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**Effect of Ultrasound on the Formation of a Lubrication Layer in Concrete Pumping**

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**Abstract**

When concrete is being pumped through a pipe, a lubrication layer is formed at the interface between the concrete and pipe, which plays a dominant role in determining the pumpability. In the present study, a method to improve the properties of the lubrication layer was suggested by imposing ultrasound on the pipe. To examine the effects of ultrasound on the formation of lubrication layer, three different intensities of ultrasonic energy were applied while conducting 170 m long full scale pumping tests. When ultrasound was applied, the lubrication layer thickness increased, which led to a decrease in pumping pressure. Therefore, the application of ultrasound can be an effective method for improving pumpability.

1. Introduction

Concrete pumping is one of the most extensively used techniques for transporting concrete because pumping enables a significant increase in the speed of delivery and allows access to difficult to reach places. Recently, its use has continued to grow due to the increased demand for super structures, such as high rise buildings and super tall structures. On the other hand, regarding the actual condition of the construction for large scale structures, it is still a challenge to transport concrete by pumping because of the limited capacity of existing pumps and the inadequate technological solutions to enhance the pumpability by altering the concrete mix. Therefore, the development of methods for accomplishing improved pumpability is one of the crucial issues for the concrete industry.

Several studies have reported that the dominant factor that facilitates concrete pumping is the lubrication layer formed at the interface between the concrete and the pipe wall (Alekseev 1952; Morinaga 1973; Browne et al. 1977; Ede 1957; Chailmo et al. 1989; Tanigawa et al. 1991; Weber 1968; Sakuta et al. 1989; Jacobsen et al. 2009; Kaplan et al. 2005; Feys et al. 2009; Kwon et al. 2013a; Kwon et al. 2013b; Choi et al. 2013a, 2013b). Since Alekseev (1952) first suggested the existence of this layer, there have been numerous attempts to estimate its properties. Morinaga (1973) reported that the pumping of concrete would not be possible without the formation of a lubricating layer. Sakuta et al. (1989) showed that only the properties that matter in concrete pumping are those related to the ability of the material to form a lubricating layer. Kaplan et al. (2005) also stated that the lubrication layer is a major factor in facilitating concrete pumping, because the layer has significantly lower viscosity and yield stress than concrete. Feys et al. (2009) mentioned two relevant issues on the prediction of flow in a pipe; one of which is the role of the lubrication layer. Kwon et al. (2013a, 2013b) derived a relation between the properties of the lubrication layer measured using a tribometer and the flow rates in concrete pumping. Choi et al. (2013a, 2013b) measured the velocity in the lubrication layer directly to predict the concrete pumping performance using an Ultrasonic Velocity Profiler (UVP). As summarized briefly herein, most studies on concrete pumping have focused on evaluating the lubrication layer to estimate the concrete pumpability. The results suggest that the technique by manipulating and controlling the properties of the lubrication layer would be a promising method to improve the concrete pumpability. As a potentially feasible method, in present study, an ultrasonic treatment of the lubrication layer by introducing ultrasound to the pipe was performed while concrete was being pumped through the pipe.

Several studies (Judina et al. 2013; Shin et al. 2015; Pelters et al. 2009; Azevedo et al. 2012; Towler et al. 2003) have indicated that ultrasound can increase the fluidity, accelerate the hydration reaction and increase the compressive strength of cementitious materials. Shin et al. (2015) used ultrasonic energy incorporating 20 kHz frequency and 1,500 W energy to examine the physical properties of cement grout and reported that ultrasound enhanced significantly the compressive strength and flowability of grout, and reduced the viscosity of grout. Peters et al. (2009) investigated the workability of cement paste with ultrasound incorporating power ultrasound up to 1 GHz and 10,000 W energy.

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and noted that ultrasound reduced the air voids and maximum pore size and increased the fluidity and strength. Azevedo et al. (2012) and Towler et al. (2003) conducted the tests incorporating 28 kHz and 25–30 kHZ frequency, respectively and reported that ultrasonic excitation promotes a more homogenous mixture and increases the tensile strength of the cement. Based on these studies, the flowability of cementitious materials could be improved by an ultrasonic treatment, which makes it a possible effective method to improve the pumpability.

