The thixotropy of plug flow can explain the decrease in workability associated with time delays in concrete at rest. However, the changes in concrete slump after pumping are greater than the changes due to time delays, so the entire decrease in workability cannot be explained by thixotropy of plug flow alone. The increase of concrete temperature after pumping was verified through the pumping test. However, despite the increase in temperature, the concrete viscosity has decreased in almost all mixtures, and even in the slump and yield stress measurement results, the effect of the temperature increase is considered to be slight. The change of molecular chain structure of superplasticizer due to decreasing the steric hindrance effect (Victoria et al. 2016) can explain the decrease in workability. However, segregation has occurred at actual high-rise building sites where not only the viscosity but also the yield stress were reduced when high-strength concrete pumping was performed using large quantities of superplasticizer, and this contradicts the hypothesis. Additional verification of the hypothesis is needed. The

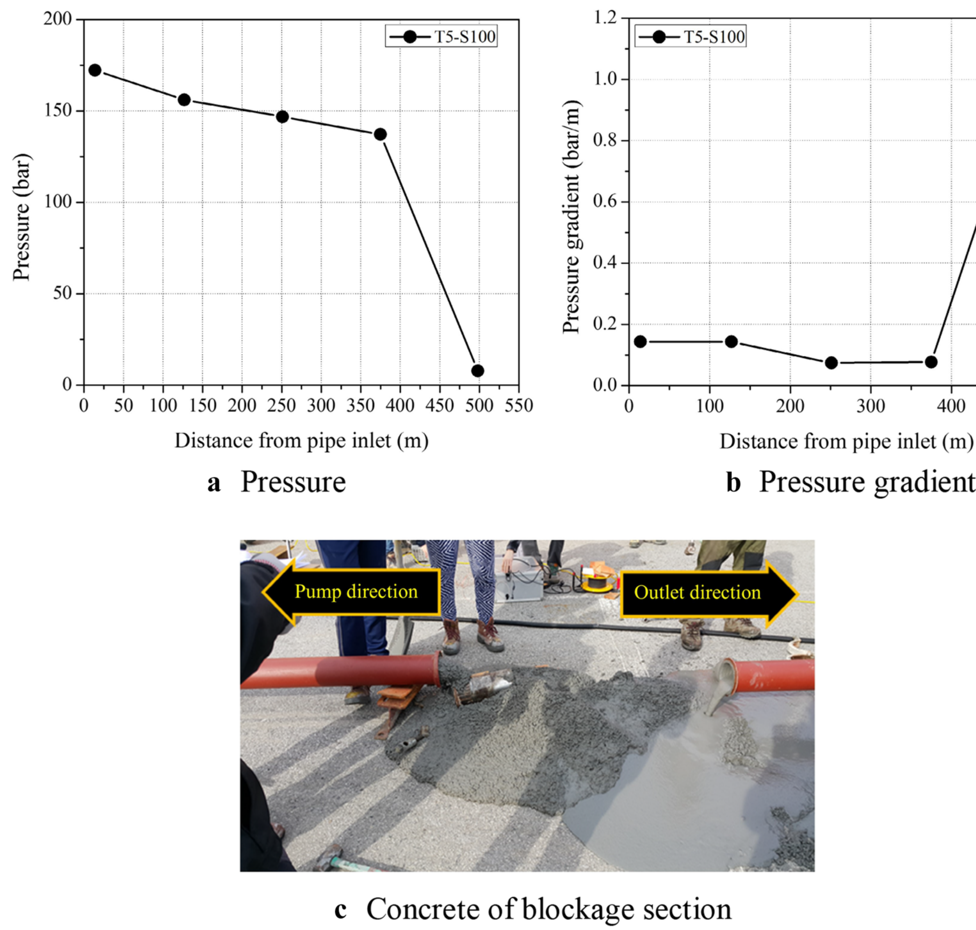

Fig. 11 Results of pressure and pressure gradient over the pipe length—blockage.

air content measurement results before and after pumping did not show clear trends of increasing or decreasing at each test. The decrease in air content has an effect on the decrease in workability, but when the test results performed in this study are considered, the decrease in concrete workability during pumping was not found to be greatly affected by air content.

