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Research paper

Shear resistance of bentonite backfill materials and their interfaces under varying hydraulic conditions in a deep rock nuclear waste repository

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ABSTRACT

This paper presents the shear behaviour and the shear resistance of different bentonite based clay backfill materials and their interfaces of Finnish KBS-3V type nuclear waste repository, under varying hydraulic conditions. The interfaces between proposed precompressed Friedland clay blocks (FCB) and other granular backfill materials (GM) such as bentonite pellets (QSEP) and granules of bentonite (GB) were tested in a conventional direct shear box apparatus under various hydraulic test conditions. The main objective of this study was to get insight into the shear behaviour of different backfill interfaces and to determine their interface shear parameters. Tests were done by changing the salinity of the interface water and the amount of interface water itself. Test results showed that the internal shear strength of QSEP and GB decreased with increasing water content due to the lubricating effect of the free-water between the granules. Furthermore, test results showed that the interface shear parameters of the FCB–FCB interface increased with increasing salinity of the interface water, which produced rough FCB surfaces and asperities as the water was absorbed. The interface friction and cohesion of the FCB–GM (i.e. QSEP and FCB) interfaces under varying amounts of interface water were investigated through two different scenarios. In scenario 1, natural FCB surface was tested against GM with varying water contents, and in scenario 2, the amount of water on the FCB surface was varied whilst the water content of the GM was fixed as high as possible at around 60% (by weight). The test results showed that in scenario 1, the interface shear of FCB–GM (both FCB–QSEP and FCB–GB) decreased with increasing water contents of GM. At water contents (of GM) less than 40% (by weight), the failure took place at the interface, whilst at water contents above 40%, the failure occurred within the GM itself. Greater interface shear was observed when the FCB was wetted (i.e. in FCB–QSEP and FCB–GB interfaces) in scenario 2, compared with natural FCB surface in the same interfaces. The interface shear results obtained from this study will be incorporated in the detailed modelling of the buffer–backfill interaction of the KBS-3V.

1. Introduction

The tunnel backfill (herein referred to as backfill) of a deep-rock nuclear waste repository is of paramount importance in the context of long-term safety, providing isolation of the radioactive waste from the surface environment (Sinnathamby et al., 2014a). Therefore a highly engineered multi-barrier system is essential for backfilling in order to provide a stable environment for the disposed spent nuclear fuel, both mechanically and chemically. KBS-3V is one such multi-barrier repository concept that has been proposed for the Finnish deep-rock nuclear waste disposal facility on Olkiluoto Island. The KBS-3V multi-barrier is comprised mainly of protective buffers in the deposition holes and backfill in the deposition tunnels (Hansen et al., 2010). Precompressed hollow cylindrical bentonite blocks are used as buffers and emplaced in vertically drilled deposition holes where the spent nuclear fuel canisters are installed. Once all the holes in a single deposition tunnel are filled with canisters and buffers, the tunnel is then backfilled with clay-based materials.

According to the current KBS-3V design, the bulk of the tunnel volume is backfilled with precompressed, rectangular clay blocks made out of Friedland clay, which has high contents of swelling clay minerals (Rautioaho and Korkiala-Tanttu, 2009). The voids between the block backfill and the host rock are filled with sprayed bentonite pellets, whilst the floor of the deposition tunnel is covered with raw bentonite granules prior to the installation of the block backfill (Keto et al., 2012) (Fig. 1).

The objective of this study is to determine the shear strength and to get insight into the shearing behaviour of different backfill interfaces such as block–block, block–pellet and block-granulated bentonite. A series of undrained direct shear tests were carried out in order to investigate the effect of interface water content and the salinity of the interface water on the interface shear of the above interfaces. Additionally, pellets and granulated bentonite were tested for internal shear strength at different water contents, and these results are also reported.

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Definitions and abbreviations

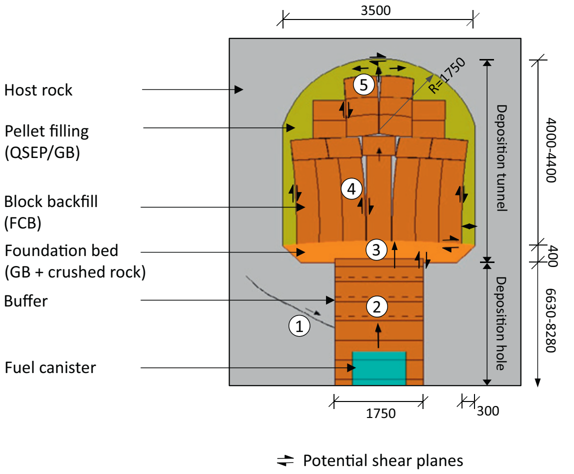
Saturation	initial water uptake by backfill and buffer for the first time when groundwater penetrates into the tunnels
Backfill	backfill is the material or materials that is/are used for backfilling of deposition tunnels
Buffer	compacted bentonite blocks surrounding the copper canister in the deposition hole
KBS-3V	disposal concept based on a multi-barrier system, where the canister is emplaced into a vertical deposition hole in the bedrock (V = vertical)
FCB	Friedland clay block
GM	granular material
QSEP	Cebogel QSEP Pellets
GB	granulated bentonite
TDS	total dissolved solids
w.c.	water content

