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Manufacturing of large scale buffer blocks

Uniaxial compaction of block – test made with three different bentonites

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Abstract

In accordance with the Swedish concept for the storage of spent nuclear fuel, the canister with the spent fuel should be surrounded by bentonite blocks. These blocks are uniaxial compacted and have a final height between 477 and 540 mm, an outer diameter of 1 650 mm and an inner diameter of 1 070 mm for the blocks placed around the canister. Up to now, these blocks have been compacted in a conical mould having an outer diameter at the top that is about 20 mm smaller than the outer diameter at the bottom to facilitate removal of the block from the mould. A lubricant has also been applied on the mould to reduce friction between mould and bentonite. A large number of blocks have been manufactured using this method but mainly with the bentonite MX-80. The method assumes that the blocks after compaction are machined to their final dimensions. This requires both additional equipment, in this case a milling machine, and space in the production plant. Furthermore, since the material which has been machined off the blocks contains lubricants, this cannot be recycled into the manufacturing process again.

In this study, three different bentonites have been used at the manufacture of buffer blocks, Bulgaria 2017, BARA-KADE 2017 and India 2018. For these test was a conical shaped mould use. The compaction was made as part of the design of the buffer within the project KBP1015 with good results for two of the chosen materials. For the third material, India 2018, cracks could be observed on the first block. The reason for this is probably due to the material being purchased as a very fine powder but it is expected that the issue could be avoided by using a granular size distribution with less fine material. After adjusting the pressing technique, another two blocks with acceptable quality was produced also with this material.

In an effort to minimize the need for machining the blocks an older mould was modified by placing a liner inside the conical shaped mould, which allows pressing of cylindrical blocks and still retain the advantage of the conical mould in conjunction with the removal of the block from the mould. This work was dome as a part of the project KBP1017. Six blocks were compacted with the modified mould with good results. Compaction without lubricant was also carried out with good results.

Sammanfattning

I enlighet med det svenska konceptet för lagring av använt kärnbränsle ska kapseln med det använda bränslet omgärdas av bentonit i form av block. Dessa block kompakteras enaxligt och har en slutlig höjd mellan 477 och 540 mm, en ytterdiameter på 1 650 mm samt en innerdiameter på 1 070 mm för de block som placeras runt kapseln. Fram till idag har dessa block kompakterats så att blocken har en ytterdiameter i toppen som är ca 20 mm mindre än ytterdiametern i botten, detta för att underlätta uttryckningen av blocket ur formen efter kompaktering. Ett smörjmedel har också applicerats på formen för att minska friktionen mellan form och bentonit under kompaktering. Ett stort antal block har tillverkats med denna metod där i huvudsak MX-80 har använts som material. Metoden förutsätter att blocken efter kompaktering bearbetas till slutlig form. Eftersom det material som bearbetas bort innehåller smörjmedel kan detta inte återanvändas i tillverkningsprocessen.

I denna undersökning har tre olika bentoniter använts vid tillverkningen av buffertblock, Bulgaria 2017, BARA-KADE 2017 och India 2018. Dessa försök genomfördes med en konisk form. Kompakteringen gjordes som en del av designen för bufferten inom projektet KBP1015 med gott resultat för två av materialen. För det tredje materialet, India 2018, blev resultatet inte det förväntade, detta på grund av att materialet köpts som ett mycket fint pulver. Kvaliteten blev inte acceptabel på det första tryckta blocket. Genomgående sprickor kunde observeras. Bedömningen är att problemen kan undvikas om materialet levereras med mindre finmaterial. Efter justering av pressningstekniken kunde två block med acceptabel kvalitet produceras.

I syfte att minimera behovet av att bearbeta blocken efter pressning modifierades en äldre form genom att ett foder placerades innanför den konformade formen, vilket möjliggjorde pressning av cylindriska block samtidigt som fördelen med den koniska formen i samband med avformningen bibehölls. Detta arbete gjordes som en del av projektet KBP1017. Sex block kompakterades med den modifierade formen med gott resultat. Även kompaktering utan smörjmedel genomfördes med gott resultat.

