Effect of Desiccation on the Hydraulic Conductivity of Compacted Bentonite–Sand Blocks

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Abstract. This study investigated the impact of drying cracks on the hydraulic conductivity of compacted bentonite–sand blocks to support the construction of buffer barriers in an underground research laboratory for the disposal of China’s high–level radioactive waste. The hydraulic conductivity of an air-dried block (the worst storage case) was measured in a flexible–wall permeameter in the directions parallel and perpendicular to the direction of compaction according to ASTM D5084. The results were compared with the hydraulic conductivity of fresh blocks. Computerized tomography (CT) images were used to visualize the internal cracks of the blocks, and the swell index was measured to represent the blocks’ swelling properties. The test results revealed that compared with fresh blocks, the drying cracks increased the hydraulic conductivity of the blocks by less than fourfold. As demonstrated by the CT images, the drying cracks were healed after permeation with distilled water. The swell index of the block was unaffected by air drying, and the swelling of montmorillonite in bentonite contributed to the healing of the drying cracks.

1. Introduction

The construction of an underground research laboratory (URL) for the deep geological disposal of high-level radioactive waste (HLW) in China has begun with the aim of developing technologies for final disposal repositories. The project started in 2020, and a goal of completing the construction and research in 2050 was established [1–2]. One of the functionalities of the URL is to examine the reliability of buffer barriers in isolating radionuclides, which requires a very low hydraulic conductivity (commonly, ≤ 10⁻¹⁰ m/s) of the barriers. Compacted bentonite–sand blocks (buffer blocks) have been produced for China’s URL for the construction of buffer barriers [3–4], and the hydraulic, thermal, and mechanical properties of the blocks were measured and validated to meet the criteria for Chinese buffers [5-7].

Before being used in URLs, blocks are produced and stored above ground. The blocks with a high montmorillonite content (44%) tend to shrink and develop drying cracks when they are exposed to above-ground atmospheric environmental conditions during the storage period [4]. Figure 1 compares the image of a fresh block (newly compacted) and a block after one day’s exposure. The drying cracks on the blocks’ surfaces are potential preferential flow paths for water to increase the hydraulic
conductivity of the block. Cracks in compacted natural clays are reported to increase hydraulic conductivity by as much as three orders of magnitude [8]. Consequently, measures such as sealing boxes [9] and humidity controls [10] are recommended for protecting the blocks before they are installed in disposal holes. Before validating the effectiveness of the proposed protection methods, additional expenditure is required for the extra procedures for protecting the block during the storage period.

![Image](image1.png)

**Figure 1.** Images of compacted bentonite–sand blocks (buffer blocks): (a) a fresh block and (b) a block after one day’s atmospheric exposure.

However, the self-healing of block joints has been reported. A block joint is an interface between two blocks, which is also a potential preferential flow path for water. The joint can be sealed by bentonite pellets and can achieve a similar hydraulic conductivity to intact blocks (9.14 × 10⁻¹² m/s for joints vs. 4.57 × 10⁻¹² m/s for intact blocks) owing to the high swelling properties of montmorillonite [11]. The results indicate the potential self-healing of fractures on or in blocks when the fractures are in contact with water, which forms an expectation for the self-healing of drying cracks. Consequently, there is a need to investigate the self-healing of drying cracks on block surfaces to omit or simplify the block protection procedures and thus reduce costs.

In this study, the hydraulic conductivity of air-dried buffer blocks was measured using four specimens extracted from blocks with axes parallel or perpendicular to the compaction direction. The healing of the drying cracks was evaluated by comparing the hydraulic conductivities of the desiccated and fresh blocks. The blocks’ anisotropic permeability was studied by comparing the hydraulic conductivities measured along the two directions. After permeation, the specimens were scanned by X-ray computerized tomography (CT) to visualize the internal cracks. The swell index of the blocks was measured to determine the blocks’ swelling properties.