The objective of present study is therefore to investigate experimentally the effects of an externally imposed ultrasound on the formation of the lubrication layer and how it influences the performance of concrete pumping. A 170 m long full scale pumping test was performed with three different intensities of ultrasonic energy. A specially designed accessory equipped with ultrasound probes was mounted on the pipe in front of the pump to induce ultrasound. The pressures inside the pipe and the flow rates were measured during concrete pumping. In addition, the velocity profile of the lubrication layer was observed using a special sensor UVP (Choi et al. 2013a, 2013b). Based on the experimental measurements, the effects of ultrasonic energy on the formation of the lubrication layer were analyzed quantitatively.

2. Theoretical aspects of ultrasound

When ultrasound is applied to a liquid, cavitation, which is defined as the phenomena of the formation, growth and subsequent collapse of microbubbles, releasing huge amounts of energy, is produced and induces localized extreme conditions (Pilli et al. 2011). Ultrasound ranging from 20 to 100 kHz is generally used to create cavitation, in which chemical and physical changes are desired (Pilli et al. 2011; Rastogi 2011). Ultrasonic waves consist of a cyclic succession of expansion and compression phases imparted by mechanical vibrations (Pang et al. 2011). The compression cycles exert a positive pressure and push the liquid molecules together, while the expansion cycles exert a negative pressure that pull the molecules apart (Vajnhandl et al. 2005). When pressure amplitude exceeds the tensile strength of a liquid, small vapor-filled voids, called cavitation bubbles, are formed (Chen 2012). Generally, pure liquids possess great tensile strength. Thus, the available ultrasonic generators are unable to produce high enough negative pressures to cause cavitation. On the other hand, most of the liquid is impure and its tensile strength is reduced due to the presence of numerous small particles, such as cement paste. The impurities in liquid represent weak points where the nucleation of cavitation bubbles can occur (Vajnhandl et al. 2005). The resulting cavitation serves as a means of concentrating the diffused sound energy. Once a cavity bubble experiences rapid growth and no longer absorbs the energy efficiently, the liquid will rush in and the cavity will eventually implode (Suslick 1989, 1990). Upon collapse, each bubble will act as a hotspot, generating energy that produces active changes in the structures of the suspension (Suslick 1990). Therefore, these sonophysical effects can help decrease the surface tension, break down particles and macromolecules, desorption, extraction, and more importantly increase fluidity (Chen 2012; Yasuda et al. 2012).

3. Experimental program

3.1 Concrete mixes

The concrete mix with 50 MPa was selected to focus on the effects of the intensities of ultrasonic energy on the formation of lubrication layer. Table 1 lists the mixture proportions. Here, to investigate the effects of ultrasound more clearly, high flowable concrete mixes which represents almost self-compacting concrete were adapted. The cement was CEM I 52.5 N with a specific gravity of 3150 kg/m³. The Class F fly ash with a specific gravity of 2180 kg/m³ and the blast-furnace slag with a specific gravity of 2900 kg/m³ were prepared. The sand was natural river sand with a density of 2590 kg/m³ and a fineness modulus of 2.81. The sand particles ranged in size from 0.08 to 5 mm with a water absorption capacity of 2.43%. The coarse aggregate was a limestone aggregate material with a water absorption capacity of 0.8%, a density of 2610 kg/m³ and the fineness modulus of 6.72. The maximum coarse aggregate size was 20 mm. The amount of mixing water was corrected to consider the water absorbed by the sand and coarse aggregates. A polycarboxylate-based high-range water-reducing admixture (HRWRA), which is marked as % HRWRA, meaning the percentage of admixture relative to the binder content (in weight) was used to obtain target the slump flow.