Contents

1 Introduction

In accordance to the Swedish concept for disposal of spent fuel (KBS-3) a canister, containing the spent fuel, is deposited in vertical deposition holes in crystalline rock at a depth of about 500 m surrounded with compacted blocks of bentonite. The configuration of the blocks is shown in Figure 1-1. The buffer consists of four types of blocks, see Figure 1-2, and they are compacted uniaxial with a somewhat conical shape of the outer surface of the blocks i.e. the upper diameter of the blocks is about 20 mm smaller than the lower diameter after compaction. Furthermore, a lubricant is used at compaction in order to minimize the friction between the bentonite and the mould. This lubricant is applied to the surfaces of the mould prior to compression and can thus contaminate the compacted blocks. The technique has been used for several years for producing buffer blocks for experiments and tests managed by SKB.

Up to now, all of the manufactured large scale blocks have been compacted with the bentonite MX-80 and therefore there is need for testing the technique with other types of bentonite. The *first objective* with this project is to, as a part of the project KBP1015, manufacture blocks with three bentonites, denoted India 2018, Bulgaria 2017 and BARA-KADE 2017, with the technique described above.

In order to get buffer blocks with a cylindrical outer surface the blocks must be machined to their final dimensions. Furthermore, the lubricants on the surfaces of the blocks must be removed, also by machining of the blocks. This implies that the material which is machined off the blocks is contaminated with the lubricant and thus cannot be recycled into the manufacturing process again. This material must be deposit in a landfill which causes extra costs. The *second objective* with this project is to, as a part of the project KBP1017, modify the compaction technique in order to minimize the need of machining of the blocks after compaction and, as a *third objective*, ensure that the machined off material can be reused in production and therefore exclude the lubricant at the compaction.