The tests performed in this study did not measure changes in unit water content or the water absorption ratio of coarse aggregate before and after pumping. However, according to the results with previous studies (Choi et al. 2016b; Ko et al. 2010), it is considered that aggregate absorbs water additionally by high pressure. In the results of previous study (Choi et al. 2016b) on the water absorption ratio of coarse aggregate before and after pressurization, the absorption ratio increased in all cases (Fig. 12). In the results of the previous tests which measured the unit water content of concrete before and after pumping

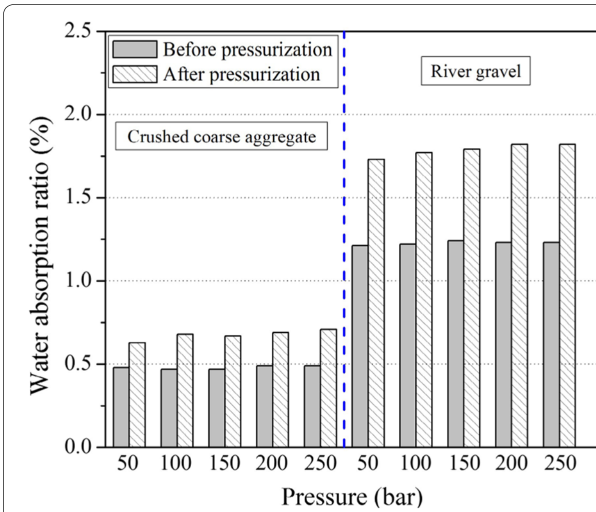

Fig. 12 Results of water absorption ratio before and after pressurization (Choi et al. 2016b).

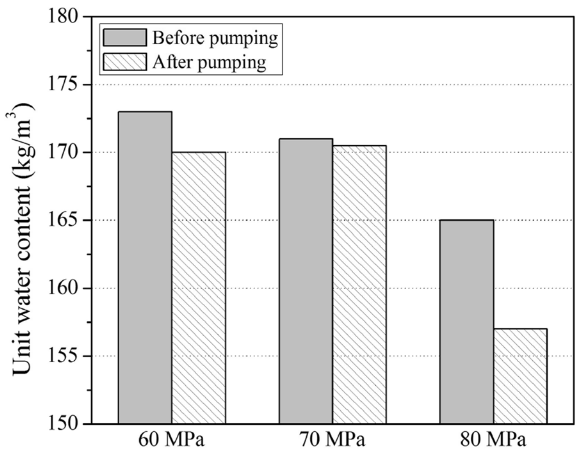

Fig. 13 Results of unit water before and after pumping (Ko et al. 2010).

(Ko et al. 2010), the unit water content tended to decrease after pumping in all cases (Fig. 13). Therefore, considering the test results for other factors such as temperature and air content, etc., it is considered that the increase in the water absorption ratio of aggregate is the factor with the greatest possibility of affecting changes in the rheological properties of concrete. In order to minimize the slump loss of the concrete after pumping, the moisture state of the aggregate must be managed well, and the aggregate is used as a surface dry saturated condition.

4.2 Reduction in Segregation Resistance

When segregation resistance of concrete reduces, the viscosity and yield stress both decrease after pumping, and this mainly occurs in high-strength concrete which uses a large amount of binder and chemical admixture. In such cases, workability can be improved, but it is a very dangerous situation for pumping because there is a possibility of segregation. In the results of the pumping tests performed in this study on 19 types of concrete, there were 5 cases where slump flow increased after pumping: T1-S60-2, T2-S80HV, T2-S80LV-1, T2-S100, and T5-S100-1. Of these, T2-S100 actually experienced segregation and the rheological properties could not be measured.

According to the test results in existing studies (Kim et al. 2017; Yim et al. 2016), yield stress decreases when cement paste was experiencing pressure and shearing. The decrease in yield stress of cement paste under pressure and shearing is especially large when chemical admixture is used. A pump can be seen as a kind of strong mixer. High-pressure pumps that are often used in concrete pumping operate at a maximum pressure of 250 bar and a minimum stroke time of 2.5 s. Due to the operation of the pump, high pressure and shearing are generated in the hydraulic cylinder. Therefore, when high-strength concrete which uses a large amount of binder and chemical admixture is experienced high pressure inside the pump and during pumping, segregation resistance could reduce caused by the further mixing effect or additional activation of the chemical admixture.

In the case of high-strength concrete, the superplasticizer may be used excessively to obtain a target slump flow within a limited mixing time and mixing intensity. In such cases, the superplasticizer may be in an insufficiently mixed state when the concrete is transported to the site. During transport to the site, the concrete is further mixed, and if excessive superplasticizer are activated due to the additional mixing caused by the high pressure inside the pump and during pumping, a situation can occur where the yield stress and viscosity both decrease. To prevent segregation of concrete during pumping, it is important to ensure sufficient mixing time and mixing intensity to activate the dispersion of superplasticizer when manufacturing the concrete.

