Physical properties of full-scale compacted bentonite-sand blocks as influenced by curing humidity

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Abstract. The relative humidity (RH) and temperature of the environment were controlled to achieve the optimum conditions for curing bentonite-sand blocks before placing them in repository for the disposal of highly radioactive waste. These prepared blocks were stored in a climate chamber at a temperature of 20°C. A constant RH environment was created by oversaturating the sodium chloride (NaCl) solution (RH=75%) and the distilled water (RH=100%) in capped canisters. During the three-month-long curing process, the moisture content of these blocks was measured periodically by recording their weights and their volumetric shrinkage as measured by fixed dial indicators. The final moisture and dry density distributions were measured by sawing a block into 64 subsamples. The test results indicated that 100% is the optimum environmental RH for a block with 17% moisture content, based on the lowest decrease in moisture content (from 17.00% to 15.15%), less than 1% shrinkage strain, and without any visible surface cracks. The curing process also contributed to the moisture homogenization in the block as demonstrated by the decreased coefficient of variation of water content (from 5.35% to 1.07%).

1. Introduction
The safe disposal of high-level radioactive waste (HLW) is a major strategic issue related to the healthy and sustainable development of China’s nuclear power industry and is a scientific and technological problem faced by all countries worldwide. Deep geological disposal is an internationally accepted method for HLW [1]. In this method, a buffer barrier is constructed by using compacted buffer blocks to protect the canisters from detrimental processes such as the release of radionuclides if the canisters leaked [2].

The buffer blocks are manufactured to the desired dry density and moisture content by special compaction equipment. Then the blocks undergo storage, transportation, and installation [3]. The RH in a block’s environment will likely change from very low at the production site to very high in tunnels with moisture inflow and stagnant air. As bentonite buffer blocks are very sensitive to RH, they will react to environmental air. In a dry environment, the blocks will lose moisture and shrink and crack, whereas in a wet environment, the blocks will absorb moisture and swell and crack [4]. Either way, the blocks’ swelling and cracking may cause high hydraulic conductivity that affects the blocks’ performance in a buffer barrier.
The Xin-chang site in the Beishan area of the Gansu Province was selected as the first underground research laboratory (URL) for the disposal of HLW in China. The site was chosen after considering the climate, geological/hydrogeological conditions, and public acceptance [5]. While the site has a typical dry, high-altitude continental climate, the average annual RH is about 37.08% and the average temperature is about 7.60°C [6]. In this environment, the buffer blocks are likely to be exposed to low RH during manufacturing and storage in this area, resulting in deterioration from drying. The existing URL in-situ test results show that these blocks will be placed in the deposit holes with canisters for up to three months before the backfill materials are put on top of the holes [7]. During this period, the blocks will be directly exposed to the humidity at the repository. Meanwhile, water will be flowing along the tunnel floor throughout the installation period. The RH in the tunnel will be high, probably close to 100% [8], and therefore the blocks might absorb water from the surrounding wet air, resulting in the blocks’ deterioration. In any event, inappropriate humidity will reduce the quality of the buffer blocks. Therefore, the initial moisture content of the blocks should be adequate for the humid environment of the repository. Also, the blocks must be cured during storage and transportation to ensure the stability of the physical properties of the blocks.

Environmental RH is one of the dominant factors affecting the quality of the blocks. When the blocks were exposed to an indoor environment without controlling the RH, then a large number of dry cracks were observed within 1.0 hour on the surfaces [9]. Thus, in order to protect the blocks from desultory effects, the environmental RH should be well-controlled from production to installation [10]. Meanwhile, controlling RH can effectively protect the compacted bentonite-sand mixtures from deformation and deterioration [11]. SKB and Posiva [12-13] reported a block’s recommended moisture content as 17%, and the environmental RH should be kept at a constant of approximately 75% at all times. However, at present, there is no suitable curing scheme for the blocks used at this HLW disposal repository in China, which may hinder the construction process of the Beishan URL.

