In-line Rheometry of Micro Cement Based Grouts – A Promising New Industrial Application of the Ultrasound Based UVP+PD Method

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Abstract:
Measurements of the viscosity of non-Newtonian fluids and suspensions having a solid volume fraction of about 30% or more is of major interest from an industrial point of view. Cement paste and cement grouts for injection grouting applications, with water to cement ratios typically in the range of 0.4 and 0.6 - 0.8 by weight, are two examples of industrial fluid systems. Few in-line techniques are available on the market that can be used for these fluid systems and under realistic field conditions. The so-called UVP+PD in-line rheometry method combining the Ultrasound Velocity Profiling (UVP) technique with Pressure Difference (PD) measurements is a promising new tool for industrial applications. This paper presents an initial pre-study that aims to demonstrate the feasibility of the UVP+PD method using cement grouts for process monitoring and control of grouting applications under realistic field conditions. The UVP+PD method was tested and found successful for continuous in-line measurements of concentrated micro cement-based grouts with water/cement ratios of 0.6 and 0.8. The test set-up consisted of a combination of an experimental "flow loop" and a conventional field grouting rig – UNIGROUT, from Atlas Copco. The rheological properties were determined, directly in-line and the parameters obtained were subsequently compared with off-line measurements using a conventional rotational rheometer.

Zusammenfassung:
Viskositätsmessungen an nicht-newtonschen Fluiden und Suspensionen mit einem Feststoff-Volumenanteil von 30% oder mehr ist für industrielle Anwendungen von höchstem Interesse. Zementleim und Verpresszement, mit einem Wasser-Zement-Gewichtsverhältnis von 0.4 und 0.6 - 0.8, sind zwei typische Beispiele für Fluide in der industriellen Anwendung. Nur wenige In-Line Methoden sind am Markt verfügbar die für solche Fluide und unter realen Bedingungen angewendet werden können. Die UVP+PD In-Line Rheometrie kombiniert Ultrasound Velocity Profiling (UVP) mit Pressure Difference (PD) Messungen und stellt eine vielversprechende neue Methode dar, die in solchen industriellen Rahmenbedingungen eingesetzt werden kann. Dieser Artikel beschreibt eine Vorabstudie, die die Ausführbarkeit der UVP+PD Methode an der Prozessüberwachung und zur Steuerung des Ausgiessens von Verpresszement unter realen Bedingungen untersucht. Die UVP+PD Methode wurde getestet und für gut befunden in durchgehenden In-Line Messungen von verdichtetem Micro Zement-based Verpresszement mit einem Wasser-Zement-Verhältnis von 0.6 und 0.8. Der Test-Aufbau bestand aus einer Kombination einer experimentellen „flow loop" und einer konventionellen Verpressanlage – UNIGROUT, Atlas Copco. Die rheologischen Eigenschaften wurden direkt In-Line gemessen und die Messwerte wurden anschließend mit offline Messungen an einem konventionellen Rotationsrheometer verglichen

Résumé:
Les mesures de viscosité de fluides non-newtoniens et de suspensions ayant une fraction volumique solide d'environ 30% ou plus sont d'un intérêt majeur d'un point de vue industriel. Les pâtes de ciment et coulis de ciment, avec des taux eau / ciment généralement dans la gamme de 0,4 à 0,6 - 0.8 en poids, sont deux exemples de systèmes de fluides industriels. Peu de techniques en ligne, disponibles sur le marché, peuvent utilisées pour ce type de fluides et dans des conditions réalistes sur le terrain. La méthode dite de rhéométrie VU+PC en ligne combinant la technique de vélocimétrie ultrasonore (VU) avec des mesures de perte de charge (PC) est un outil nouveau et prometteur pour des applications industrielles. Cet article présente une pré-étude visant à démontrer la faisabilité de la méthode VU+PC en utilisant les coulis de ciment pour le contrôle des processus et le contrôle des applications d'injection dans des conditions réalistes sur le terrain. La méthode VU+PC a été testée et il a été démontré qu´elle est efficace pour effectuer des mesures continues en ligne de micro coulis concentrés à base de ciment avec des taux eau / ciment de 0,6 à 0,8. Le banc d'essai est constitué d´un dispositif d'écoule-

