Compaction of large buffer block for disposal of high-level radioactive waste

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Abstract. The concept model of high-level radioactive waste (HLW) repositories in deep geological media is based on a multi-barrier system. In accordance with this concept for the storage of spent nuclear fuel, the canister with the fuel should be surrounded by bentonite blocks. A useful technique for producing compacted blocks of bentonite is described in this work. These blocks were uniaxially compacted with a mold that yielded blocks with an outer diameter of 1200 mm, inner diameter of 600 mm, and angle of 45 degrees. A technique has been developed for manufacturing blocks from GMZ-Na bentonite using a large press machine. During these tests, blocks were compacted for studying different factors that affect the quality of the blocks. The blocks were also examined with respect to damage and cracks. The results from these tests revealed that the natural water content of the bentonite powder leads to several problems that affect the quality of the blocks. In the subsequent test, the blocks were manufactured with different compaction rates using powders with high water content. Samples (nine cylindrical samples in total) were taken from the two examined blocks, and the water content and the density were determined. The results revealed that the solid block is rather homogenous. This indicates that the technique of compacting bentonite blocks established in the present study is suitable for manufacturing buffer blocks.

1. Introduction

The concept model of high-level radioactive waste (HLW) repositories in deep geological media is based on a multi-barrier system. In accordance with this concept for the storage of spent nuclear fuel, the canister with the fuel should be surrounded by highly compacted bentonite blocks. Two methods, isostatic compaction and uniaxial compaction, are typically employed for compacting blocks of bentonite. Considering the feasibility and the efficiency of manufacturing buffer blocks, the uniaxial compaction method is the most widely used technique worldwide.

Laboratory-scale mock-up tests and field tests considering the properties of a buffer material under coupled conditions focus almost exclusively on prefabricated bentonite blocks. These prefabricated blocks of full size and partial dimension are used in the uniaxial compaction method. In accordance with the Swedish concept for the storage of spent nuclear fuel, SKB also uses this method to manufacture the full-sized bentonite blocks in the Prototype Repository test and Canister Retrieval Test. The final height, outer diameter, and inner diameter of the blocks placed around the canister are 477–540 mm, 1650 mm, and 1070 mm, respectively. The compaction of the bentonite is achieved with
a press which, after upgrading, has a maximum capacity of 30000 tons. The compaction is performed using a stepwise approach, where the load is increased to the desired level in 10-min intervals. The maximal load is then applied for 10 min, and the unloading of the mold is then performed for 10 min [1].

A large experiment at almost full scale and under controlled boundary conditions, referred to as the FEBEX-Mock-up test, is performed by ENRESA. The tested material is FEBEX bentonite, which mainly consists of montmorillonite. The material is used in the form of compacted blocks in the mock-up test. The blocks are manufactured via uniaxial compaction of the corresponding clay. An average water content of 14% and a dry density of 1770±20 kg/m³ are realized. A single-acting, uniaxial hydraulic press is used to fabricate the blocks. The compaction force is provided by three successive strokes of 40 MPa to 50 MPa pressure. The blocks have been arranged in 48 sections: 26 sections of two concentric rings around the heaters and 22 other sections of two rings and a core [2].

The Mock-Up-CZ experiment simulated the vertical placement of a container with radioactive waste, an approach that is consistent with the Swedish KBS-3 system. The physical model consisted of a barrier composed of bentonite blocks, powdered bentonite backfill, a heater, and hydration and monitoring systems. The basic material used in the experiment consisted of a mixture of Czech bentonite from Rokle deposit (85%), quartz sand (10%), and graphite (5%). The bentonite mixture as used in the Mock-Up-CZ experiment is highly compacted to a dry density of 1760 kg/m³ via uniaxial compaction [3].

The KAERI Engineering-scale T–H–M Experiment for an Engineered Barrier System (KENTEX) was designed as an intermediate-scale test of the reference disposal system. The system is a steel body with a length of 1.36 m and an inner diameter of 0.75 m. The bentonite blocks are fabricated from Kyungju bentonite, which is being considered as a candidate buffer for the reference disposal system. The average gravimetric water content of the blocks is 13% and the average dry density of the blocks in the confining cylinder is 1500 kg/m³. Furthermore, 176 blocks are placed in 16 sections of the confining cylinder [4].

The compressibility of GMZ Na-bentonite with different water content and different compacted density has been considered in previous studies. The results revealed that GMZ Na-bentonite with 15% water content is easily compacted to high density [5]. Molds were used to compact the bentonite into cubic and fan-shaped blocks. The compactibility and the compressive behaviors of the blocks were analyzed, and curve fitting equations were established. The results showed that the compactibility and the compressive behaviors are affected greatly by the compacting dry density, moisture content and other factors. The interactions between the bound water of bentonite and the particle surface of the bentonite played a key role in this property and behaviors. A minimum compacting pressure was required when the water content of the compacted bentonite block reached 14%–15%, and these blocks exhibited better compactibility than the other blocks [6].