The purpose of this work is to find a feasible curing environmental RH for bentonite-sand blocks. Therefore, full-scale blocks were compacted and placed in an RH controllable curing device to investigate the stability of the blocks in different RH environments. While the bentonite is sensitive to moisture changes, the quartz sand in the bentonite-sand blocks does not absorb moisture. Thus, when the bentonite-sand blocks and pure bentonite blocks are in the same environment with the same moisture content, the actual moisture content in the former bentonite is higher. Moreover, the curing humidity of both kinds of blocks should increase with the increase of moisture content of the bentonite. For bentonite blocks, the suitable curing RH is 75%. Therefore, the curing RH of bentonite-sand blocks should not be less than 75%. Considering this situation, the bentonite-sand blocks’ curing RH percentages were 75% and 100%. During the curing process, the moisture content of the blocks was monitored by regular weighing, and the volumetric shrinkage was monitored by a specifically designed device equipped with dial indicators. When the moisture content and volume of the blocks reached equilibrium, they were divided into 64 subsamples to measure their moisture content and density distributions. Based on the results, the optimal curing RH of bentonite-sand blocks could be determined.

![Figure 1](image-url)

**Figure.** 1. A conception of buffer barrier based on bentonite-sand blocks (Unit: mm). (a) Buffer barrier geometry; (b) Type-A block (1/6); (c) Type-B block (1/12).
2. Block preparation

2.1 Material characteristics
Gaomiaozi (GMZ) bentonite has been proposed as the main material for building buffer barriers of HLW repository in China due to its engineering properties [14]. Adding the quartz sand into bentonite to form the bentonite-sand mixtures, comparing to the pure bentonite, which can improve the mechanical strength [15] and reduce volumetric shrinkage and crack development [16], and does not significantly increase the hydraulic conductivity [17]. Therefore, the GMZ bentonite-sand mixtures were used to prepare the blocks, and the optimal sand mixing mass rate is 30% based on fuzzy integrated evaluation [18].

This GMZ bentonite was mined in Inner Mongolia, China, and quartz sand was produced in Yongdeng County, Gansu Province, China. The basic properties of these two materials used are summarized in table 1.

Table 1. Basic physical properties of using materials

| GMZ bentonite | Quartz sand |
|---------------|-------------|
| Specific gravity | 2.70 | 2.65 |
| Particle diameter | main<0.075mm | 0.5-2.0mm |
| Liquid limit | 152 | >99% |
| Plastic limit | 28 | |
| Hygroscopic moisture content | 9.56% | |
| Specific gravity | 2.70 | 2.65 |
| Particle diameter | main<0.075mm | 0.5-2.0mm |
| Silica content | 9.56% | >99% |

2.2 Block compactions
The type-B block was prepared in this work, which is an idealized conception of a buffer barrier [9, 19], as shown in figure 1. The manufacturing process of bentonite-sand blocks mainly involves mixing and block compaction. First, the quartz sand is added into bentonite according to a step-by-step mixing method. Second, a 17% moisture content level was achieved by spraying moisture on these mixtures [20]. After sealing the mixtures in a plastic bag for at least 48 hours, these uniformly wet mixtures were poured into a mold and compacted into blocks. The blocks’ dry density was about 1.85g/cm³. After compaction, the blocks were demolded and measured immediately, and then sealed with plastic film.

2.3 Deformation monitoring method of a block
During the curing process, the moisture content of the blocks was monitored by regular weighing, the temperature of curing room was controlled by a climate controller, and the RH was balanced by the oversaturated NaCl solution (RH75%) and distilled water (RH100%) at the bottom of the curing devices.

The change of a block’s moisture will cause a change of its shape, but the block was compacted as an industrial size, and the maximum deformation measurement length is about 400mm. In addition, the
deformation of a block is limited by the high degree of compaction, and the deformation is a few millimeters only. It is difficult to meet the measurement accuracy requirements by conventional methods. In order to ensure the accuracy of the deformation measurements, we designed a bentonite-sand block deformation monitoring device equipped with dial indicators, as shown in figure. 2. In addition, two parallel blocks were prepared under the same conditions. One block was used to monitor the deformation, and the other block was used to monitor the weight.

