

THE USE OF ISOSTATIC COMPRESSION TO PRODUCE FULL-SCALE HIGHLY COMPACTED BENTONITE BLOCKS

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Abstract

A feature of the NWMO buffer design concept involves pre-packaging the used fuel container in a rectangular shaped, Highly Compacted Bentonite (HCB) over-pack to form a Buffer Box. The shape and dimensions of the Buffer Box concept are unique to the Nuclear Waste Management Organization. To simplify assembly of the Buffer Box, the over-pack consists of a top and bottom HCB block with cavities for the used fuel container. This requires pressed blocks of approximately 0.5 m x 1 m x 3 m.

The NWMO undertook a program to manufacture large blocks by cold-isostatic pressing in order to develop an understanding of the process and to verify that design requirements can be met, specifically a uniform minimum dry density of 1.7 g/cm³. An initial ¼ scale program produced a 700 kg HCB block with an average dry density of 1.745 g/cm³ and a moisture content of 19.7%.

Following the success of the ¼ scale block program equipment and tooling were developed to produce rough, near net shape full-size blocks at approximately 0.56 m x 1.07 m x 3.20 m. These dimensions are maximized due to the limitations of available presses. This tooling allowed us to produce full size blocks weighing approximately 4000 kg and with dry densities of ≈ 1.74 g/cm³ at a bentonite moisture content of $\approx 20\%$.

Keywords: Bentonite, Cold-isostatic Pressing

1. Introduction

In the NWMO design concept, the used fuel container is pre-packaged in a rectangular shaped, Highly Compacted Bentonite (HCB) over-pack to form the Buffer Box. In this concept, the HCB over-pack consists of a top and a bottom block with cavities for the used fuel container. Each block requires near net shape pressed blocks of approximately 0.5 m x 1 m x 3 m.

Several international nuclear waste management organizations are manufacturing blocks for their specific storage concept. However, the Canadian program is unique due to the specific shape and size of the Buffer Box. The high volumetric compaction of bentonite requires a large mold, which in turn requires a large cold-isostatic press. Unfortunately, these commercially-available presses are rare.

The purpose of this work was to develop an understanding of cold-isostatic pressing and to initiate a program to manufacture HCB blocks for the NWMO Buffer Box concept. These HCB blocks would be full scale and meet the dry density requirement of 1.7 g/cm³. This paper will cover the development of the NWMO HCB block manufacturing and verification program.

This paper will present; a description of the isostatic press tooling, including the container, the latex rubber bag, the bentonite loading process, and the isostatic pressing; and the confirmatory inspection and testing process.

2. Background

2.1 Bentonite

The bentonite buffer serves multiple roles in the engineered barrier system. Its swelling characteristic fills voids to block pathways for radionuclide migration and provides support to the surrounding rock and container. Its low permeability inhibits porewater flow to and from the container and its sorption properties inhibit radionuclide movement in the event of container breach. The bentonite also transfers heat from the container to the surrounding rock. Perhaps most importantly, at the right dry density, it reduces water activity to <0.96 [1]. This is required to suppress microbiologically influenced corrosion of the used fuel container. Given the geometry of the placement room and the requirement to be suitable in both sedimentary and crystalline rock geospheres, The NWMO requires a minimum HCB block dry density of 1.7 g/cm³.

Prior to initiating the large block pressing program, trials were carried out using a small scale uniaxial brick maker to determine suitable moisture content and bentonite type. The NWMO brick maker produced HCB bricks (360 mm x 105 mm x 100 mm), and was used to evaluate two types of raw bentonite, MX-80 and National Standard. The primary difference between the two types is the particle size distribution. The MX-80 has a similar particle size distribution to fine to medium grained sand, whereas the National Standard bentonite is of clay and silt size particles. Bricks of both types were pressed at varying moisture contents and it was found the MX-80 at a moisture content of 20% consistently produced bricks with the highest dry density. Based on this, MX-80 at 20% moisture content was used for the ¼ scale HCB block.

2.2 Cold Isostatic Pressing

The NWMO is considering cold isostatic pressing (CIP) as the reference process for manufacturing HCB blocks. Cold isostatic pressing is also known as wet bag pressing, where the material is loaded into a

flexible rubber bag, supported by a perforated metallic container. The bag is sealed and the assembly placed in a pressure vessel where it is hydrostatically compressed at high pressure. The flexible bag and powder is compressed with the powder uniformly in all directions. The result is a more uniform density distribution throughout the pressed bentonite compared to uniaxial pressing 10[2].