Notations

R_a	average roughness parameter
c	cohesion
e_0	initial void ratio
w	water content
w_0	initial water content
ρ	density
ρ_d	dry density
ρ_s	density of solids
ρ_w	density of water
ϕ	friction angle

2. Background

One of the key aspects in ensuring the proper functionality of the protective buffer–backfill system in KBS-3V is that the saturated density of the buffer should be maintained within a narrow range of 1950 kg/m^3 to 2050 kg/m^3 at all times during the lifetime of the repository (Hansen et al., 2010). The lower boundary of the saturated buffer density ensures the impermeable properties of the buffer are maintained, and thus groundwater movement is prevented. It also prevents microbial activities near the canister surface, and therefore the fuel canisters are protected from the potential causes of corrosion. The long-term safe disposal of spent nuclear fuel is therefore thought to be ensured (Pastina and Hellä, 2006). The upper boundary for the saturated buffer density is defined in order to prevent the host rock from cracking due to excessive swelling pressures generated by the buffer.



(1) Groundwater seepage through fractures
(2) swelling & subsequent upheaval of buffer
(3) upheaval of the foundation bed [FCB-GB interface]
(4) shearing between blocks [FCB-FCB interface]
(5) shearing between blocks & pellet filling [FCB-QSEP interface]

Fig. 1. Schematic of the KBS-3V backfill components and a sequence of events creating shear-planes inside the backfill (dimensions are in mm).
Modified after Leoni (2012) and Sievänen et al. (2012).

The density criteria become crucial at the early stages of the saturation of the tunnels when a fully saturated buffer swells and penetrates into a partially dry backfill by pushing the backfill upwards and eventually reducing the buffer density (Fig. 1). In order to function as designed, the buffer requires counter-pressure produced by backfill installed in the deposition tunnel. As the saturation also progresses in the backfill, it creates a counter swelling pressure, limiting the upward expansion of the buffer and keeping it in place so that the aforementioned density requirements are met. The interfaces between backfill materials will disappear as the saturation progresses, leaving the backfill as a continuous mass. As a result, the interface shear behaviour of backfill materials is crucial only during the early stages of saturation (i.e., when interfaces exist). On the other hand, the internal shear of backfill materials becomes vital during the long-term performance (i.e., when the backfill is fully saturated and no interfaces exist). Therefore, the early stages of saturation can be considered as the worst-case-scenario, because the dry backfill is more prone to deformation, due to the presence of interfaces that have relatively lower shear resistance, compared to the combination of counter-swelling pressure and internal shear resistance of the entire backfill when it is fully saturated. Additionally, the backfill is also expected to enhance the mechanical stability of the deposition tunnels, and to some extent, restore the original conditions of the host rock (Keto et al., 2012).

At the repository depth of approximately 420 m below the ground level, conditions such as groundwater salinity and rate of ground water penetration into the backfill can vary significantly during the lifetime of the repository. As such, the backfill has to be designed to accommodate any transient and permanent changes that could occur in the repository environment. Several studies have been carried out in the past on the strength and swelling properties of individual backfill materials under varying repository conditions such as groundwater penetration and salinity (e.g. Karnland et al., 1992; Börgesson et al., 1995; Dixon et al., 1996; Johannesson et al., 2010). However, to date very little is known about the effect of varying interface water and groundwater salinity on the shear resistance between backfill interfaces, and how they could affect the overall performance on the backfill as the saturation progresses, and eventually in controlling the saturated density of the buffer. A numerical modelling study of the KBS-3V buffer-backfill interaction done by Leoni (2012) indicated that the material parameters, such as interface shear, are the major uncertainties of the modelling as these values were assumed (or estimated from existing limited amount of data). Therefore, there is a need for a detailed experimental study in order to determine the interface shear properties of proposed backfill material and their interfaces. These experimental interface shear resistance data would help to improve the modelling of the buffer–backfill interaction and to predict the upheaval of the buffer accurately (Börgesson and Hernelind, 2009; Korkiala-Tanttu, 2009; Leoni, 2012).

3. Materials

Expansive bentonite clay materials with high swelling potential (composed mainly of montmorillonite and other smectites) have been chosen for tunnel backfilling as they swell when they come into contact with water and subsequently yield very low water permeability, which is often preferred in barrier applications (Gunnarsson et al., 2006; Phillips et al., 2011; Keto et al., 2012; Sinnathamby et al., 2014a,b). If