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Condensed summary of current R & D on cementitious sealants for deep boreholes with HLW

Roland Pusch[a], Laurence N. Warr[b], Sven Knutsson[a], Ting Yang[a,*]

[a] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden
[b] Department of Geography and Geology, University of Greifswald, F.-L.-Jahn-Straße 17A, Germany

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ABSTRACT

Cement-based materials for use as sealants in underground waste storages must be erosion-resistant and chemically stable. Placement of highly radioactive waste (HLW) in boreholes may require that the rock is cement-grouted and stabilized by constructing concrete plugs. Where smectitic clay seals are in contact with concrete there is mutual degradation, and low-pH cement with inorganic superplasticizers, like talc, are recommended for preparing the concrete. This paper reviews our current state-of-knowledge concerning the grout and concrete sealing very deep boreholes (DBD) for purpose of high-level radioactive waste disposal. In this concept, the lower 2 km section of 4 km deep holes bored in crystalline rock could host waste-containers while the upper parts are sealed by dense clay and concrete.[1] The parts of such a hole that intersect fracture-poor rock are sealed with dense expandable clay while concrete is cast where fracture zones are intersected. The paper summarizes the available experimental results concerning the performance of grouts and concrete with talc as superplasticizer in contact with smectitic clay.

1. Scope

The basic idea of disposal of high-level radioactive waste (HLW) according to concepts termed DBD is to locate the waste deep in rock with very heavy, saline, stagnant formational waters that are unlikely to rise to contaminate shallow ground waters (Brady et al., 2009; Sapiie and Driscol, 2009). Internationally, several models for deep disposal of highly radioactive waste (HLW) have been launched (cf. Nirex, 2004), in the UK by the University of Sheffield, and in the USA by Sandia National Laboratories. The present authors propose a concept (cf. Pusch et al., 2012) for the disposal of highly radioactive waste, involving placement of the heat-producing waste in the lower 2 km part of 4 km deep holes bored in granitic rock, i.e. the deployment zone, that relies on the sealing capacity of engineered barriers in the form of concrete and clay in the upper parts of the so-called VDH holes (Fig. 1). The described concept requires that those parts of such holes that are located in fracture-poor rock are sealed with dense expandable clay, while concrete is cast where pre-grouted fracture zones are intersected. Matters of particular importance are 1) function of the grout, concrete, and clay seals, 2) chemical stability and physico/chemical evolution of contacting concrete and clay seals. The clay seals consist of highly compacted smectite clay confined in perforated tubes ("supercontainers"), that are used also for hosting HLW canisters separated and surrounded by well fitting very dense clay blocks.

The criteria for the cement-based grout are to be sufficiently fluid for sealing off finer fractures and to provide erosion resistance during the installation of concrete and clay seals. For the concrete it is required that it is coherent at casting and has a sufficiently high bearing capacity and low compressibility for carrying the load of subsequently installed series of clay and concrete seals. The hydraulic conductivity of the hardened concrete should be lower than that of the surrounding fracture zone. Since the concrete must perform acceptably for up to 100,000 years according to most national environmental protection agencies, and the cement component will ultimately be dissolved and lost, the rest, i.e. the aggregate components of the concrete, must still provide sufficient support for overlying clay and concrete seals in deep boreholes. The aggregate grains must therefore be very densely packed and have a granular composition that resists erosion.

The present study reviews new types of chemically stable organic-free cement-poor grout for sealing fractured rock, and talc-based concrete for casting under water-saturated conditions within deep boreholes. The properties of special importance considered are fluidity, mechanical strength, rate of strengthening, and minimized weakening when in contact with smectite-rich clay.

* Corresponding author.
E-mail address: ting.yang@ltu.se (T. Yang).

[1] At present, continued R & D will show if the holes can be only 2.5 km deep with HLW in the lower 2 km parts.

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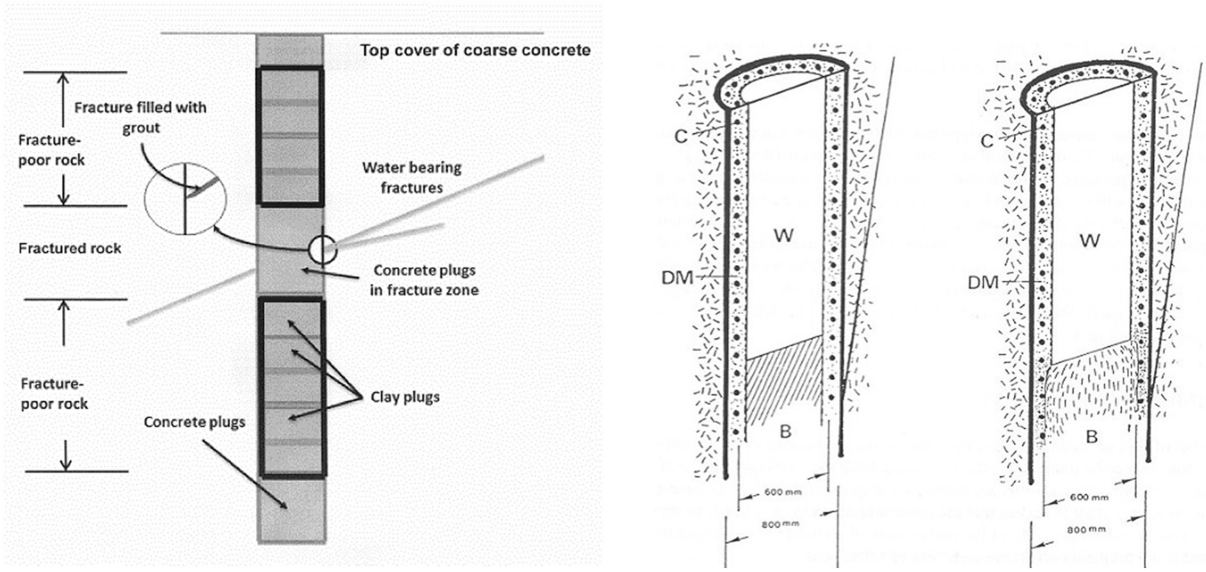