3. Quarter and Full Scale HCB Block Trials

The NWMO program to press full scale blocks was developed in a sequential manner. Prior to pressing a full scale block, a quarter scale block was pressed using CIP methods. Following the quarter scale block pressing program, the same suppliers were selected to (i) blend the large scale batches of bentonite; (ii) fabricate the full scale perforated container and isostatic bags; (iii) load the blended bentonite into the container; and (iv) press the bentonite using the CIP method.

3.1 Large Scale Blending for Cold Isostatic Pressing

The supply and blending of the MX-80 was contracted to Caldic Canada Inc. The material was blended with a Marion mixer. Caldic supplied 4 metric tons of blended MX-80 Bentonite for the $\frac{1}{4}$ scale program and 16 metric tons of blended MX-80 Bentonite for the full scale trial work.

3.2 Isostatic Press Tooling

The NWMO worked with the Trexler Rubber Company of Ravenna, Ohio to fabricate the latex rubber bags and tooling needed to press both the $\frac{1}{4}$ and full scale blocks. Trexler Rubber fabricated a custom perforated container and isostatic bags for these block trials. Figure 1 shows the $\frac{1}{4}$ scale container (left) along with the rubber isostatic bag installed on the right.



Figure 1 – Quarter Scale Container (left) and with Isostatic Bag (right)

3.2.1 Full Scale Isostatic Container

The isostatic container for the full size block was designed and fabricated by Trexler so that it could be disassembled into 4 pieces (Figure 2 - left). Disassembly of the container is necessary to facilitate block removal. The 3.86 m high container is made from structural steel and weighs 2688 kilograms. The container is designed to maximize the space within the 1.524 m (inside diameter) press at the Advanced Research Lab at the Pennsylvania State University. To ensure the bag would be properly filled with no folds or voids, a vacuum can (Figure 2 - right) was designed and built to be setup on the outside of the perforated container during filling. Applying a vacuum pulls the bag tightly against the inside of the container thereby eliminating any bunching or creasing of the rubber bag.



Figure 2 – Full-size Block Isostatic Container (left), Vacuum Can Assembly (right)

3.2.2 Latex Rubber Bag

The latex rubber bags were sized to ensure the near net shape was large enough to allow for trimming of the block. The inside dimensions of the full scale bag are 0.66 m x 1.27 m x 3.78 m with a wall thickness of 3.2 mm. The bag and latex rubber top weigh 57 kg. Due to the weight of the bag, a special tool was made to help hoist the bag up to lower it into the isostatic container. This was the largest bag Trexler Rubber has made and required modifications to their dip tank.



Figure 3 - Isostatic Bag rolled for installation (left), Bag secured over Vacuum Can (right) prior to bentonite loading for the full scale blocks

3.3 Bentonite Loading

The Isostatic bags and containers were loaded with blended MX-80 bentonite at 20% moisture content at NWMO's test facility in Oakville Ontario. For the ¼ scale block no additional actions were taken to further densify the initial bentonite charge (e.g. vibration) whereas a concrete vibrating wand was used for the 2 full scale blocks.

Full scale Block #1 was loaded in August 2015. The blended MX-80 bentonite was delivered in 1 m³ lined totes, each weighing approximately 900-950 kg. After each bag was hoisted above the container and emptied into the isostatic bag, a concrete vibrating wand was repeatedly lowered into the bentonite to densify the material. The use of the wand allowed for more material to be placed into the isostatic bag. The rubber topper and aluminum lid were then installed and sealed with Ruscoe #4 cement.

Prior to shipping the full scale blocks, a vacuum was connected to the rubber top to evacuate any latent air in the bag during the loading process. This is an important step due to the high compaction the bentonite undergoes at pressure. The volume reduction of the bentonite is between 35% and 40%, leaving a large volume of air after compaction, if it is not evacuated. The concern is that if the bag becomes pinched under the block, and doesn't allow the bag to re-expand to volume at atmospheric pressure, the bag could rupture. For Block #1, the vacuum was applied for 24 hours to ensure enough air was evacuated to prevent the bag from ballooning when de-pressurizing the vessel.