2.4 Segmentation method of the block
In the long-term curing process, the internal moisture of the blocks was adjusted under the gradient of moisture distribution, which may become more homogeneous during this adjustment process. Therefore, the homogeneity of the blocks was analyzed before and after curing. Because the blocks are an industrial size, the homogeneity was difficult to analyze by direct measurements. Thus, a block was cut into multiple subsamples for measuring the moisture content and dry density by dividing height (Z), angle (R), and radius (θ) equally into four parts (figure. 3). A total of 64 subsamples were taken from the block for analysis of the homogeneity.

All subsamples were divided into two parts for the determination of moisture content and dry density distributions. Moisture content measurements were performed in accordance with standard ASTM D2216-19 [21]. The moisture content was determined by drying the sample in an oven for 24 hours at a temperature of 105°C. The density was determined based on Archimedes principle by weighing the sample in the air and then submerged into paraffin oil [16].

3. Experimental results and discussion

3.1 Moisture content change of the block
During the curing process, the moisture content of the block was monitored by regular weighing. Gradually, the moisture content of all blocks decreased, as shown in figure. 4. In the two humidity curing environments, the moisture content of the block had decreased slowly until it reached equilibrium. However, the moisture content of the exposed indoor block [9] decreased rapidly in the early stage and then gradually trended toward a constant. The equilibrium moisture content increased with the increase of the curing RH and the time required for the block’s moisture content to reach equilibrium is related to the curing RH. That is the larger the difference between the initial moisture content and the equilibrium moisture content, the longer the curing time. The block’s moisture content was 15.15% for the RH100% environment, 10.48% for the RH75% environment, and 6.92% for the atmospheric environment.
The constant evaporation stage in the block curing process was too transitory to be monitored, as the block’s evaporation rate gradually decreases with the curing time, and then it is maintained at a low level. This phenomenon occurs mainly because the block’s evaporation is a hierarchical evaporating process [9]. During the evaporation process, the block’s surface is desiccated first. However, due to the high density and low permeability, the internal moisture cannot be transported to the block’s surface in time to maintain a constant evaporation rate, and so the evaporation surface gradually migrates to the interior, resulting in the extension of the moisture transmission path.

3.2 Deformation of the block
As shown in figure .2, the block deformation monitoring device was used to determine the deformation in the R and θ directions during the curing process. In the deformation monitoring device, two corresponding dial indicators constitute a measuring line. In the R direction, the measuring line segments from 1-6 to 3-4. And, in the θ direction, the measuring line segments from F-A to D-C.

In one block, the linear strains development path along with the R direction were similar, as indicated by the measuring lines 1-6 to 3-4 in figure 5. However, figure 6 shows that the linear strain in θ direction was significantly different, presenting as the linear shrinkage strain decreased gradually from lines F-A to D-C; i.e., the longer measuring lines presented less shrinkage strain. This phenomenon is because that the block’s external shrinkage is greater than the internal one. The longer measuring lines present longer internal length, and the external shrinkage was greater, so the linear shrinkage strain of the whole measuring line will decrease with the increase of the measuring line.
In figure .5 and figure .6, the linear strains were positively correlated with the change of moisture content; i.e., the shrinkage strain increased as the moisture decreased. The change of moisture content was 1.35% for block curing at RH100%, 5.92% for RH75%, and 9.08% for exposed indoor environment. The shrinkage strain of the block was lower than 1.0% for the RH100% environment, 1.5% for the RH75%, and higher than 2.0% for the atmospheric environmental conditions [9]. Moreover, figure .5 and figure .6 show that the change curves linear shrinkage strain in different RH environments basically coincides with moisture content, indicating that the linear shrinkage strain was only related to the change of water content, and it was not affected by the evaporation rate. Therefore, considering the moisture content and shape stability, RH100% is the best for curing the blocks with 17% moisture content. Moreover, cracks on blocks exposed indoor began to appear after 1.0 hour of exposure, while cracks in the RH75% environment began to appear after 48 hours of maintenance, and no cracks were observed on the block surface after curing for three months in an RH100% environment.

