Application of the Ultrasound Velocity Profiling + Pressure Difference (UVP+PD) method for cement based grouts

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For grouting applications in underground construction, cement grouts with a water to cement ratio (w/c) typically 0.6 - 1.0 by weight, are used. Measurement of the rheological properties of the cement grouts and suspensions, consisting of a solid volume fraction up to 30 %, during field grouting operation directly in-line is of major interest from an industrial point of view. However, no such in-line monitoring device is available today. The present data recording system, to monitor and control the grouting operations in the field, are only performed by measuring the pressure and the grout volumetric flow in real time. Now for the first time, the ultrasound velocity profiling + pressure difference (UVP+PD) method has been applied directly in-line in field like conditions to determineits feasibility for cement based grouts. The experiments were performed with water to cement ratios 0.6 and 0.8 in a flow loop consisting of a standard grouting rig (UNIGROUT E22H) and LOGAC data recording system, to ensure field like conditions. The UVP+PD method was found successful to measure the rheological properties of micro fine cement suspensions during field like conditions. A further study in a laboratory based flow loop, consisting of a progressive cavity pump was also performed to measure the rheological properties during such conditions. The UVP+PD method was proven successful to obtain satisfactory and promising results and it was also found to be an effective tool for the determination of grout pump characteristics.

Keywords: Cement grouts, in-line rheometry, cement suspensions, UVP+PD method, grouting, cement rheology.

1 INTRODUCTION

Rock grouting is a common practice to increase the water tightness of rock fractures and strength stiffness of the rock mass in underground construction. Grouting practice is still based on rules of thumb and an in-line system for the measurement of cement grout properties, continuously during field operations, is still unavailable [1]. Difficulties associated with conventional rheometers have been pointed out by Håkansson [2] and in a recently proposed methodology it has been showed that the design and steering of a grouting operation necessitates an accurate and reliable determination of the rheological properties, as well as their change with time [3]. For the first time, the ultrasound velocity profiling + pressure difference (UVP+PD) method was applied directly in-line in field like conditions to determine the feasibility of this method for cement based grouts. The results from the feasibility study showed that it is possible to use the UVP+PD method for determining the rheological properties of cement grouts in field like conditions [4,5]. Subsequently it was found that the UVP+PD method could also be an efficient tool for grout pump characterization [6]. However, further development is required concerning the ultrasound transducers. A further study was performed using a laboratory based flow loop to determine the rheological properties of the grouts in a stable flowing condition. This paper presents an overview of the works that has been performed using the UVP+PD method on cement based grout together with a future outlook.

2 MATERIALS AND METHODS

2.1 Materials

In this work, Cementa IC 30 micro fine cement has been used to prepare the grout. Cementa IC 30 has a particle size distribution where 95% of the cement particles are less than 30 microns and the setting time of the cement is approximately 100 minutes. The cement grout was prepared with water/cement ratio 0.6, 0.7 and 0.8 (by weight). A mixing time of 4 minutes was used for all batches. A commercial high performance binding time regulator, Cementa SetControl II was used as additive and a dosage of 2% (by weight) was used. Cementa SetControl II is used in the field to reduce the setting time of the prepared grout. In the experiments, SetControl II was used to keep the conditions the same as in the field. A total of 8 batches were made with w/c ratio 0.6, 0.8 and 5 batches with w/c ratio 0.7.

2.2 Experimental flow loop

Two sets of flow loops were used for the experimental works. One flow loop consisted of the conventional UNIGROUT E22H grouting rig from Atlas Copco, a commercial flow meter and pressure sensor LOGAC unit and the UVP+PD test section. The equipment's were connected using high pressure grouting hoses and stainless steel pipe with an inner diameter of 22.5 mm. A standard grouting rig, UNIGROUT E22H from Atlas Copco, was used to perform the feasibility studies with conditions the same as in the field. A schematic illustration of the experimental flow loop is shown in Figure 1. The second flow loop was used to perform a follow up study in laboratory like conditions. The UNIGROUT E22H was replaced by a progressive cavity pump to obtain a stable flow rate of the grout. The LOGAC flow meter and pressure sensor was used as a reference instrument to compare the flow properties determined with the UVP. The flow was circulated through a storage tank, a progressive cavity single screw pump, UVP+PD test section, LOGAC flow meter and temperature sensors. A schematic illustration of the second flow loop is shown in Figure 2.