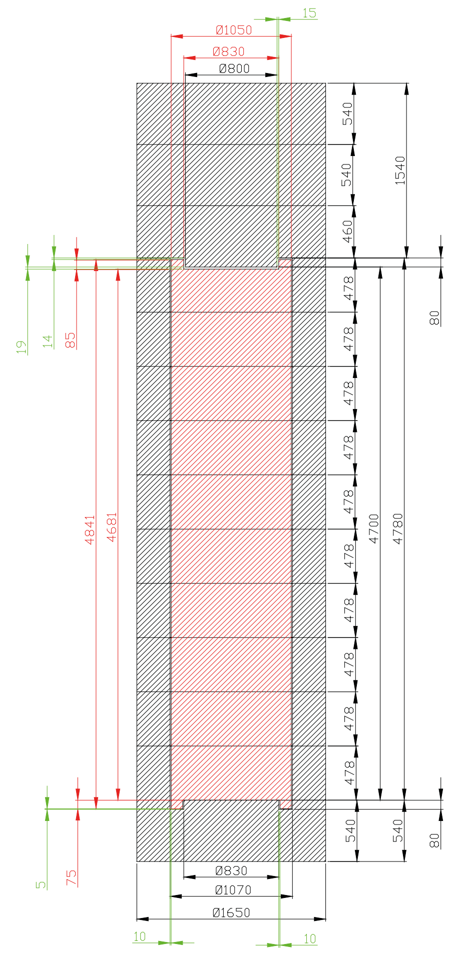


Figure 1-1. *The configuration of buffer blocks in a deposition hole.*

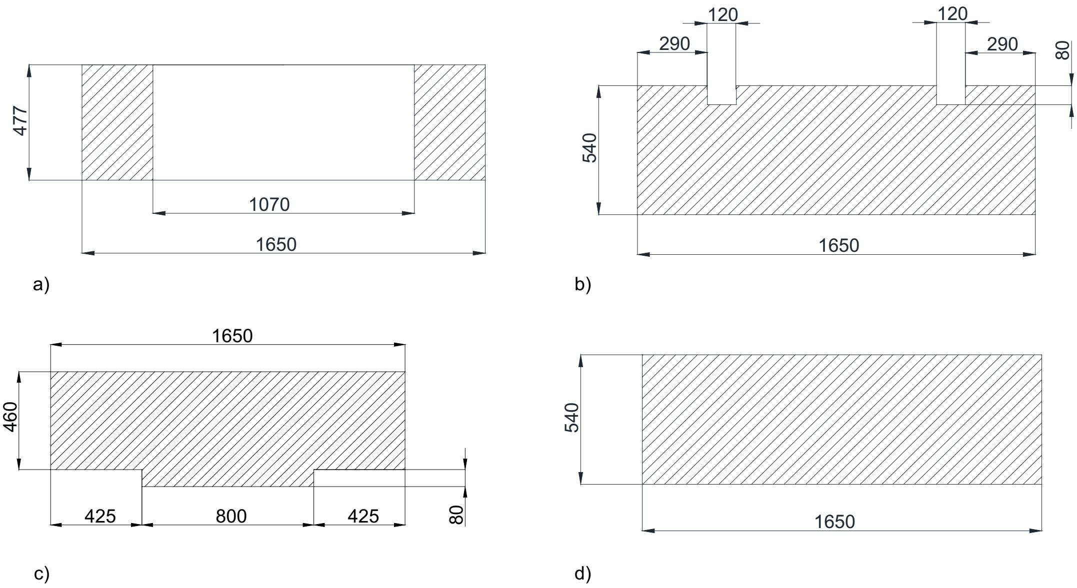


Figure 1-2. *Nominal dimensions of buffer blocks for a) the ten ring-shaped blocks surrounding the canister, b) the solid block at the bottom of the deposition hole, c) the block at the top of the canister and d) the four most upper solid blocks in the deposition hole. Note that the acceptable variation for all of the specified dimensions is ± 1 mm.*

2 Mould design

Two different moulds are used in the performed tests. The testing of compaction of different bentonites is made with a mould which originally was constructed for compacting blocks for horizontal disposal (KBS-3H). Blocks compacted with this mould is somewhat larger than the blocks for KBS-3V, see Figure 2-1. The compacted blocks have an outer diameter at the top of about 1 775 mm and at the bottom of about 1 800 mm. The inner diameter of the ring shaped blocks is about 1 055 mm. In order to get the desired dimensions of the blocks, see Figure 1-2, a large amount of bentonite must be machined off.

The current technique for producing buffer blocks requires that the press is used for removing the block from the mould by lifting the block with the mould from the bottom plate and use the piston to press out the block, see also Chapter 4. The conical shape of the mould is essential to facilitate this since only a small axial displacement is required in order to detach the block from it. With a cylindrical mould the block will not release from the mould until it is completely out of the mould. This might cause damages on the block because the part of the block inside the mould is constrained while the part outside the mould is free to swell, which will cause stresses in the block. Furthermore, compared to a conical mould a cylindrical requires a larger gap inside the press, with the chosen technique to remove the block from the mould.