4.3 Gradual Variation of Rheological Property Along Pipe Line

The research results reported up to this point have only included results from before and after pumping (Feys et al. 2016; Ko et al. 2008, 2010; Kwon et al. 2013; Secrieru et al. 2018), and it was not possible to understand changes that occurred during pumping. Figures 7, 8, 9, 10 indicate the variation of the pressure gradient over the pipe length, which shows the variation patterns of rheological properties of concrete during pumping. The cases where the pressure gradient almost did not change, decreased, and increased were all appeared. In the total of 19 test results, the cases where there was almost no change in the pressure gradient were the most numerous at 9, while there were 8 cases where it decreased and 2 cases where it increased. It was found that the pressure gradient is gradually changed along the length of the pipeline in most cases. As such, it seems that generally rheological property of concrete was changed gradually along the length of the pipeline. The study also observed that the pressure gradient largely changed in the front part of the pipeline near the pump in some cases. In the cases, rheological properties of concrete could also change greatly in the front part of the pipeline near the pump.

4.4 Abrupt Variation of Rheological Property Due to Pump

In this study, concrete was collected from a location 3.6 m from the pump and its rheological properties were measured in order to understand how rheological properties change when concrete experiences sudden pressure and shearing inside the pump. Looking at the rheological properties and slump test results from T7-S30, T7-S50, and T7-S80 (in Table 3, Figs. 2 and 3), it was found that the rheological properties of concrete changed due to pressure and shearing inside the pump. In all three cases in the T7 test, the slump and the slump flow increased, and the viscosity decreased. The yield stress increased slightly from 413 to 425 Pa in T7-S30, and it decreased in both T7-S50 and T7-S80. As mentioned in Sects. 4.1 and 4.2, these test results show that the water absorption ratio of aggregates and the mixing effect caused by high pressure and shearing inside the pump can change the rheological properties of concrete.

4.5 Increase in Viscosity After Pumping

In the previous pumping test results (Kwon et al. 2013; Secrieru et al. 2018) and the results from pumping tests performed in this study, the viscosity decreased after pumping in most cases, but a very rare case was also observed in which the viscosity clearly increased, as in T4-S30. Looking at T4-S30's changes in pressure and the pressure gradient in Fig. 10, the pressure gradient gradually increased over the pipe length. However, there is still no hypothesis to explain this phenomenon.

According to the existing study (Han and Ferron 2015), the viscosity of cement paste can increase due to very high mixing intensity and additional mixing time. These results completely contradict the viscosity of cement paste change in the study by Williams et al. (1999). The maximum mixing intensities used in the studies by Han and Ferron (2015) and Williams et al. (1999) were 12,000 rpm and 2500 rpm, respectively. Therefore, it seems that the change in the viscosity of cement paste varies according to the level of mixing intensity. As mentioned previously, the pump can perform the role of a kind of powerful mixer. When the concrete momentarily experiences very high mixing intensity, there is a possibility that a phenomenon will occur in which the viscosity increase, as in the results of the previous study (Han and Ferron 2015). However, this is currently just assumption, and more research on this matter is needed.

5 Conclusion

The following conclusions were obtained from this study.

1. The pressure gradient over the pipe length is related to the change in the rheological properties of the concrete during pumping. The rheological properties of concrete generally change gradually along the pipeline. In most cases viscosity decreases and yield stress increases after pumping. It was also observed that the pressure gradient largely changed in the front part of the pipeline near the pump in some cases. In the cases, rheological properties of concrete could also change greatly in the front part of the pipeline near the pump.
2. The rheological properties of concrete change due to pump itself. The pump can perform the role of a kind of powerful mixer. If the concrete experiences sudden pressure and shearing inside the pump, its rheological properties can change due to the additional mixing. The rheological properties of concrete can also change due to the increase in the water absorption ratio of coarse aggregate caused by the high pressure of pump.
3. The increase in the water absorption of aggregates under high pressure seems to be a definite cause of slump loss due to pumping. In order to minimize the slump loss of the concrete after pumping, the moisture state of the aggregate must be managed well, and the aggregate should be used as a surface dry saturated condition.
4. This study observed a reduction in segregation resistance (an increase in slump and slump flow and a decrease in viscosity and yield stress) during pumping. This phenomenon mainly occurred in high-strength concrete which uses a large amount of binder and chemical admixture. This could be caused by mixing effect due to pump, that is, additional activation of the chemical admixture under high pressure and intensive shearing inside pump.

This study was based on results observed from real-scale pumping tests. In the near future, it needs to perform additional research which precisely examines mechanisms for the variation of workability due to pumping.

Authors' Contributions

KP, MS, YJ, CK and SH performed pumping tests, and analyzed the experimental data. SP was a contributor to analyzing the data and discussion on the mechanism. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Availability of Data and Materials
The datasets supporting the conclusions of this article are included within the article.

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