Block #2 was loaded in October 2015 in the same manner as Block #1. For Block #2, the concrete vibrating wand that was used was not as effective as the one used for Block #1 and resulted in less compaction and settling while loading. This resulted in less MX-80 being loaded, only 4000 kg. The result is a slightly smaller block. Additionally, for Block #2, the vacuum was left on for approximately 46 hours. Some observations from this were that the vacuum was left on long enough that the bentonite compressed slightly under atmospheric pressure.

3.4 Isostatic Press

The large Cold Isostatic Presses needed to make the full size block are rare. No suitable commercial presses were found in Canada and only three were located in the USA. It was important to locate a press that could accommodate the full size block so that the block size could be increased if the quarter scale block trials were successful.

Of the facilities located, the Advanced Research Lab (ARL), High Pressure Test Facility at the Pennsylvania State University (Penn State) was the best suited to accommodate the development work. The pressure vessel has an inside diameter of 1.524 m, an inside void length of 4.191 m, and a peak operating pressure of 110 MPa.

3.5 Bentonite Pressing

The loaded containers were shipped to the Penn State ARL and then inspected. The blocks were pressed without incident and returned to the NWMO Oakville facility for inspection and testing.

The pressure loading sequence for the ¼ scale block is shown in Figure 5 and is representative of the sequence for the full scale blocks. The isostatic pressure was raised slowly to 100 MPa, for a period of approximately 36 minutes, held constant for roughly 10 minutes and then returned to atmospheric pressure over a 50 minute period.