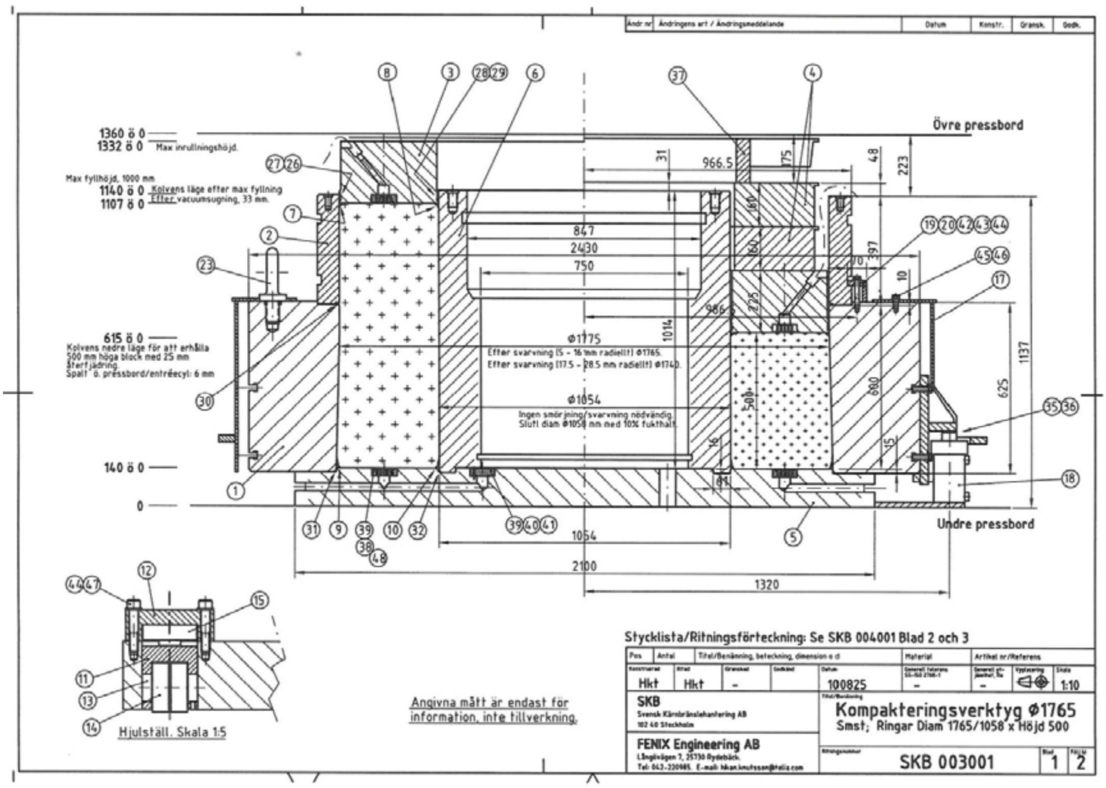
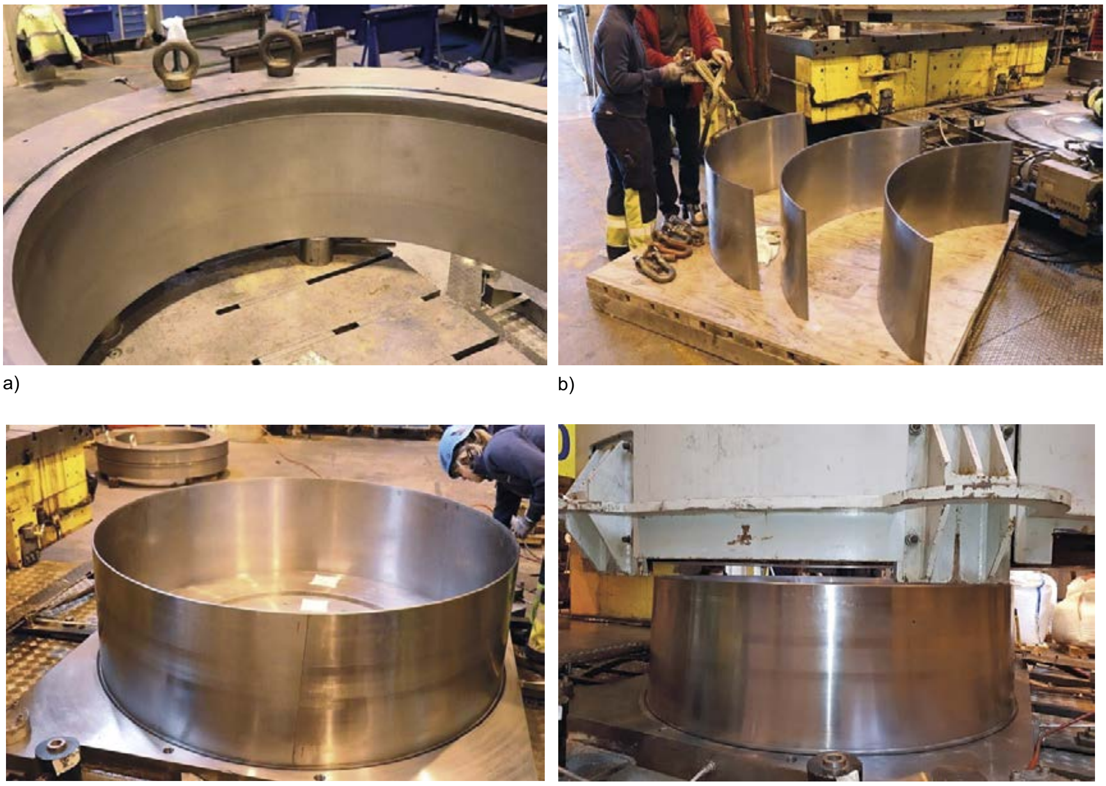


Figure 2-1. The conical shaped mould used at the tests.

To be able to compact cylindrical blocks and still retains the advantages of a conical shaped mould in conjunction with the removal of the block from the mould, a possible solution might be to mount a cylindrical liner on the inside of a conical mould. A previous used mould was therefore modified for this purpose by machining the inner surface to fit a liner divided in three parts, see Figure 2-2. These parts are put together, placed on the bottom plate and the cylinder is placed around them.