2. Materials and Methods

2.1 Bentonite–sand block

The studied blocks comprised a 1/12 circular ring with an inner radius of 480 mm, an outer radius of 795 mm, and a height of ~100 mm [3]. The blocks consisted of Gaomiaozi (GMZ) bentonite and quartz sand with a 7:3 mass ratio, which is a promising buffer material in China [12–15]. The physical properties of the bentonite and quartz sand used are summarized in Table 1 [16–17]. Bentonite (dry mass: 14 kg) and quartz sand (6 kg) were premixed with tap water to a water content of 17% and were uniaxially compressed in a module to a dry density of ~1.8 Mg/m³. The compression of the block involved three steps: First, 10 MPa of pressure was applied from above the bentonite–sand mixture, and the piston was held in place for 10 min. Then, 15 MPa of pressure was applied from above the mixture, and the piston was held in place for another 10 min. Finally, 25 MPa of pressure was applied from above the mixture, and the piston was held in place for 60 min [4]. After compression, the fresh block was extruded from the module and was covered by plastic wrap to prevent desiccation.

In this study, a fresh block without a protective plastic wrap was exposed to atmospheric environmental conditions in which the relative humidity and temperature ranged from 20% to 50% and from 15 °C to 30 °C, respectively, to simulate the worst storage condition. After three months of
exposure to the atmosphere, the water content of the block reached 5.3%, which is close to the air-dried (hygroscopic) water content of bentonite–sand mixtures.

Two circular specimens with a diameter of 100 mm and a thickness of 20 mm were extracted from the top surface of the air-dried block to measure the hydraulic conductivity of the block along the direction parallel to the direction of compression. Another two specimens with the same geometry were extracted from the side of the block to measure its hydraulic conductivity perpendicular to the direction of compression.

| Table 1. Physical properties of the used GMZ bentonite and quartz sand [16–17]. |
|-------------------------------------------------|-------------------------------------------------|
| Hygroscopic Montmorillonite Liquid Plastic Specific Swell | Silica Quartz Sand |
| water content Montmorillonite limit limit gravity index | content gravity |
| [%] [%] [%] [%] [-] [mL/2g] | [%] [-] [mm] |
| 9.0 44 208.1 32.8 2.70 0.007 15.0 | > 99 2.65 0.8 |

Figure 2 contains images of the four specimens. Those with a permeation direction parallel to the compression direction are referred to as PII, and those with a permeation direction perpendicular to the compression direction are referred to as Ppd. The specimens with and without penetrating cracks are referred to as DPC and DB, respectively. The sampling process using a metal cutting ring damaged the integrity of the specimens and resulted in penetrating cracks.

In Figure 2, the length and dip angle of the surface cracks on the specimens were counted using an image-processing technique, and rose diagrams were plotted to illustrate the orientation of the surface cracks. The radius of the diagram is the proportion of the length of the cracks that fall into the angle interval, which can be calculated as follows [7]:

\[
\text{Proportion in length} = \frac{\text{Length of cracks that fall into a dip–angle interval}}{\text{Total length of cracks}}
\]  

(1)

As presented in Figure 2, the cracks on the specimens displayed orientations, e.g., in specimen DB–Ppd, 37% of the cracks developed along the compaction direction (45% < dip angle < 135%), and 62% of the cracks were nearly perpendicular to the compaction direction (dip angle < 45% or > 135%). The sampling process using the cutting ring generated new cracks, resulting in different crack orientations compared with the original drying cracks, as reported by Tan et al. [7].

2.2 Hydraulic conductivity test

The hydraulic conductivity of the specimens was measured in flexible-wall permeameters according to the falling headwater-constant tailwater method in ASTM D5084 [18]. Before permeation, the specimens were hydrated in permeameters for 48 h using distilled water with a closed effluent valve. To simulate underground high-stress conditions, the applied confining stress was 300 kPa, and the applied inflow air pressure was 240 kPa. Permeation was continued until the termination criteria in D5084 were met, i.e., the hydraulic conductivity was steady, the ratio of the outflow and inflow rates was between 0.75 and 1.25, and two pore volumes of flow (PVFs) had passed through the specimens. The hydraulic conductivity of a fresh block was tested by Tan et al. [7] under the same stress conditions and was cited in this work as a control.