2.3 UNIGROUT E22H

The UNIGROUT E22H is a standard grouting rig commonly used for field applications. It consists of a grout mixer - Cemix 203H, a grout agitator - Cemag 402H, a grout pump - Pumpac, control unit and necessary hoses.

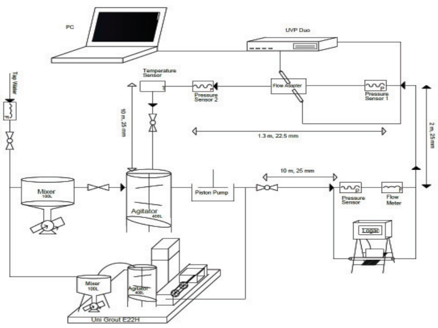

Figure 1 Schematic illustration of the flow loop used for field like conditions

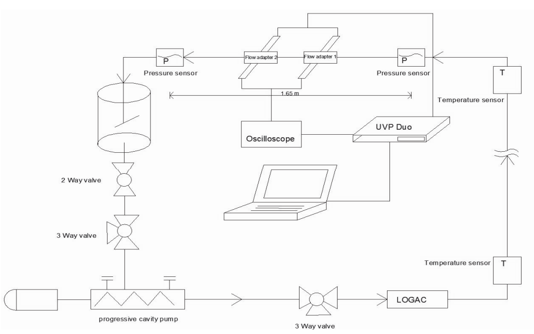

Figure 2 Schematic illustration of the flow loop used for laboratory experiments

2.4 LOGAC recording system

LOGAC 4000 is a recording system for storing and sampling data during a grouting operation. The parameters that can be logged are the volumetric flow, pressure, volume, time and real time. Data can be stored in every 1st, 5th and 10th second. It consists of an electromagnetic flow meter and a pressure sensor. LOGAC was primarily used as a reference to compare the volumetric flow rate obtained using the ultrasound velocity profiling (UVP) technique.

2.5 Progressive cavity pump

A progressive cavity pump type MAE 50-2/BB.BBNT32 Pompe-Raccordea, known as single screw pump, was used in the laboratory based flow loop. Stable flow condition were achieved while using the progressive cavity pump. The objective of using the progressive cavity pump and the laboratory based flow loop was to obtain repetitive velocity profiles in stable flow condition. The pump can be operated at a flow rate range up to 10 l/min and with a pressure limit of maximum 1.2 MPa.

2.6 UVP+PD method and instrumentation

The LOGAC recording system is based on the capillary and pipe viscometry which is well described in the literature [7]. The capillary and pipe viscometry methodology can perform single point measurement for corresponding shear rate, thereby limiting its use to Newtonian fluids. In this work, the ultrasound velocity profiling (UVP) technique was used in combination with pressure difference (PD) measurements. The UVP+PD method is a multi-point method that has been reported to perform rheological property measurements under true dynamic industrial processing conditions [8]. The UVP+PD methodology and system has been developed by SIK – The Swedish Institute for Food and Biotechnology. Details about the system and applications for industrial and model fluids can be found in other literatures [9].

In this work, a test section comprising of a flow adapter cell consisting of a pair of custom made 4 MHz ultrasound transducers and a differential pressure sensor was used. The transducers featured a delay line, which made it possible to measure the velocity of the cement particles just in front of the transducers. The pressure sensors were installed to measure the pressure difference over a distance of 1.3 m for the field like set up and over a distance of 1.65 m for the laboratory based set up. A detail description of the test section can be found in [4]. The velocity profiles were measured using UVP-DUO-MX Monitor (Met-Flow SA, Switzerland), a pulser/receiver instrument. Velocity estimation was performed using both time domain and Fast Fourier Frequency (FFT) algorithms. A Matlab based software 'Rheoflow', developed by SIK, was used to control all hardware devices for data acquisition, signal-processing, visualization of the data and real time monitoring of the rheological properties.