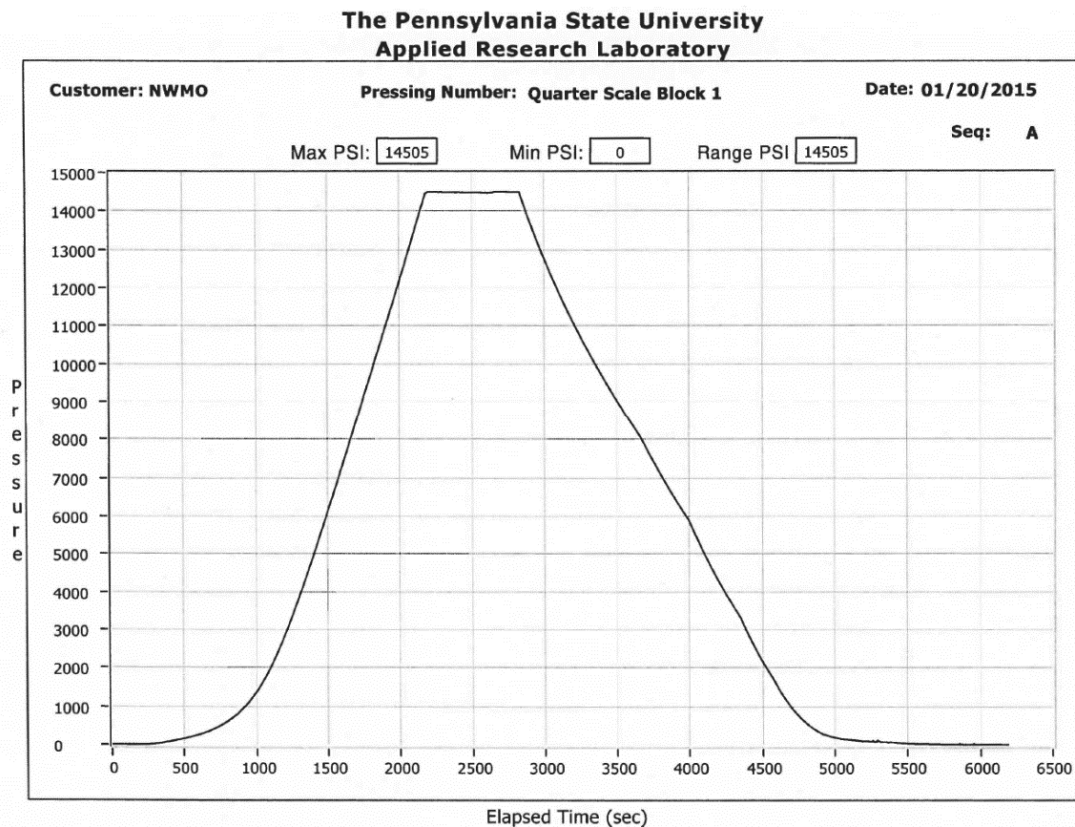


Figure 4 - ¼ scale Block Trial Pressure vs. Time

4. CHARACTERIZATION PROGRAM

Once the blocks were returned to the Oakville facility, the containers were disassembled and the bags and blocks were examined. A characterization program was followed that included a visual assessment of block quality, as well as the sampling of the pressed block for moisture and dry density, and for mechanical properties. The blocks were contained within the rubber bag or wrapped in a plastic vapor barrier so as to not expose them to the relatively dry humidity within the laboratory. The following describes the characterization of the ¼ scale block and the first 2 full scale blocks pressed by NWMO.

4.1.1 Block Sampling Program

Each of the blocks were sectioned into either five or six reference lines and evenly spaced core holes were drilled over the surface of the block. Prior to coring the blocks, scaffolding was assembled over the blocks so the drill could core without disturbing the bentonite. A dust extractor was used during the coring process to control dust. Concrete coring apparatus was used to drill 64 mm (2 1/2 inch) diameter holes for the moisture and dry density determinations as well as for the triaxial and the unconfined compressive strength (UCS) testing. The cores were drilled to an approximate depth of 300 mm from the surface of the block. Water was not used in the coring process so as not to impact the properties of the bentonite.

4.1.2 Sample Preparation and Testing Program

The samples collected for moisture and dry density determination were measured, weighed and then placed in the oven to determine the dry density of the sample as per ASTM D2216. The cores collected from the moisture and dry density core holes were cut into three sections from the approximate depths of 10 to 60 mm (upper disk), 65 mm to 115 mm (middle disk) and 135 mm to 185 mm (lower disk). The upper disk represented near surface conditions and the lower disk represented the HCB as the centre of the block. The diameter and the length of the core samples were measured using calipers. The mass of the core before and after drying was measured using a calibrated Ohaus scale with a readability of 0.01 g, and a capacity of 3100 g. Both the diameter and length of the core was measured 3 times and the average measurement was used to calculate the volume. The diameter of select samples of the core was confirmed using the 3-dimensional imaging equipment. For the quarter scale block additional tests were also carried out for unconfined compressive strength, elastic (Young's) modulus and Poisson's ratio (ASTM D7012), and Brazilian splitting tensile strength (ASTM D3967).

5. OBSERVATIONS

5.1 Visual Observations and Scan Results

Prior to exposing the pressed bentonite blocks, the conditions of the bags were noted. The bag for Block #2 was pulled tight against the block, whereas for Block # 1 there is evidence that some air remained in the bag as shown in Figure 5. This likely occurred due to the longer vacuum hold pre-compaction of Block #2.

After each press, the condition of the bag is examined for damage to determine if it can be re-used. Although there were no through wall tears in the bag used for block #1, there were several areas of concern and the bag was not re-used. The bag used for block #2 was in good condition after pressing and was re-used to press a third block.



Figure 5 - Block #1 before Removal (left), Block #2 before removal (right)

Photographs of the $\frac{1}{4}$ scale block and the full scale blocks are shown in Figure 6, and a summary of the pressed geometries is listed in Table 1. No cracking of the blocks were observed upon the immediate uncovering of the blocks, and the edges were found to be in good condition. No zones of spalling, flaking or fissured areas were noted once the blocks were unwrapped. It should be noted that minor surface cracking of the block became evident once the block was exposed to the dry air of the air for a period of roughly 2 hours. The quarter scale block was also scanned with a laser Faro arm and the deviation in comparison to the design block showed that the block was formed to within 25 mm of its design shape.