2.3 Computerized tomography test

The air–dried specimens were scanned by an X-ray beam along the permeation direction before and after the hydraulic conductivity test. The spatial resolution of the CT instrument was 24 LP/cm (0.208 mm), and the scanning interval between each cross section was 3 mm.

2.4 Swell index test

The swell index of the fresh and air–dried blocks was measured in accordance with ASTM D5890 [19] using distilled water as a hydrating liquid. Part of the block was ground with a mortar and pestle until
100% had passed through a #100 U.S. standard sieve (0.15 mm) and a minimum of 65% had passed through a #200 sieve (0.075 mm). The mechanical sieves segregated the quartz sand from the bentonite. Then, two grams of sieved and oven-dried materials were gradually added to a 100–mL graduated cylinder that was pre–filled with 90–mL distilled water before being allowed to sit for 24 h. The volume of the hydrated materials was recorded as the swell index [20].

Figure 2. Images of the specimens extracted from air-dried blocks for hydraulic conductivity testing with rose diagrams above to illustrate the orientation of the surface cracks. (a) DB-Pl: moderate damage in sampling with permeation parallel to the compaction direction. (b) DB-Ppd: moderate damage in sampling with permeation perpendicular to the compaction direction. (c) DPC-Pl: severe damage in sampling with permeation parallel to the compaction direction. (d) DPC-Ppd: severe damage in sampling with permeation perpendicular to the compaction direction.
3. Results

3.1 Hydraulic conductivity of the blocks

The hydraulic conductivities of the blocks (K) are shown in Figure 3 and summarized in Table 2. The fresh block presents a similar hydraulic conductivity along the directions parallel and perpendicular to the compression direction (i.e., \(K_{\text{F-PII}} = 1.1 \times 10^{-12} \text{ m/s}\) and \(K_{\text{F-Ppd}} = 1.3 \times 10^{-12} \text{ m/s}\), respectively) [7]. The hydraulic conductivity of the moderately damaged air–dried block (specimens DB-PII and DB-Ppd) was less than three times higher than the fresh block. The specimens with penetrating cracks demonstrated the highest hydraulic conductivity (\(K_{\text{DPC-PII}} = 4.5 \times 10^{-12} \text{ m/s}\)) even with the PVFs exceeding seven. However, the highest hydraulic conductivity of the air–dried block was less than four times higher than that of the fresh block, which still meets the criteria for Chinese buffer (\(K < 10^{-10} \text{ m/s}\)). No obvious anisotropic permeation was found in either the fresh or air–dried blocks.

Table 2. Summary of hydraulic conductivity, number of cracks, and swell index of blocks.

| Specimen | \(K\) (m/s) | Number of cracks | Swell index (mL/2g) |
|----------|-------------|------------------|---------------------|
| F–Pll    | \(1.1 \times 10^{-12}\) [7] | - | 14.0 |
| F–Ppd    | \(1.3 \times 10^{-12}\) [7] | - | 14.0 |
| DB–Pll   | \(2.9 \times 10^{-12}\) | 516 | 13.0 |
| DB–Ppd   | \(2.0 \times 10^{-12}\) | 410 | 13.0 |
| DPC–Pll  | \(4.3 \times 10^{-12}\) | 592 | 13.0 |
| DPC–Ppd  | \(4.5 \times 10^{-12}\) | 523 | 13.0 |

The ratio between the hydraulic conductivity of the air–dried and fresh blocks (< 4) was lower than the ratio between the hydraulic conductivity of the block joints and the intact blocks. The hydraulic conductivity of the interface between two blocks (joint) was \(4.54 \times 10^{-11} \text{ m/s}\), and the hydraulic conductivity of the corresponding block was \(4.57 \times 10^{-12} \text{ m/s}\), which were measured using a rigid-wall permeameter [11]. The joint represented a penetrating crack through the entire block, and the width of the joint (typically, 2 mm) was wider than the drying cracks (typically, < 1 mm [4]) in the block. Consequently, the joint resulted in a higher increase in the hydraulic conductivity of the block compared with the drying cracks.