Fig. 1. VDH. Left: Casing-supported (C) holes sealed with clay in "supercontainers", and concrete, cast on site, to 2 km depth. Right: In the lower, "deployment" zone (2–4 km), sets of supercontainers with HLW canisters (W) surrounded by clay, and separated by blocks (B). The supercontainers are of copper, steel or titanium and submerged in soft clay mud (DM), (Pusch, 1994, 2012; Pusch et al., 2012).

2. Composition and function of cementitious sealing materials for VDH storage of radioactive waste

2.1. Grout in fracture zones

The role of the grout in sealing VDHs is to minimize the risk of erosion and loss of cement particles and ultra-fine aggregate particles from the concrete to be cast, and from adjacent clay seals. The recommended recipe is a mixture of 10% low-pH cement, 10% talc and 80% finely milled quartzite and silica flour (Pusch, 2012; Mohammed et al., 2013; Mohammed, 2014; Mohammed et al., 2014a, 2015a). The grouting is made through 70–100 mm cored holes that are bored in conjunction with the detailed site characterization of host rock during exploration of the VDH location. Injection is made using the highest pressures possible with vibrations superimposed (Pusch, 1994; Mohammed, 2014). Very fine fissures will not be sealed but fractures with a hydraulic aperture of a few tens of micrometers can be successfully tightened.

The proposed grout type contains a low concentration of cement for minimizing the increase in porosity that will follow during dissolution and erosion of the cement component over the long-term. The granular composition is optimized according to packing theory (Pusch, 2012; Mohammed et al., 2013). Using a fly ash-based low-pH cement, which is more stable than Portland cement and chemically reacts with talc, provides an ultimately high strength but a slow strengthening rate, which can be accelerated by adding the strongly thixotropic clay mineral, palygorskite. Once forced into rock fractures the grout stiffens and serves as a filter that hinders fine particles from adjacent clay seals to migrate through it and be lost in the fracture zone (Pusch, 2012; Mohammed, 2014). Talc ($3MgO{\cdot}4SiO_2{\cdot}H_2O$)[2] is hydrophobic and low-viscous and does not form gels. It has no negative impact on the environment and is chemically stable in ordinary groundwater.

Penetration of new cement grouts, containing low-pH cement, powdered quartz and talc, has been investigated in laboratory experiments (Mohammed, 2014). The aggregate/cement ratio was very high 11.2–17.6 and hence also the density, but the water/cement ratio was also high (1.18–1.60) making the grouts behave as Bingham fluids. The penetrability into slots simulating rock fractures with an aperture of 100–500 µm was determined using static, constant pressure, and superpositioning oscillatory pressure waves on the injection pressure. The aim was to test the hypothesis that "dynamic" injection can increase the penetrability of cement-based grouts (Pusch, 1994), and to work out theoretical models for predicting the penetration into fractures.

The experiments highlight the role of the rheological properties and the filtering behaviour of certain grouts (Mohammed et al., 2014b). The following observations were drawn from the study of the low-pH cement-talc grout types:

- Effective penetration of grouts into fractures with smaller aperture than 100 µm requires that the viscosity is lower than 0.05 Pa s. Here, injection under static, constant pressure is preferable.
- Effective penetration of grouts in fractures with an aperture of 100–500 µm can be achieved for grouts with a viscosity of 0.05–1.0 Pa s. Injection under dynamic pressure conditions is optimal.
- Grouts with a viscosity of 1–50 Pa s can enter fractures with apertures larger than a few millimeters.
- Measuring of the viscosity of freshly prepared grouts can be made by viscosimeters and capillaries. The latter is practical for rapid checking of the fluidity on the construction site.
- Theoretically predicted penetration depths are in fair agreement with laboratory test data.
- Dynamic injection has successfully been made on full scale in 760 mm diameter boreholes (Pusch, 1994).

2.2. Concrete cast in VDH

2.2.1. Preparation of holes

Deep VDHs have varying diameters which causes rock fall and other types of excavation damage that must be smoothened and stabilized by first boring to a somewhat larger diameter than intended, followed by casting of concrete between packers, in turn followed by re-boring to the intended diameter (Pusch et al., 2013a). The holes need to be stabilized and rinsed before installation of the supercontainers (cf. Fig. 1). Stabilization involving reaming, concrete casting and re-boring can be made by applying techniques used commercially in deep drilling projects (Brady et al., 2009). After cleaning, the topography of the borehole walls is scanned for determining the actual hole geometry as part of exploring placeability of the supercontainers. Techniques, tools and

[2] VWR International Company, UK.