To carry out the pumping tests in a 170 m long circuit, each concrete mix was produced in a 2 m³ batch and dumped into a 6 m³ mixer and delivered by a ready-mix concrete company. The mixing procedure was as follows. Sand and coarse aggregate materials were mixed for 15 seconds. All other dry components were added over a 15 second period. Water and HRWRA were then added during an additional two minutes of mixing. The total mixing duration was two and half minutes.
3.2 Pumping circuit
A horizontal pumping circuit using lengths of 170 m was installed (Cf. Fig. 1). For the full scale pumping circuit, eight 180º and three 90º bends with a diameter of 0.7 m were set up. The pipe diameter was 125 mm and its thickness was 7.7 mm. The concrete pump was a high pressure piston pump. Table 2 lists the specifications, which can be found in earlier studies (Choi et al. 2013a).

The filling rate of the pump cylinder, which measures the degree of filling in the cylinder per stroke and directly affects the flow rate, was calibrated with 1 m³ reservoirs connected to a linear variable differential transformer (LVDT) and found to be approximately 85% of the filling rate for the pump tested (Choi et al. 2013a, 2013b). The pumping circuit was equipped with 11 pressure gauges to examine the pressure distribution along the entire pipe. Figure 2 shows the detailed locations of the gauges.

3.3 Ultrasonic energy
To determine the effects of the intensities of ultrasonic energy on the formation of the lubrication layer, three different intensities of ultrasonic energy, i.e. 1,000 W, 2,000 W and 3,000 W were selected with a constant 20 kHz frequency, which were determined from previous studies and preliminary tests. To generate such ultrasonic intensities, a specially designed accessory equipped with eight ultrasound probes were mounted at ten locations with 0.5 m intervals on the pipe in front of the pump, as shown in Fig. 3. Under the region of flow rates tested, i.e. from 30 m³/h to 50 m³/h, the distance of concrete movement in the pipe per stroke of the pump was approximately 4.5 m. Therefore, the total installation length of the ultrasound probes, 4.5 m, was determined. Therefore, during a single stroke, the pipe flow could be influenced fully by the ultrasonic energy. One

Table 2 Pump specifications.

<table>
<thead>
<tr>
<th>Item</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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</tr>
<tr>
<td>Flow rate (m³/h)</td>
<td>82*/54**</td>
</tr>
<tr>
<td>Max. pressure (bar)</td>
<td>185*260**</td>
</tr>
<tr>
<td>Engine house (kW)</td>
<td>350</td>
</tr>
<tr>
<td>Stroke/min</td>
<td>26*/17**</td>
</tr>
</tbody>
</table>

* Rod side, ** Piston side

![Fig. 1 Overview of the 170 m long full scale pumping circuit.](image1)

![Fig. 2 Schematic ground plan of the pumping circuits and the location of the pressure gauges for 170 m long full scale circuit. (The values indicate the distance from the beginning of the circuit)](image2)

![Fig. 3 Installment of ultrasonic probes at the front part of the pipe with eight ultrasound probes set at ten locations with 0.5 m interval to generate an ultrasonic energy.](image3)
ultrasound probe, 0.045 m diameter and 0.085 m in height, was operated at a frequency of 20 kHz and at maximum supplied power of 50 W. The ultrasonic waves were generated by an ultrasonic processor (Dongshin Ultrasound, Co. Ltd., DSG-1228). The desired three ultrasonic energies could be adjusted, and harmonized with the conductivity and the speed of the current of the concrete.

3.4 Ultrasonic velocity profiler (UVP)
To investigate the thickness variations of the lubrication layer depending on the induced ultrasonic energies, an ultrasonic velocity profiler (UVP) was used to measure the velocity profile in the pipe. To apply this device to measure the concrete flow in the pipe, stable positioning of the ultrasonic probe (transducer) is essential. The position of the effective ultrasound beam axis was checked by installing a wire across the ultrasound beam, while simultaneously observing the echo from the wire on an oscilloscope. As the maximum amplitude of ultrasound is located on the beam effective axis, this procedure can determine the location of the effective beam axis and obtained 85 degrees. In addition, for application of the UVP using ultrasonic waves, a 1 m transparent engineered plastic pipe with the same diameter as a standard pipe was installed in the last section, as shown in Fig. 4.