It should be noted that the rebuilt existing mould might not be optimized for this type of manufacturing of buffer blocks. However, the aim of the tests with the rebuilt mould is to find out whether the chosen technique is feasible.



a) b) c) d)

Figure 2-2. *The preparation of the mould before starting of the compaction, a) the ring shaped part of the mould, b) the three parts of the liner, c) the cylindrical liner mounted together and d) the ring placed over the liner.*

3 Material and design of the blocks

One of the bentonite used for the large scale test is designated BARA-KADE 2017. It is originated from Wyoming USA and was delivered in big-bags of about 1 ton and mixed to a water content of 17 % in a large mixer at Äspö. The material was characterised in accordance with SKB's planned quality control of buffer materials including investigation of swelling pressure and hydraulic conductivity (Svensson et al. 2019). This data was input for the design of the buffer blocks i.e. their dry density necessary to fulfil the long term requirements on the buffer which ended up in the requirements on the dry density of the blocks of 1 730 kg/m^3 for the ring shaped blocks and 1 700 kg/m^3 for the solid blocks. Tests were then made in the laboratory with the purpose to evaluate the necessary compaction stress in order to reach the required densities on the compacted blocks, also as a part of the quality control of the buffer material. These tests are summarised in Figure 3-1 where the achieved dry density of the bentonite is plotted as function of the water content of the bentonite at different compaction pressures, which are denoted compaction curves. The data in Figure 3-1 indicates that to achieve a dry density on the blocks of 1 700 kg/m^3 a compression pressure of about 30 MPa is required assuming a water content of 17 % (0.17 on x-axis in Figure 3-1). The pressure for reaching the dry density of 1 730 kg/m^3 (the solid blocks) is about 53 MPa.

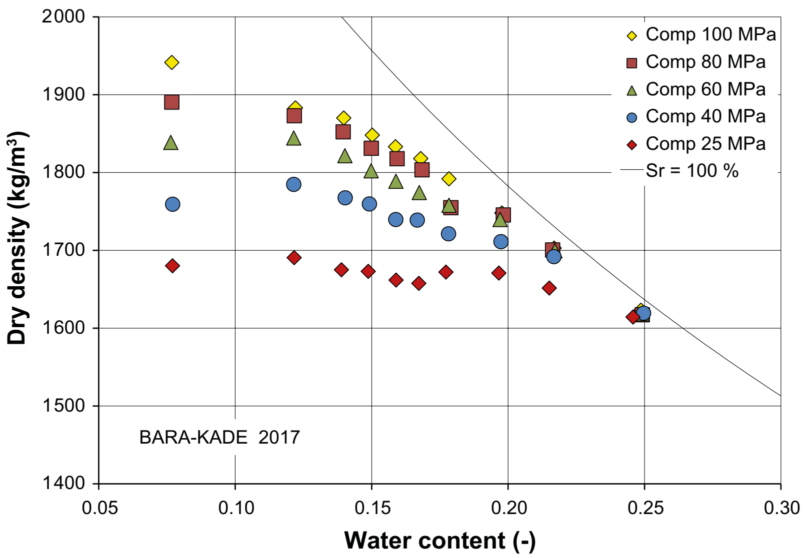


Figure 3-1. *Determined dry density as function of both water content and compaction pressure for the bentonite BARA-KADE 2017.*

The bentonite India 2018, considered as a sodium bentonite, was delivered in Big Bags with an initial water content of about 14 %. The bentonite was purchased as a very fine powder, which resulted in a very low density in uncompact form. A preliminary design of a buffer, made with this bentonite, ended up in the requirements on the dry density of both the ring shaped blocks and the solid blocks of 1 670 kg/m^3. The laboratory tests which are the base for the design together with the requirements is described in Svensson et al. (2019).The compaction curve, see Figure 3-2 shows that the required compaction pressure, at a water content of the bentonite of 17 %, is about 30 MPa.