3.3 Homogeneity of the block
During the block preparation process, due to the influence of the materials’ mixing method and compaction process, the block’s moisture content and dry density distribution will become inhomogeneous. This inhomogeneity distribution may lead to mechanical and hydraulic defects, thereby affecting block’s basic buffering function.

Therefore, the purpose of block curing is not only to prevent the block from a moisture loss and deterioration but also to make the block become more homogeneous. In the long-term curing process, the internal material will be adjusted independently by the action of moisture content and dry density gradient, so as to promote the homogenization, and then eliminate the defects caused by the block preparation period. Before and after curing, the blocks were segmented according to figure. 3, and then the moisture content and dry density of the segmented subsamples were measured. Then, the blocks’ average moisture content and dry density and the coefficient of variation (CV) of the layers and the whole blocks were calculated, as shown in figure. 7 and figure. 8.

The average moisture content and CV of a block’s layers before and after curing were plotted in figure. 7. From figure. 8a, the average moisture content of the layers before curing varied greatly, while the variation range after curing was obviously smaller, indicating the overall homogeneity of the moisture content distribution had been significantly improved. Before block curing, the CV of moisture content was between 2.41% and 6.18%, and the overall CV was 5.35%. Moreover, the CV of the Z2 and Z1 layers was higher, indicating that the water distribution at the bottom of the blocks was relatively more inhomogeneous. After block curing, the CV of moisture content was significantly smaller than before curing. The CV of block curing at RH75% was between 1.04% and 1.59%, and at RH100% was between 0.84% and 1.10%, and the overall CV was 1.07%, indicating that the moisture content of the blocks was homogeneously distributed after curing. Therefore, the curing process had significantly improved the homogeneity of the moisture content, and the homogeneity of the block curing at RH100% is best.

Figure .8 shows the average dry density and CV of a block’s layers before and after curing. As shown in figure. 8a, the difference of average dry density of the layers before and after curing were small, within 0.02g/cm³, indicating that the distribution of solid substances in the block was relatively homogeneous. However, after block curing, the CV of dry density (figure .8b) of the layers after curing were smaller than that before curing, indicating that the curing process can improve the homogeneity of solid material distribution to a certain extent.

By comparing the CV of moisture content and dry density in the same block (figure .7b and figure .8b), the CV of dry density of the layers was smaller, indicating that the solid materials inside the block were more homogeneous than moisture. Therefore, the homogeneity of the solid material inside the block before curing is favorable, while the moisture distribution is not that good. After block curing, the moisture homogeneity was significantly improved.
Figure 7. Moisture content statistics of block layers; (a) Average moisture content; (b) CV of moisture content.

Figure 8. Dry density statistics of block layers; (a) Average dry density; (b) CV of dry density.

During the long-term curing process, the moisture in a newly compacted block will diffuse from the high moisture area to the low moisture area in the action of the moisture content gradient, and then promote the homogeneity of moisture content. However, due to over-compacting, the block had a large dry density, the movement of solid materials (bentonite and quartz sand particles) was largely restricted, and the degree of material migration was far lower than that of moisture diffusion. Therefore, during the curing process, the improvement of moisture homogeneity is more obvious, and the change of dry density was mainly affected by moisture diffusion.

4. Conclusions
Bentonite-sand buffer blocks with an initial moisture content of 17% were cured at different RHs to study the optimal curing RH environment. During the curing process, the blocks’ moisture content change, volumetric shrinkage, and the influence of curing process on the blocks' homogeneity of moisture content and dry density distribution were discussed. The following conclusions were obtained.
(1) RH100% is the best for curing the blocks with 17% moisture content. The experimental results show that a block will be dry at all RH environments, but the block’s equilibrium moisture content
will increase with the increase of curing RH. The blocks’ moisture content was 15.15% for the RH100% environment, 10.48% for the RH75% environment, and 6.92% for the atmospheric environment.

(2) The blocks’ deformation decreases with the increase of the curing humidity. The shrinkage strain of a block was lower than 1.0% for the RH100% environment, 1.5% for the RH75% and higher than 2.0% for the atmospheric environmental conditions.

