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Study of cement-grout penetration into fractures under static and oscillatory conditions

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ABSTRACT

Grouting of the rock surrounding high-level waste (HLW) can serve to minimize groundwater flow around it and thereby to retard erosion of waste-embedding clay (buffer) and transport of possibly released radionuclides. Earlier attempts have shown the efficiency of superimposing the injection pressure with oscillations for bringing cement-rich grouts into narrow fractures using organic superplasticizers. However, these are short-lived and can produce radionuclide-bearing organic colloids, and should be replaced by inorganic agents. Portland cement in grouts is not long lived and low-pH cements are preferable as is also reduction of the cement content to an absolute minimum. The present study describes the composition and performance of candidate grouts in laboratory experiments with injection into plane-parallel slots with different aperture. The study included development of a simple and quick method for estimating the viscosity on the construction site for adapting the grout recipe to the injectability of the rock. A simple theoretical model for predicting grout penetration gives fair agreement with laboratory data. The longevity of the grout under various conditions is believed to be sufficient for use in HLW repositories implying waste placement in very deep holes.

1. Introduction

Cement grouting is required for stabilizing fracture zones through which holes for disposal of highly radioactive waste (HLW) will be bored. Such a concept is "VDH" according to which 0.8 m diameter holes are bored to 4000 m depth. The upper 2000 m parts of the holes are sealed by use of highly compacted smectite-rich clay while the lower parts contain canisters with HLW surrounded and separated by dense clay (Fujita et al., 2012; Pusch et al., 1988). For both parts the principle is to cast concrete where fracture zones are intersected. Here, groundwater flow can degrade the concrete by dissolving its cement component and cause dispersion and softening of adjacent clay seals. For minimizing this risk grouting is suitable as indicated in Fig. 1, either from prebored slim pilot holes or from the large holes using large packers, (Mohammed et al., 2013a). The concrete seals in the boreholes shall provide axial support to the clay seals, which requires that they remain physically intact also after seismically induced shearing of the fracture zones. This criterion implies that the concrete and injected grout have a high density and only little cement. A further demand is that neither of them are allowed to significantly degrade the contacting clay seals (Pusch et al., 2013a). The present study describes the composition and performance of suitable grouts in laboratory experiments. It also shows a simple and quick method for estimating the viscosity on the construction site for adapting the grout recipe to the structural constitution and injectability of the rock, and applicability of a simple theoretical model for predicting grout penetration in fractures. The grouts and concretes can be used in steep or flat-lying slim or large-diameter holes.

1.1. Background

The matter of longevity of cement materials for grouting and as binder in concrete was investigated in a comprehensive research program conducted or supported by the atomic energy company AECL in Canada and the federal department DOE in the US in the late eighties (Alcorn et al., 1992). The conclusion was that grout with Portland cement is expected loose most of its sealing potential in 100 years and that other cement types should be considered for reducing the hydraulic conductivity of fractured rock that is

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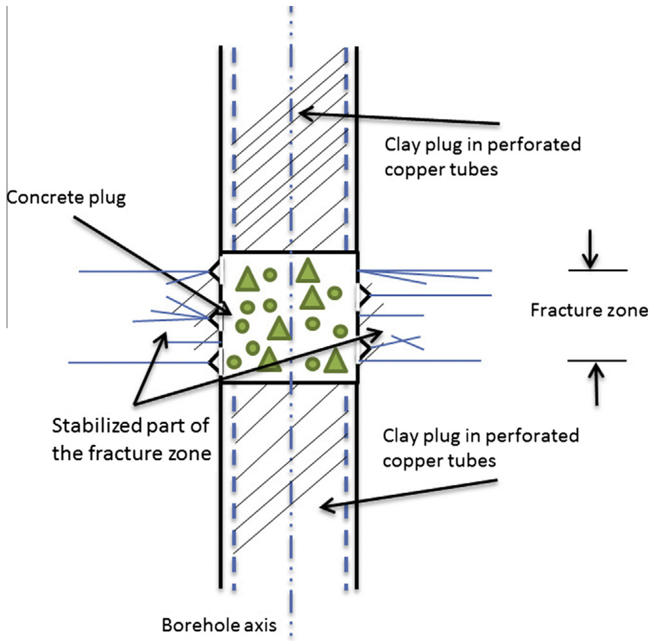

Fig. 1. Seals in boreholes passing through a fracture zone.

present in HLW repositories. The hydraulic conductivity of the hardened grout does not have to be very low but the erodability should be low and the strength and chemical stability high (Pusch et al., 2011).