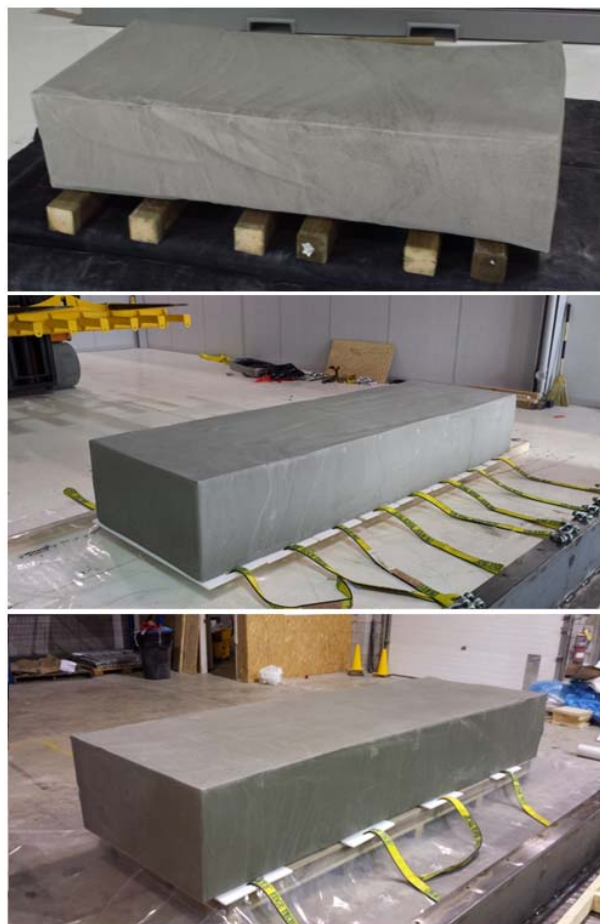


Figure 6 - 1/4 Scale HCB Block (top) Block #1 Unwrapped (middle), Block #2 Unwrapped (bottom)

Table 1 - Block Final Dimensions

Block	L (mm)	W (mm)	H (mm)
¼	1486	698	318
Full – 1	3280	1075	560
Full – 2	3270	1070	550

5.2 Results of Moisture Content, Dry Density and Other Test Results

The calculated moisture and dry density values for each of the collected samples are tabulated in Table 2. For the three blocks tested, each of the 194 samples collected exceeded the minimum required dry density of 1.7 g/cm³. A similar standard deviation was noted between the three blocks and deemed to be insignificant. It should also be noted that no significant redistribution of moisture occurred during pressing, and only an insignificant amount of moisture was lost, if any, and this was likely due to loss during handling of the core and the dry coring process. The individual core results were also reviewed to assess whether there was any significant deviation in the moisture contents and the dry densities of the samples in relationship to the location of the samples, and none was noted. The average dry density and moisture content for the blocks as well as the standard deviation for density correlates well with the relationship described by Ritola and Pyy [3] for an isostatic compression pressure of 100 MPa. The visual uniformity of the HCB block was confirmed by the uniformity of the test results.

Table 2 - Summary of dry density testing program

Block	# of core holes for ρ_d and w	# of samples	Max. dry density (ρ_d) (kg/m ³)	Min. dry density (ρ_d) (kg/m ³)	Avg. dry density (ρ_d) (kg/m ³)	Standard deviation (ρ_d) (kg/m ³)	Average moisture content (w) (%)	Standard deviation moisture (w) (%)
¼ scale	31	89	1758	1729	1745	6.5	19.7	0.2
Full 1	25	75	1759	1738	1747	4.7	20.0	0.1
Full 2	10	30	1747	1727	1738	5.8	20.4	0.2

A contractor was provided with samples of the core from the quarter scale block. The average dry density matched the value determined in the NWMO program, and the average of 9 tests on core samples for; (i) unconfined compressive strength tests was 8.0 MPa. (ii) Young's modulus tests was 700 MPa, (iii) Poisson ratio was 0.36; and (iv) splitting tensile strength was 0.8 MPa. The results of the Unconfined Compressive Strength tests showed the average strength of the pressed bentonite to be similar to a weak rock or a lean mix concrete.

6. Conclusion

Based on the Block pressing program and subsequent coring program, the following conclusions can be drawn:

- Large scale blocks that can be shaped into a single Buffer Box top or bottom can be pressed using commercial suppliers and a large isostatic press.

- b) A uniform block was pressed under an isostatic pressure of 100 MPa to within 25 mm of the expected dimensions.
- c) The resulting dry density for both the quarter and full scale blocks exceeded the minimum required dry density of 1.7 g/cm³. These dry densities were similar to other large scale blocks pressed to similar pressures.
- d) The strength of the blocks were similar to that of a very weak rock or a lean concrete mix.

This work has demonstrated the feasibility of manufacturing HCB blocks to the required size and dry density requirements for the Canadian Deep Geological Repository.

7. References

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