The bentonite Bulgaria 2018 which according to the laboratory tests is a Ca-dominated bentonite (Svensson et al. 2019), was very different compared to the other two investigated bentonites. Thus, the swelling pressure was much higher resulting in a lower dry density of the blocks in order to fulfil the requirements on the buffer. Furthermore, the bentonite had much higher initial water content, about 19 %. The preliminary design of the buffer with this bentonite implies a dry density of 1 540 kg/m^3 for both the ring shaped and the solid blocks. From the compaction curve, see Figure 3-3, can the compaction pressure, at a water content of 19 %, in order to fulfil the requirement on the dry density thus be estimated to about 30 MPa.

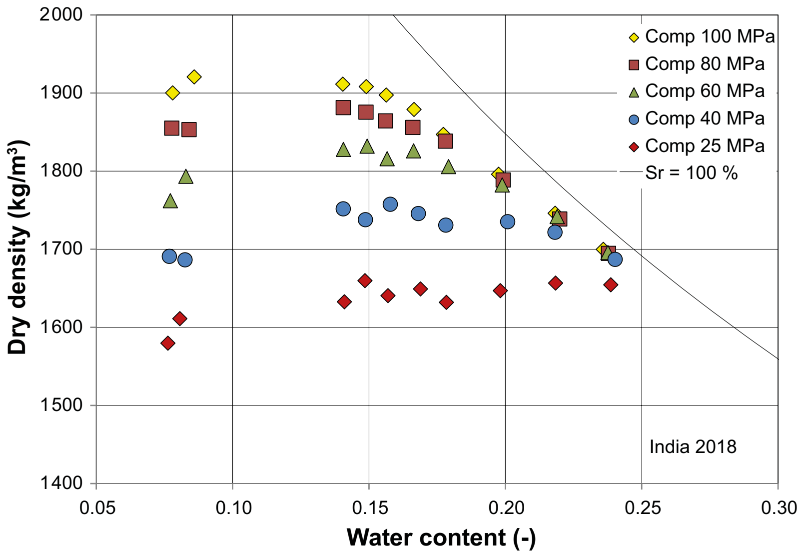


Figure 3-2. *Determined dry density as function of both water content and compaction pressure for the bentonite India 2018.*

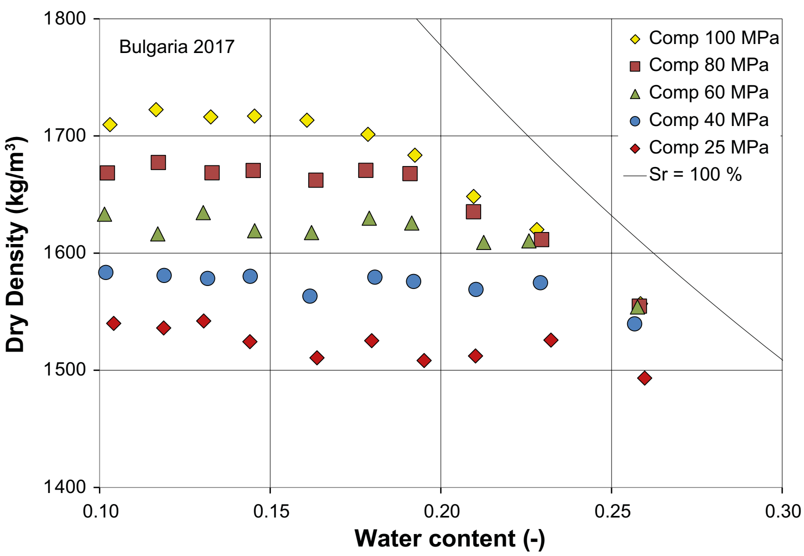


Figure 3-3. *Determined dry density as function of both water content and compaction pressure for the bentonite Bulgaria 2017.*

4 Compaction of the blocks

The compaction of the bentonite is made with a press which, after upgrading, has a maximum capacity of about 10 000 tons, see Figure 4-1. It is situated at a workshop owned by the company KELVION AB in the city of Ystad. The press is normally used for pressing plates for heat exchangers.

The gap between the bottom and the top of the press is limited to about 1.3 m which implies that the maximum height of the compacted blocks is about 500 mm. Two types of moulds are used at the compaction, see Chapter 2.

4.1 Compaction with the conical mould

Up to now all large scale buffer blocks, used for test simulating the KBS-3 concept, has been compacted with a conical shaped mould. The advantage with this shape of the mould is that the removal of the block after compaction is facilitated, see Chapter 2. In the project this mould was used for testing the possibility to compact blocks with three new materials, BARA-KADE 2017, India 2018 and Bulgaria 2017.