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er, a higher yield stress was also observed for *w/c* ratio 0.8 since the sample was measured after a longer period of time after mixing. A time dependent behaviour of the cement grouts was observed by the yield stress increasing with time for both *w/c* ratios 0.6 and 0.8, which agrees well with the in-line results. As can be seen from the flow index in Table 3, *w/c* ratio 0.8 also showed a more shear thinning behaviour than 0.6 and, for *w/c* ratio 0.8 after 30 minutes mixing, a comparatively higher flow index was achieved. The consistency index was found to be higher for the water/cement ratio of 0.6 than 0.8 which indicates a higher viscosity for the thicker grout, as expected. The largest discrepancy in the flow curves is associated with the sample measured 66 minutes after the mixing for *w/c* ratio 0.6. It is believed that this is an erroneous result caused by a non-representative sample taken from the field equipment and into the laboratory, as discussed above. It should be noted that the problem of obtaining a representative sample from the process clearly illustrates the main disadvantage with conventional off-line measurements for process monitoring and control and thus gives a strong motivation/argument for measuring in-line, directly in the process pipe, using e.g. the UVP+PD method.

The viscosity versus shear rate flow curve is shown in Figure 7b for the off-line measurements obtained using the ARES-G2 rheometer. This curve shows the apparent viscosity as given by the slope from the origin to the respective raw data points. As expected, the flow curves show a Newtonian plateau and a time dependent behaviour, especially seen in the *w/c* 0.8 grout. It should be noted that, for the UVP+PD method, the viscosity is determined by taking the gradient of the shear stress versus shear rate flow curve at individual shear rates, which is often called the "shear rate dependent viscosity". It is thus important to be aware of the difference between the two methods when comparing the data presented in Figures 6b and 7b.

5 CONCLUSIONS

There is a need in the construction industry and in grouting practice to develop an in-line measuring device to determine the rheological properties of cement based grouts in the actual process, continuously and in real-time. Such a device would facilitate the steering of the grouting procedure, enable pro-active decision making during execution and give continuous quality assurance. A pre-requisite is that such monitoring equipment should be reliable, robust and easy to use.

In this feasibility study, the UVP+PD method developed at SIK was demonstrated to be a promising new tool for flow visualization and in-line viscometry of micro cement based grouts. The grouts used were prepared with water/cement (*w/c*) ratios in the range of 0.6 - 0.8, by weight, which are typical for grouting applications in practice. A new type of transducer was tested that allows measurements directly from the transducer/wall interface and offers both higher energy output and increased spatial resolution compared to commercially available transducers. It was demonstrated that instantaneous velocity profiles could be measured under realistic field conditions across at least half of the pipe diameter, which is required for determination of volumetric flow rate and rheological properties. In contrast to the conventional flow meters currently used in the field, the high data acquisition rate of the UVP+PD method in combination with the possibility to determine the complete radial velocity distribution allows real-time monitoring of the flow as well as optimization of the pump type and operations. Moreover, the UVP+PD method and system used were demonstrated to be capable of determining the true flow curve and rheological properties of cement based grouts, both directly with the non-model gradient method and by curve fitting to the Herschel-Bulkley rheological model. Although not the main objective of this study, relatively good agreement with conventional rheometers was found for measurements made under steady-state flow conditions and over the same range of shear rates. Still, more work on optimization of the transducer and flow adapter design is needed for better measurement accuracy and robustness under actual field conditions.