3 RESULTS AND DISCUSSION

3.1 Velocity profile

The velocity profiles were measured for cement grouts with w/c 0.6 and 0.8 during the field like conditions and with w/c 0.7 during the laboratory based conditions. For w/c 0.6 and 0.8, velocity profiles were captured over a time period of 1-3 hours. The velocity profiles were measured in ambient temperature 16^0-20^0 C and over a flow rate range of 15-30L/min.

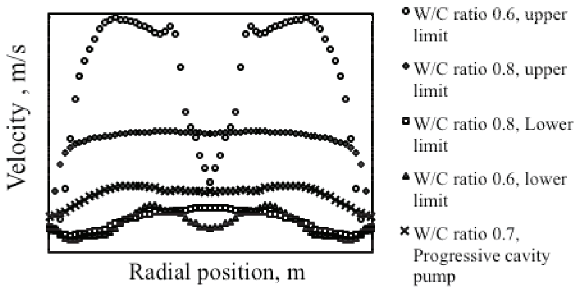

Figure 3 Velocity profiles measured by UVP

In Figure 3, the measured velocity profiles are shown as a function of the radial position, whereposition zero indicates the center of the pipe. Since the profile on both sides of the center of the pipe should ideally be identical, a mirrored image is shown to illustrate the full velocity profiles. For the field like conditions, a piston pump was used as an integral part of the UNIGROUT E22H and as a result, high fluctuations of the velocity profiles were observed. Only the maximum and minimum velocity profiles have been shown in Figure 3 to demonstrate the fluctuation of the velocity profiles. For the w/c 0.7 laboratory based experiments, a progressive cavity pump was used which yielded a very stable flow rate. Therefore, the average velocity profile has been shown. For w/c 0.6, 512 profiles were captured over 1 minute, 60 minutes after mixing and for w/c 0.8, 1024 profiles were captured over 3 minutes, 90 minutes after mixing. As can be seen, for w/c 0.6, the velocity profiles fluctuated from 1.6 m/s to 1 m/s and for w/c 0.8, the velocity profiles fluctuated from 0.8 m/s to 0.1 m/s. However, it should be noted that the pressure was higher for the w/c 0.6 measurements. Negative velocity was observed, which resembles the suction force occurring due to the cyclic pressure of the piston pump. Nevertheless, the visualization of the velocity profiles in real time is a significant application of the UVP in cement grouts since no other instrument used in the grouting industry are capable of providing this. For w/c 0.6, a lack of signal penetration is observed as the velocity profile was erroneous near the center of the pipe. This distortion was due to the strong attenuation of the ultrasound signal in a thick grout mix, such as w/c 0.6.

3.2 Comparison of the flow rate measured by the LOGAC and UVP

The UVP determines the volumetric flow rate by integration of the velocity profile. The LOGAC flow meter is capable of continuously measuring the volumetric flow rate. However, the measured flow rate is the average over a certain period of time; hence the true fluctuation of the flow rate remains unknown.

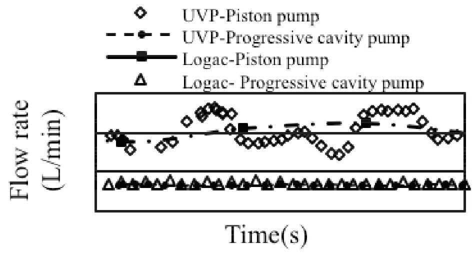

Figure 4 Comparison of the volumetric flow rate determined by the UVP and measured by the LOGAC

Figure 4 shows the comparison of the volumetric flow rate determined by the UVP and measured by the LOGAC. As can be seen, both of the methods yield results of the same order of magnitude. While using the UNIGROUT E22H, flow rate measurement was stored at LOGAC at every 10^{th} seconds and for the progressive cavity pump, it was stored every second. From Figure 4, it is evident that during a field grouting operation the true fluctuation of the flow rate remains unknown. Moreover, negative velocity due to the cyclic pressure of the piston pump cannot be measured using the commercial coriolis flow meters and, in addition, they are not capable of measuring a flow rate when it is less than 1 l/min, which is common at the later stage of grouting. Since the stop criteria for grouting operation depends on the flow of grouts into the rock fractures, a more accurate measurement of the flow rate will lead to a improved decisions. In addition, UVP can be used as an efficient tool for grout pump characterization and optimization of the pulsation effect.