***Figure 4-1.** The mould placed in the press.*

The compaction is done in the following sequence:

1. The cleaned cylinder is placed on the bottom plate and lubricated with grease (molycote).
2. The mould is filled with correct mass of bentonite. A reference sample is taken from the mould and saved.
3. The piston is placed on the bentonite in the mould and a vacuum pump is attached to the filters on the piston and bottom plate through hoses.
4. Air is pumped out of the bentonite in the form with the use of a vacuum pump.
5. The mould is rolled into the press.
6. A load is applied to the piston with the use of the press. When the upper part of the piston is just above the cylinder top part the load is removed.
7. A second piston is placed upon the first and the load is applied again. When the piston is just above the cylinder top part the load is removed. This stepwise approach with pistons is used due to the height limitation in the press.
8. A third piston is placed upon the second and the load is applied again. The load is increased to the desired load during a time interval of 10 minutes. The maximal load is then applied during 10 minutes, and the unloading of the mould is then made during 10 minutes.
9. The block, cylinder and pistons are lifted from the bottom plate with jacks. Steel distances are then placed underneath the cylinder.
10. The block is pushed out from the cylinder with the press.
11. The mould is rolled out of the press and the block is lifted off the bottom plate and placed on a pallet. The weight and dimensions of the block are then recorded and documented in a memo.
12. The block is placed on a special designed transport pallet. The blocks are marked with a note inside the transport container.
13. The mould is cleaned.

In total 18 blocks, nine ring-shaped and nine solid blocks were planned to be manufactured. The expected outcomes from the pressing are listed in Table 4-1.

Table 4-1. The planned compaction pressure and load at compaction with the conical shaped mould together with the expected dimensions, mass and bulk density of the compacted blocks (Ring and Solid blocks).

			Compaction		Expected outcome from the pressing					
Type	No	Mtrl	Pressure (MPa)	Load (ton)	Height (mm)	D1 (mm)	D2 (mm)	D3 (mm)	Mass (kg)	Bulk density (kg/m^3)
Solid	3	BARA-KADE	30	7584	500	1776	1800	0	2497	1989
Ring	3	BARA-KADE	53	8836	500	1776	1800	1055	1656	2024
Solid	3	India 2018	30	7584	500	1776	1800	0	2452	1953
Ring	3	India 2018	30	5002	500	1776	1800	1055	1598	1953
Solid	3	Bulgaria 2017	30	7584	500	1776	1800	0	2452	1828
Ring	3	Bulgaria 2017	30	5002	500	1776	1800	1055	1598	1828

4.2 Compaction with the cylindrical mould

The reconstruction of an old mould makes it possible compact both solid and ring-shaped blocks with cylindrical outer diameter, see description in Chapter 2. The compaction of the blocks is made in the same way as described in Section 4.1, except for a first step where the liner is mounted inside the mould and also the removal of it, after the block and the liner is pressed out from the mould, see Figure 4-2.

In total six blocks, three ring-shaped and three solid blocks was planned to be manufactured with the bentonite BARA-KADE 2017. The expected outcomes from the pressing are listed in Table 4-2.

Table 4-2. The planned compaction pressure and load at compaction together with the expected dimensions, mass and bulk density of the two types of blocks (Ring and Solid blocks).

Type	No	Mtrl	Compaction		Expected outcome from the pressing					
			Pressure (MPa)	Load (ton)	Height (mm)	D1 (mm)	D2 (mm)	D3 (mm)	Mass (kg)	Bulk density (kg/m^3)
Solid	3	BARA-KADE	30	6350	500	1627	1627	0	2068	1989
Ring	3	BARA-KADE	53	6370	500	1627	1627	1070	1194	2024

Figure 4-2. *The production of the bentonite blocks.*

5 Quality of the compacted blocks

5.1 Introduction

The investigation of the compacted blocks included the following:

- Measuring of the dimensions and weight of the compacted blocks just after the compaction. These data were used for determining the average density of the blocks.
- Visual inspection of the compacted blocks and notation of cracks and any other damages on the blocks after compaction. Photos were also taken on the blocks.