Some of the earlier studies that formed the basis of the present investigation were an attempt to develop a grouting technique by Pusch et al. (1988), that could bring cement and clay grouts into fractures with a "hydraulic" aperture of 100 μm or somewhat smaller by using "dynamic injection technique", implying superposition of static pressure and superimposed oscillations.

A grout penetration theory for fractured rock was developed by (Hässler, 1991; Hässler et al., 1988) treating the grout as a Bingham fluid. Eriksson and Stille (2000, 2003) modified this model by considering also clogging of fractures by penetrating grout. This and a similar, complex model worked out by Gustafson and Stille (1996, 2005) for predicting grout penetration in real rock, was examined by Fujita et al. (2012) considering 1D conditions. The latter also reviewed various other grout penetration models developed and used in Japan and elsewhere. Yang et al. (2011), investigated the rheological properties of cement grouts with different water cement ratios, and their flow in fractures. Börgesson et al. (1992), determined the rheological properties of grouts based on smectite clay and cement with and without superplasticizers, and with different *w*/*c* ratios. They also derived a model for calculating the penetration of grout into fractures under static and dynamic pressure conditions. According to Draganović and Stille (2011), many factors such as the grain-size curve of the cement, hydration and flocculation, pressure, grout density, and the geometry of constriction affect the complex processes of penetration and filtration of the injected grout. They found that the best penetrability is achieved by using cement of medium grain size rather than coarse or very fine-grained. Eriksson (2002) concluded that aperture size, variability in aperture and other geometrical measures are the most important rock features that affect the penetrability. Axelsson et al. (2009) identified three retarding conditions for penetrating cementitious grouts, the major one being the ratio of the maximum grain size of the cement grains and the aperture of the fractures. An additional very important parameter for practitioners is the impact of grout pressure on the aperture and interconnectivity of fractures to be sealed (Pusch, 1994), The present study deals with some of these issues and describes and discusses theoretical grout flow models for predicting flow into plane-parallel fractures of candidate cement grout materials that behave as Bingham fluids under static pressure and as Newton liquids under oscillatory pressure.

1.2. Scope

A fundamental requirement for bringing grout deep into rock fractures is that it must be very finegrained and be effectively forced into them. For conventional grouting, fine grained Portland cement is most commonly used, while low-pH cement was in focus of the present study (Mohammed et al., 2013b), both for providing suitable pH conditions for preservation of adjacent clay seals in the VDH and for giving the grout a high strength by reacting with talc, which is used as superplasticizer and conditioner. It replaces organic superplasticizers, which are short-lived and can produce radionuclide-bearing organic colloids. Long-lasting grouts require chemical integrity, which is provided by using quartzite aggregate, which has a very high internal friction angle and hence gives a high residual strength if shearing would take place. The rheological properties of different cement grouts have been investigated with respect to their fluidity in order to select the most suitable mixture and for modeling the flow of grout experimentally into artificial fractures with different apertures (100, 250 and 500 μm).

2. Laboratory test

2.1. Materials

Merit 5000 low-pH cement was used in the study. It was delivered by the SSAB Merox AB, Oxelösund, Sweden, and has the composition listed in Table 1. The aggregate consisted of quartz powder, Norquartz 45 delivered by the Sibelco Nordic, Lillesand, Norway. Table 2 presents the chemical compositions and grain size of the grout components. Finally, milled "talc" manufactured by VWR International Company UK was added for providing fluidity and long-term strength. Talc serves as lubricator and reacts with low-pH cement to provide mechanical strength. This hydrophobic mineral has the chemical composition $3MgO{\cdot}4SiO_2{\cdot}H_2O$ and has been selected as superplasticizer of the concrete intended for use in borehole plugs (Mohammed et al., 2013a; Pusch et al., 2013b,c).

Table 1
Characteristics of Merit 5000 cement according to SS-EN 196-1, 2 and 3.

Analysis	Merit 5000 cement
MgO	16.6
LOI	−1.23
LOI compensated for S^{-2} oxidation	1.43
SO_3	0.085
Sulfide	1.33
cl^-	<0.01
Glass content (%)	99
Density (kg/m^3)	2912
Specific surface area (m^2/kg)	470
Moisture content	0.09
Initial setting	
Water content (%)	27.0
Setting time (min)	210
Compressive strength	
7 d (MPa)	23.3
28 d (MPa)	50.4