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REFERENCES

[1] Håkansson U, Rahman M: Rheological measurements of cement based grouts using the UVP+PD method, Nordic Symposium of Rock Grouting, Helsinki (2009).
[2] Banfill PFG: Rheology of fresh cement and concrete. The British Society of Rheology (2006).
[3] Håkansson U, Hässler L, Stille H: Rheological properties of cement-based grouts - Measuring techniques and factors of influence, Int. Conference on Grouting in Rock and Concrete, Rotterdam (1993) 491-500.
[4] Gustafson G, Claesson J: Steering parameters for rock grouting, personal communication.
[5] Gustafson G, Stille H: Stop criteria for cement grouting, Felsbau Rock and Soil Engineering 3 (2005) 62-68.
[6] Håkansson U: Rheology of fresh cement based grouts, PhD Thesis, Royal Institute of Technology (KTH), Stockholm (1993).
[7] Kobayashi S, Stille H, Gustafson G, Stille B: Real time grouting control method – Development and application using Äspö HRL data, Swedish Nuclear Fuel and Waste Management Co, SKB (2008).
[8] Roussel N, Roy LR: The marsh cone or a rheological apparatus? Cement and Concrete Research 35 (2005) 823-830.
[9] Lombardi G: The role of cohesion in cement grouting of rock, Congres des Grandes Barrage 58 (1985).
[10] Axelsson M: Prevention of erosion of fresh grout in hard rock, PhD Thesis, Chalmers University of Technology, Sweden (2005).
[11] Barnes HA: On-line or process viscometry – a review, Applied Rheology 9 (1999) 102-107.
[12] Roberts I: In-line and on-line rheology measurements, Instrumentation and Sensors for the Food Industry, Woodhead Publishing Limited, Cambridge (2001).
[13] Takeda Y: Ultrasonic Doppler method for velocity profile measurement in fluid dynamics and fluid engineering, International Journal of Heat and Fluid Flow 7 (1985) 313-318.
[14] Takeda Y: Velocity profile Measurement by Ultrasonic Doppler Method, Experimental Thermal and Fluid Science 10 (1995) 444-453.
[15] Wunderlich T, Brunn PO: Ultrasound pulse Doppler method as a viscometer for process monitoring, Flow Measurement and Instrumentation 10 (1999) 201-205.
[16] Ouriev B, Breitschuh B, Windhab E: Rheological investigation of concentrated suspensions using a novel in-line doppler ultrasound method, Colloid Journal 62 (1999) 234-237.
[17] Wiklund J, Johansson M, Shaik J, Fischer P, Stading M, Hermansson A: In-line ultrasound based rheometry of industrial and model suspensions flowing through pipes, 3rd International Symposium on Ultrasound Doppler Methods for Fluid Mech and Fluid Eng, Lausanne (2002) 69-76.
[18] Dogan N, McCarthy MJ, Powell RL: Measurement of polymer melt rheology using ultrasonic-based in-line rheometry, Measurement Science and Technology 16 (2005) 1684-1690.
[19] Jensen AJ: Estimation of Blood Velocities Using Ultrasound: A Signal Processing Approach, Cambridge University Press (1996).
[20] Chhabra R, Richardson J: Non-Newtonian Flow in the Process Industry: Fundamentals and engineering applications, Oxford, Great Britain (1999).
[21] Wiklund J, Shahram I, Stading M: Methodology for in-line rheology by Ultrasound Doppler velocity profiling and pressure difference techniques, Chemical Engineering Science 62 (2007) 4277-4293.
[22] Wiklund J: Ultrasound Doppler Based In-Line Rheometry: Development, Validation and Application, PhD Thesis, SIK – The Swedish Institute for Food and Biotechnology, Lund University, Sweden (2007).
[23] Birkhofer B: Ultrasonic in-line characterization of suspensions. PhD Thesis, Swiss Federal Institute of Technology (ETH), Switzerland (2007).
[24] Wiklund J, Stading M: Application of in-line ultrasound Doppler based UVP+PD rheometry method to concentrated model and industrial suspensions, Flow Measurement and Instrumentation 18 (2008) 171-179.
[25] Birkhofer B, Jeelani SA, Windhab E, Ouriev B, Lisner KJ, Braun P: Monitoring of fat crystallization process using UVP+PD technique, Flow Measurement and Instrumentation 19 (2007) 163-169.
[26] Young N, Wassell P, Wiklund J, Stading M: Monitoring struturants of fat blends with ultrasound based in-line rheometry (UVP+PD), International Journal of Food Science and Technology 43 (2008) 2083-2089.
[27] Kotze R, Haldenwang R, Slatter P: Rheological characterization of highly concentrated mineral suspensions using an Ultrasonic Velocity Profiling with combined Pressure Difference method, Appl. Rheol. 18 (2008).
[28] Wiklund J, Stading M, Trägårdh C: Monitoring liquid displacement of model and industrial fluids in pipes by in-line ultrasonic rheometry, Journal of Food Engineering 99 (2010) 330-337.
[29] Wassell P, Wiklund J, Stading M, Bonwick G, Smith C, Almiron-Roig E: In-line viscosity and solid fat content (SFC) measurement of fat blends with ultrasound based in-line rheometry, International Journal of Food Science and Technology 45 (2012) 877-883.

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