When ultrasonic waves propagate in a medium containing coarse particles, such as concrete, the ultrasound pulse hits the particles and part of the ultrasound energy is scattered and lost for the echo measurement. Therefore, the amplitude of echoed ultrasound energy decreases as the measuring depth increases. Although such a limitation does not allow a full velocity profile in the cross section, the measured thickness (around 5 mm) exceeds the expected maximum thickness (around 4 mm) of the lubrication layer and provides valuable information regarding the variations of the thickness depending on ultrasound energy. Table 3 provides details of the specifications of the device and more information about this device, such as its principle of measurement, and some limitations found in previous works (Choi et al. 2013a, 2013b).

4. Results and discussion

4.1 Pressure measurements

Figure 5 shows the pressure variations with time after inducing ultrasonic energy, where the pressures are the averaged values of the 0 m position, which were calculated using a linear extrapolation process with the data from pressure gauges at 11 designated positions. As shown in Fig. 5, after ultrasonic energy was induced in the pipe, the measured pressure decreased gradually for a certain period and then reached a steady state of pressure, i.e. the equilibrium state, which means the effects of an ultrasonic energy were fully reflected in the pipe flow along the pipe. These results show that the effects of an ultrasonic energy on the pipe flow of pumped concrete was detected simultaneously. More importantly, the ultrasonic energy applied was sufficient to influence the properties of pipe flow, particularly for those of the location where the lubrication layer is formed.

When examining the pressure variations depending on the different intensities of ultrasonic energy, as expected, the reduction rates of pressures display a dependence on the ultrasonic energy. The pressures of the

![Table 3 Experimental UVP parameters.](image)

![Fig. 4 Application point of the UVP and transparent engineered plastic.](image)

![Fig. 5 Pressure variations along with time depending on intensities of ultrasonic energy.](image)
equilibrium state after inducing ultrasound had reduction rates of 10%, 15% and 30% corresponding to ultrasonic energies of 1,000 W, 2,000 W and 3,000 W, respectively, compared to the original condition in which ultrasound was not applied. Under the current system, by inducing ultrasonic energy, the pressure required to obtain the targeted flow rate could be reduced by 30%. This significant reduction could make it possible to secure pump use for concrete in the construction of super structures.

The times to reach an equilibrium state were in the range of approximately 6 to 10 minutes after inducing ultrasonic energy and also varied depending on the intensities of ultrasonic energy. As the ultrasonic energy increases, the time taken to reach a steady state decreases, which means it requires more time to fully show the effects of the ultrasonic energy on the pipe flow of pumped concrete when a lower ultrasonic energy is applied.

Figure 6 presents the pressure distributions depending on the intensities of the ultrasonic energy along the entire pipeline. Similar to reduction rates of pressure at the inlet, an almost 10%, 15% and 30% pressure drop was observed at each location of the pressure gauges along the entire pipeline. Moreover, although the ultrasonic probes creating ultrasonic energy were mounted only at the front region of the pipe over a distance of approximately 4.5 m, the measured pressures along the entire pipe showed an almost linear relationship with the extrapolated ordinate at the origin in the investigated regime almost equal to zero. This suggests that the effects of ultrasonic energy on the pipe flow of pumped concrete might influence the entire length eventually, which means that the lubrication layer formed due to an ultrasonic energy section is maintained along the pipe as concrete passes through the entire pipe. In addition, the results of the linear distributions of measured pressures showed that pumping pressure does not appear to be affected by the shear thickening or shear thinning of pumped material properties in this regime tested (Cyr et al. 2000; Lachemi et al. 2004; Roussel et al. 2010; Feys et al. 2008).