![Figure 3. Hydraulic conductivity of the fresh and air–dried blocks.](image-url)

3.2 Computerized tomography image of the air–dried block

Each specimen was scanned by an X–ray beam at a 3–mm interval and thus, ~36 cross sections from each specimen were examined. The total number of cracks on the CT images were counted for each
specimen and are listed in Table 2. There were 410 to 592 cracks in the air-dried specimens, while no obvious cracks were found in these specimens after permeation. Five CT images that were uniformly distributed through the specimens (20-mm intervals) were selected to show the inner cracks of the blocks (Figure 4). Before permeation, obvious cracks were found on each examined cross section. In specimen DPC–Pll, a crack along with the permeation direction penetrated the specimen. After permeation, all the cracks were healed and became invisible in the CT images under a 0.208-mm spatial resolution.

3.3 Healing of the drying crack
As presented in Table 2, the swell index of the fresh and air-dried blocks was similar, i.e., 14.0 and 13.0 mL/2g, respectively. The air-drying process did not affect the swelling of bentonite significantly. The GMZ bentonite used in this study contains 44% montmorillonite, which can undergo osmotic swelling when it comes into contact with water. The swelling of montmorillonite contributes to the healing of the cracks under the high confining stress conditions. Therefore, 1) no obvious cracks were observed in the CT images of the specimens after permeation, 2) the increase in the hydraulic conductivity of the block due to the drying cracks was less than fourfold, which was significantly lower than the decrease in hydraulic conductivity measured on a compacted clay liner (up to a 1,000-fold increase), and 3) no obvious anisotropic hydraulic conductivity was observed on the air-dried block, although the surface cracks presented some orientations.

Figure 4. CT images of the air-dried specimens before and after permeation: (a) DB–Pll, (b) DB–Ppd, (c) DPC–Pll, and (d) DPC–Ppd.

4. Conclusions
The hydraulic conductivity of the air–dried buffer block was measured along the directions parallel and perpendicular to the compression direction to study the potential effects caused by drying cracks. CT and swell index tests were conducted to demonstrate the healing of the cracks.

Compared with the hydraulic conductivity of fresh blocks, the obvious drying cracks resulted in a below fourfold increase in hydraulic conductivity from $1.1 \times 10^{-12}$ m/s to $4.3 \times 10^{-12}$ m/s, which still meets the criteria for Chinese buffers ($K < 10^{-10}$ m/s). No obvious anisotropic permeation was caused by the cracks. The obvious cracks in the block, including the penetrating cracks, were healed after the permeation with distilled water as demonstrated by the CT images. As the air–dry process did not significantly affect the swell index of bentonite, the healing of the cracks was attribute to the osmotic swelling of the montmorillonite in bentonite. Therefore, complicated and expensive methods of protecting blocks from desiccation during the storage period are not recommended.

Acknowledgments
The authors gratefully acknowledge their cooperators, Dr. Ju Wang, Dr. Yuemiao Liu, and Dr. Shengfei Cao (Beijing Research Institute of Uranium Geology), for providing GMZ bentonite and financial support. This work was supported by the National Nature Science Foundation of China (41972265). The authors also gratefully acknowledge the Organizing Committee of ARMS 11 for the English language assistance. The first author (Yu Tan) acknowledges the China Scholarship Council for supporting his study at the University of Virginia.

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