(3) The curing process can promote the moisture homogenization of a block. A block curing in the RH100% environment resulted in the moisture homogenization demonstrated by the decrease of the coefficient of change (CV) of moisture content, that is, the CV of moisture content decreased from 5.35% to 1.07% after three months of curing.

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References
[1] National Research Council (US) Committee on Waste Disposal 1957 The disposal of radioactive waste on land. Washington D C: National Academies Press (US)
[2] IAEA 2013 Characterization of Swelling Clays as Components of the Engineered Barrier System for Geological Repositories. IAEA, Austria
[3] SKB 2010 Design, production and initial state of the buffer. TR-10-15, SKB, Sweden
[4] Torbjörn S 2014 Investigation of backfill candidate materials. R-13-08, Sweden: SKB
[5] Wang J, Chen L, Su R and Zhao X 2018 The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: planning, site selection, site characterization and in situ tests. Rock Mech. Geotech. Eng. 10(3), 411–435
[6] Xia Z T, Wu S X, Zhang B Z and Wang W 2020 Environmental Impact Report of China Beishan Underground Laboratory Construction Project. Beijing, Beijing Research Institute of Uranium Geology (In Chinese)
[7] TORBJÖRN S, L Börgesson and A Dueck 2008 KBS-3H Description of buffer tests in 2005-2007. R-08-40, Sweden: SKB
[8] PETER E 2018 Investigation of alternatives to the buffer protection. P-16-07, Sweden: SKB
[9] Tan Y, Zhang H Y, He D J and Zhang G C 2019 Deterioration of exposed buffer block: desiccation shrinkage and cracking. Bull. Eng. Geol. Environ.
[10] Markku Juvankoski 2013 Buffer Design 2012. POSIVA 2012-14, Posiva, Finland
[11] Zhang H, Ding Z, Tan Y, Zhu J and Cao Z 2019 Optimal curing humidity for compacted bentonite-sand mixtures. Rock Soil Mech. (Accepted, in Chinese)
[12] Eriksson P 2014 Basic engineering of buffer production system. P-14-11, SKB, Sweden
[13] Jouko Ritola and Erkko Pyy 2012 Isostatic Compression of Buffer Blocks-Middle Scale. Working Report 2011-62, Posiva, Finland
[14] Chen, L, Liu Y M, Wang J, Cao S F, Xie J L, Ma L K, Zhao, X G, Li Y W and Liu J 2014 Investigation of the thermal-hydro-mechanical (THM) behavior of GMZ bentonite in the China-Mock-up test. Eng. Geol. 172, 57–68
[15] Zhang H Y, Luo G, Yu R G and Wang Z M 2020 Study on compressive strength characteristics of bentonite-sand mixed block. Rock Soil Mech. (S2): 1-11
[16] Zhang H Y, Tan Y, Zhu F, He D J and Zhu J H 2019 Shrinkage property of bentonite-sand mixtures as influenced by sand content and water salinity. Constr. Build. Mater. 224, 78-88
[17] Zhou L, Zhang H Y, Yan M, Chen H and Zhang M 2013 Laboratory determination of migration of Eu(III) in compacted bentonite-sand mixtures as buffer/backfill material for high-level waste disposal. Appl. Radiat. Isot. 82, 139-144
[18] Zhu L P, Zhang H Y, Tan Y, Yuan W and Liu P 2018 The determination of the optimal
bentonite-sand ration based on fuzzy integrated evaluation. *Journal of Lanzhou University (Natural Sciences)*, 54(3):310-316 (In Chinese)

[19] Tan Y, Zhang H Y, Zhang T W, Zhang G C, He D J and Ding Z N 2021 Anisotropic hydro-mechanical behavior of full-scale compacted bentonite-sand blocks. *Eng. Geol.* Volume 287, 106093

[20] Zhang M, Zhang H Y, Jia L Y and Cui SL 2012 Salt content impact on the unsaturated property of bentonite-sand buffer backfilling materials. *Nucl. Eng. Des.* 250, 35-41

[21] ASTM D2216-19 2019 Standard Test Methods for Laboratory Determination of Moisture (Moisture) Content of Soil and Rock by Mass, ASTM International, West Conshohocken, PA