3.3 Rheological analysis

The rheological properties obtained off line, using a conventional rheometer and in-line, using the UVP+PD method, is shown in Table 1. The recorded data were fitted to the Herschel-Bulkley model since this model is capable of incorporating the yield stress and the shear thinning behavior. As can be seen, the flow index, n decreases and consistency index, K increases with decreasing w/c ratio, as expected. From Table 1, a higher yield stress for higher w/c ratio is observed, which however can be explained by the fact that the data was sampled after a longer period of time from mixing, which will have an influence on the rheological properties, due to the hydration of the cement.

Figure 5 and 6 show the corresponding shear stress vs. shear rate plot and the viscosity vs. shear rate plot, respectively. A higher shear stress is observed for the decreased w/c ratio, as expected. A time dependent behavior was observed for w/c 0.8 with an increased yield stress with time.

Table 1 Rheological parameters obtained by H-B model

W/C	Set up	Time min	H-B Parameter		H-B Yield stress, Pa	R^2
			n	k		
0.6	Off line	71	0.33	2.2	2.5	0.98
0.6	Field	68	0.25	2.01	2.4	0.96
0.7	Laboratory	52	0.62	0.45	3.6	0.98
0.8	Off line	30	0.52	0.37	1.3	0.99
0.8	Field	30	0.47	0.35	1.1	0.98
0.8	Laboratory	105	0.63	0.58	3.5	0.98

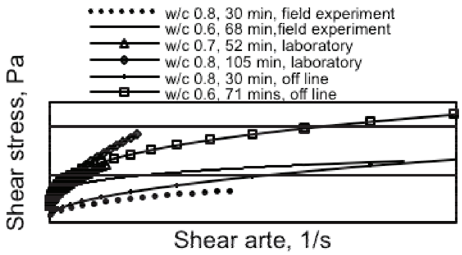

Figure 5 Shear stress vs. shear rate curve for different w/c ratio

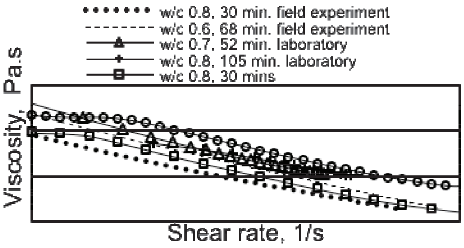

Figure 6 Viscosity vs. shear rate curve for different w/c ratio

From Table 1, it is observed that a higher flow index, n was achieved from the laboratory based set up. This can however be explained due to the short shear rate range. Since, the flow rate was lower (~6 l/min) for the progressive cavity pump compared to the field set up, a lower shear rate range was obtained. From Figure 6, a higher viscosity was observed for decreased w/c, which was expected.

A higher viscosity was observed for w/c 0.8, laboratory based set up, which can be explained by the longer time of performing data sampling after the mixing of the cement grouts. The off-line results showed the apparent viscosity as given by the slope from the origin to the individual data points. A Newtonean plateu was observed at low shear rates, which was expected. On the contrary, it should be noted that the in-line is showing the shear rate dependent viscosity as the slope of the each data point of the shear stress vs. shear rate curve, i.e. not starting from the origin.

4 CONCLUSION

The primary objective of this study was achieved since it was possible to measure the rheological properties of cement based grouts in field like conditions. It was demonstrated possible to obtain the velocity profiles up to the center of the pipe for cement grouts with w/c 0.6, and 0.8 and subsequently determine the rheological properties. In addition, it was observed that the pulsation of the piston pump, used for field grouting operations, can be visualized using the UVP technique. This makes it a promising tool for grout pump characterization. From the studies performed with the laboratory based set up, it was shown that it is possible to obtain the velocity profile nearly to the center of the pipe, but a change of the rheological properties over time was not observed due to the strong attenuation of the signal. Nevertheless, it can be concluded that the UVP+PD method is a promising new method for process monitoring and control of cement based grouts in the field. The future outlook of this method concerns the optimization, characterization of the ultrasound transducers for cement based grouts, observing the change of the rheological properties of cement over time and the characterization of different kind of pumps, used for grouting.

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