The compaction properties of GMZ001 bentonite-sand mixtures with sand additions ranging from 0% to 50% are studied via standard and modified proctor compaction tests. Furthermore, static compaction tests under pressures of 20 MPa and 50 MPa are designed. The test results show that the relationship between the maximum dry density and optimum water content of the mixture specimens prepared through different compaction methods with different compaction efforts is described by the same power function. However, linear correlations are obtained for mixture specimens prepared through different compaction methods and the same compaction efforts [7].

A series of compaction tests employing various L/D ratios are performed in this study, and the compression equation developed by Gurnham is applied to obtain the friction-free compressive curve of a bentonite block. This friction-free compaction curve can eliminate the wall friction force and the geometric effect. The effects (stress rate, wall lubrication, and crushed rock content) that may influence the friction force during the compaction procedure are analyzed and discussed [8].

In this paper, a useful technique for producing large compacted blocks of bentonite is described. These blocks are uniaxially compacted with a mold and are characterized by an outer diameter of 1200 mm, inner diameter of 600 mm, and angle of 45 degrees.
2. Material and equipment

2.1. Material
The test is performed with a GMZ Na-bentonite from the northern Chinese Inner Mongolia autonomous region, 300 km northwest of Beijing. The processing at the factory consisted of disaggregation and gently grinding, drying under natural conditions, and sieving with 200 meshes. The mineralogical composition of the GMZ Na-bentonite is analyzed via X-ray diffraction. The results revealed that the clay mineralogy is dominated by montmorillonite (47.7%), which is essential for ensuring the sealing properties. Furthermore, the GMZ bentonite also contains variable quantities of quartz (23%), feldspar (16.6%), cristobalite (0.9%), clinoptilolite (7.3%), and mica (1.2%).

The hygroscopic water content of the bentonite in equilibrium with the laboratory atmosphere is \(\sim 8.7\%\). Bentonite with water content levels of \(\sim 8.7\%\) and \(13\%\) is used for the blocks. To realize a water content of \(13\%\), water is added to the bentonite in a mixer. The mixing of the bentonite is performed in a mixer and the maximum batch that can be handled is \(\sim 30\) kg. This water content and the total amount of bentonite are used for calculating the amount of water required to determine the final water content. Each batch is mixed for \(\sim 10\) min and the water is gradually added during the mixing process. The final water content of the batches is determined from drying small samples at \(105^\circ\)C for 48 h. After mixing, the bentonite is stored in sealed boxes in order to prevent water volatilization, and the average water content is \(13\% \pm 1\%\).

2.2. Equipment
A technique has been developed for manufacturing blocks from GMZ-Na bentonite using a large press machine (maximum capacity: 2000 tons) and a steel mold.

A computer-controlled press machine and a specially designed steel mould are used to compact the bentonite powder via static uniaxial compaction until the desired density and height of the fan-shaped compacted blocks are reached. The mold consists of three main parts, a bottom plate, a confining outline border which can withstand a high radial pressure, and a piston, as shown in figure 1. After the mold has been prepared, the required amount of bentonite for one block is slowly poured into the mold by hand, and a crane is used to place the piston on the surface of the bentonite. The filled mold is then placed in the platform of the press, and the compaction process starts with the preparation. The compaction pressure is then applied and increased gradually until the desired height of the block is reached. After compaction, the mold is dismantled, and the block is removed from the bottom plate using specially designed lifting equipment. The weight of bentonite used for the blocks, time for compaction, maximum compaction force, hold time at the desired height, and time for reloading are all noted in a protocol.

Figure 1. Vertical view of the mold
3. Results of the compaction tests

Altogether, 12 blocks (four blocks with natural water content and eight blocks with high water content) are compacted. These blocks are uniaxially compacted with the mold. Blocks with outer diameter, inner diameter, height, weight, and angle of 1200 mm, 600 mm, 200–250 mm, 30–60 kg, and 45 degrees, respectively, are obtained. The influence of the water content and the compaction rate on the block quality is investigated. After compaction, the height and diameters of each block are measured, and the finished blocks are inspected by eye for outer defects. Any observed damage and cracks are noted in the protocol.

3.1. Influence of water content

The integrality and homogeneity are the main indices used to evaluate the quality of the compacted blocks. After compaction, the cracks in the blocks and other damage are examined by eye. During the compaction tests, damage and cracks occur in many blocks. Some damage and cracks are prevalent on blocks with low water content while other types occur at high water content. The observed damage can roughly be divided into the following groups: damage caused by the dismantling of the mold and damage caused by material sticking to the inside of the mold and piston. Similarly, the groups of cracks result from brittle edges of the blocks, friction between the mold and bentonite, and the elastic swelling at unloading.

Owing to the low cohesion of the bentonite and high friction between the mold and bentonite, damage occurs at almost all four blocks with natural water content. Cracks caused by the elastic swelling at unloading occur mainly in the blocks with low water content. The measures parameter shows that samples containing bentonite with low water content undergo significant elastic volume expansion after compaction. Owing mainly to the excessively wide gap between the piston and the mold, damage and cracks occur on the brittle edges of the blocks. The pressure added by the large press machine can only be partly applied to the bentonite.