4.2 Thickness of lubrication layer
To determine the thickness variations of the lubrication layer according to the ultrasonic energy, Figure 7 presents the axial velocities measured experimentally by UVP, where the normalized velocity is defined as the ratio of axial velocity to its own maximum velocity. As shown in Fig. 7, a dramatic change in the slope can be observed within a limited zone representing the lubrication layer and shear rates, i.e., approximately the slope of the velocity profiles, concentrated in this layer. In previous studies (Choi et al. 2013a, 2013b), the average thickness of the lubrication layer in the mixture proportion studied in this paper was approximately 2 mm. When examining the thickness variation, all cases incorporating ultrasonic energy became slightly wider than the original thickness and the degrees of expansion differed according to the intensities of ultrasonic energy. The measured thickness increased to approximately 2.5 mm for a 1,000 W ultrasonic energy and 2,000 W causes additional expansion to approximately 3.0 mm. In case of 3,000 W ultrasonic energy, the thickness expanded to approximately 4.0 mm, which is almost 2 times larger than the original thickness. Based on the experimental measurements for the thickness of the lubrication layer, the thickness of the lubrication layer also displayed strong dependence on the ultrasonic energy under the pumping conditions tested.

When comparing the thickness variations of the lubrication layer with the reduction rates of pressures, the rate of the pressure reduction increased with increasing thickness of the lubrication layer due to the higher ultrasonic energy intensity. Therefore, by applying ultrasonic
energy to the pipe, the properties of the lubrication layer, particularly the thickness, are dominantly affected, resulting in an improvement in the performance of concrete pumping.

4.3 Discussion
One tentative reason for these changes is the cavitation produced in the suspension by the ultrasonic energy, particularly at the lubrication layer, where the ultrasonic wave can influence, activate and excite with higher energy, resulting in an increase in the activation zone, i.e., the thickness of the lubrication layer. Another reason is that by inducing ultrasonic energy, the rheological properties of the lubrication layer decrease, which in turn increase the absolute velocity near the wall. Based on the experimental measurements by UVP, the normalized velocity showed that the velocity after inducing ultrasound energies increased up to 10% at 3,000 W energy. From these analyses, it was hypothesized that the decrease in rheological properties of the lubrication layer results in increasing the velocity depending on the ultrasound energies. However, the experiment could not be verified because there was no way to extract the materials of the lubrication layer itself.

Therefore, the application of an ultrasonic energy in concrete pumping can increase the pump efficiency by affecting the properties of the lubrication layer. From a practical point of view, this can help overcome the pump limitations for the construction of high rise buildings and super structures and achieve cost savings by allowing the use of a lower specification pump while still satisfying the construction requirements.

5. Conclusions
When concrete is being pumped through a pipe, the lubrication layer formed at the interface between the concrete and pipe wall plays a dominant role in facilitating concrete pumping. In the present study, to enhance the concrete pumpability, the properties of the lubrication layer were manipulated by ultrasound while the concrete was pumped through the pipe. A 170 m full scale pumping test was conducted with three different ultrasonic energy intensities and the following conclusions were obtained.

1. After imposing ultrasonic energy incorporating a constant 20 KHz frequency on the pipe, the measured pressure showed a gradual decrease for a certain period and then reached a steady state. Through these results, it could be noted that the effects of ultrasonic energy on the pipe flow of pumped concrete was detected simultaneously and was also sufficient to influence the properties of the material inside the steel pipe.

2. When examining the pressure variations according to three different ultrasonic energy intensities, the reduction rates were dependent on the ultrasonic energy. The pressure drop in the regime tested in this study increased with increasing ultrasonic energy.

3. The thickness variations of the lubrication layer increased with increasing ultrasonic energies. The rate of the pressure reduction increased with increasing thickness of the lubrication layer due to the higher ultrasonic energy intensity.

4. When ultrasound is applied, cavitation occurs in the suspension, which causes activation and excitation with higher energy, resulting in a change in the properties of the lubrication layer.

5. The application of an ultrasonic energy in concrete pumping can improve the pumping efficiency by changing the formation of the lubrication layer. Therefore, the technique of ultrasound on concrete pumping might help overcome the pumping limitations when constructing high rise buildings and super structures.

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