The blocks can be damage due to friction between the bentonite and the mold, and the expansion during unloading and dismantling from the mold. To prevent this damage, bentonite with relatively high water content should be used during testing. Various small-compaction tests revealed that the appropriate water content ranges from 12% to 17%. Homogeneous mixing of the bentonite powders is difficult to achieve at content higher than these levels, and the blocks may stick to the inside of the mold. After the blocks are removed from the mold, material can adhere to the mold and this material lost from the blocks may lead to large cavities on the surface of the blocks.

From the viewpoint of the integrality, the natural water content and extremely high water content of the bentonite powder is unsuitable for manufacturing highly compacted large blocks. The problems are discovered and solved during the test series. An optimum technique that yields blocks of good quality at the desired density and height is employed in the subsequent steps.

3.2. Influence of compaction rate

The effect of the compaction rate on the homogeneity of the compacted blocks is determined via compaction tests conducted at stain rates ranging from 1 mm/min to 10 mm/min.

Various tests are performed on GMZ Na-bentonite with dry density and height of 1.7–2.0 g/cm³ and 200–250 mm, respectively, as shown in table 1. Three different press velocities, ranging from 1 mm/min to 10 mm/min, are used for a fixed water ratio of ~13%.

| Block number | Weight/kg | Height/mm | Water content/% | Dry density/g/cm³ | Compaction rate/mm/min |
|--------------|-----------|-----------|-----------------|-------------------|-----------------------|
| 2018-S05     | 43.32     | 200       | 13.48           | 1.8               | 1                     |
| 2018-S06     | 43.25     | 200       | 13.32           | 1.8               | 5                     |
From the viewpoint of integrality, almost all the bentonite blocks compacted with high water content exhibit good quality. Samples are taken from several locations in blocks 2018-S05 and 2018-S07, as shown in figure 2. Approximately nine cylindrical samples each with a diameter of 72 mm are drilled from the blocks. Afterward, the cores are cut into nine small nine pieces (height of each piece: 20 mm) from which the water content and the dry density are determined. The parameters of the cores are calculated from the mean values of the water ratio and the density of each piece. The average parameter of the eight cores is presented in table 2.

![Figure 2](image_url)

**Table 2.** Parameters of each sample core

| block number | sample number | water content/% | dry density /g/cm³ | bulk density /g/cm³ |
|--------------|---------------|-----------------|--------------------|---------------------|
| 2018-S05     | 5-1           | 13.41           | 1.72               | 1.95                |
|              | 5-2           | 13.47           | 1.72               | 1.95                |
|              | 5-3           | 13.45           | 1.71               | 1.95                |
|              | 5-4           | 13.53           | 1.71               | 1.94                |
|              | 7-1           | 13.21           | 1.71               | 1.94                |
| 2018-S07     | 7-2           | 13.22           | 1.72               | 1.95                |
|              | 7-4           | 13.45           | 1.72               | 1.95                |
|              | 7-5           | 13.59           | 1.72               | 1.95                |
The dry densities of the eight cores are plotted as functions of the distance from the bottom of the blocks shown in figures 3 and 4. The results show that the dry density varies only slightly along the height direction of the blocks. The largest difference between the maximum and minimum dry density in a block compacted with high pressure (0.05 g/cm$^3$) is ~3% of the average dry density. The figures and parameters indicate that the density distribution of the blocks is relatively independent of the compaction rate. This also suggests that for the same buffer material and desired blocks, the compaction rate has only modest impact on the formability and uniformity of the blocks. Therefore, in order to improve the efficiency of compacting, a suitable increase in the compaction rate employed during the industrial process of manufacturing buffer blocks is required. Based on the designed density and height of the bentonite blocks, the displacement of the large press machine was held at the desired height for ~30 min. The pressure was, accordingly, applied to the surface of the bentonite in order to restrict the rebound of the blocks. This procedure proved very useful in controlling the density and height of the blocks.

![Figure 3](image3.png)

**Figure 3.** Dependence of the dry density on the height of block number 2018-S05

![Figure 4](image4.png)

**Figure 4.** Dependence of the dry density on the height of block number 2018-S07

4. **Conclusions**
A technique has been developed for manufacturing large buffer blocks from GMZ-Na bentonite using a large press machine. During these tests, blocks are compacted for studying different factors that
affect the quality of the blocks. Based on the results of the compacted bentonite blocks, several preliminary conclusions can be drawn:

Several problems (such as damage and cracks) affect the quality of the blocks, owing to the natural water content of the bentonite powder. From the viewpoint of the integrality, the natural water content of the powder is unsuitable for manufacturing the highly compacted large blocks.

The density distribution of the blocks compacted with high water content seems relatively independent of the compaction rate. A significant increase (by 10 times) in the rate has no effect on the distribution. The result is very useful for the industrial compaction procedure.

The technique of compacting large bentonite blocks established in this study is suitable for manufacturing buffer blocks.

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