After the compaction, the blocks were stored for about two months. Previous investigations indicate that during storage there will be some swelling of the blocks (Eriksson 2014). Selected blocks were examined after the storage period. This investigation included:

- Measurement of the dimensions and weight of the blocks and calculations of the average density of them.
- Sampling and measurement of density and water content on the samples. The sampling is made in four perpendicular directions and at five levels i.e. 50, 150, 250, 350 and 450 mm from the bottom of the block. The purpose with the investigation is to evaluate the variation in density and water content within a block.

5.2 The conical blocks

5.2.1 BARA-KADE 2017

Immediately after the compaction, the dimensions of the compacted blocks, the outer dimeter at the top of the block (D_{out1}) and at the bottom (D_{out2}), the inner diameter (D_{inner}) and the height (H) were measured. Furthermore, the total mass (m) of the blocks was measured. With the known dimensions and weight of the blocks it was possible to calculate the bulk density of the blocks. In Table 5-1 are the results from the investigations of the block summarised.

No large damages were observed at the examination of the blocks after compaction. Furthermore, Table 5-1 shows that there are very small variations in the average density between the solid blocks (C1A–C3A). This is also valid for the ring shaped blocks. When comparing the expected densities, which are listed in Table 4-1 with the measured densities, it is obvious that the measured densities are higher, about 40–70 kg/m^3 higher. One explanation for this might be that the expected densities are based on compaction tests made in the laboratory with a small cylindrical mould, while the large scale compacted blocks are compacted with a conical mould.

After the storage period two blocks, C3A and R3A, were examined. This examination includes measurements of the average density and the variation of the density within the blocks, see Section 5.1. The measurements of the average densities are summarised in the lower rows of Table 5-1. When comparing this data with the corresponding data collected directly after compaction, it is obvious that the dimensions of blocks C3A and R3A have increased during storage, about 2 mm in height and about 1–2 mm in outer diameter, resulting in a decrease in density.

Samples were taken from the two examined blocks, in total about 150 samples from block C3 and about 200 from block R3, on which the water content and the density were determined. The samples were taken evenly spread in four profiles of each block. From the measurements it is possible to determine the dry density of the samples. An example of data from one profile in Block R3A is shown in Figure 5-1. Data from the rest of the investigated profiles for both block R3A and C3A are shown in Appendix 1–2. In Figure 5-2 are contour plots of the dry density of both block R3A and C3A shown, based on data in Appendix 1–2. The figure shows the dry density in two perpendicular sections of the blocks. They indicate that the solid block is rather homogenous except for the areas close to the outer surface of the block. The dry density varies in the block between 1 750 and 1 710 kg/m^3 while variation in density in the centre of the block is much smaller. Furthermore, the figure is indicating that for block R3 the dry density varies between 1 750 and 1 800 kg/m^3. The lowest densities were measured close to the bottom of the block, see also Figure 5-1. It is obvious that the variation in density for block R3 is not just limited to the peripheral areas of it. An explanation for this is that the friction, both on the inside and the outside of the mould, is affecting the density of the block.

Table 5-1. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the six compacted blocks (BARA-KADE 2017).

Block No.	σ_c (MPa)	D_{out1} (mm)	D_{out2} (mm)	D_{inner} (mm)	H (mm)	m (kg)	w* (-)	ρ_{bulk}** (kg/m^3)	ρ_{dry} (kg/m^3)
KBP1015_C1A	30	1780.4	1795.2	-	500.9	2538	0.169	2028	1735
KBP1015_C2A	30	1780.2	1795.7	-	500.8	2536	0.168	2027	1736
KBP1015_C3A	30	1779.5	1795.0	-	502.6	2546	0.170	2029	1734
KBP1015_R1A	53	1778.3	1794.9	1055.0	508.6	1725	0.170	2096	1791
KBP1015_R2A	53	1778.1	1795.7	1056.0	510.2	1731	0.168	2098	1796
KBP1015_R3A	53	1778.4	1794.7	1055.0	509.7	1731	0.170	2099	1794
Measurements on the blocks made about two months after compaction									
KBP1015_C3A	30	1780.5	1797.1	-	504.4	2544	0.169	2017	1725
KBP1015_R3A	53	1780.2	1795.5	1055.0	512.1	1723	0.169	2075	1775

* The water content was determined on samples taken from the material at the compaction.

** At the calculation of the bulk density are the volumes of the blocks adjusted for the seals used at the manufacturing.

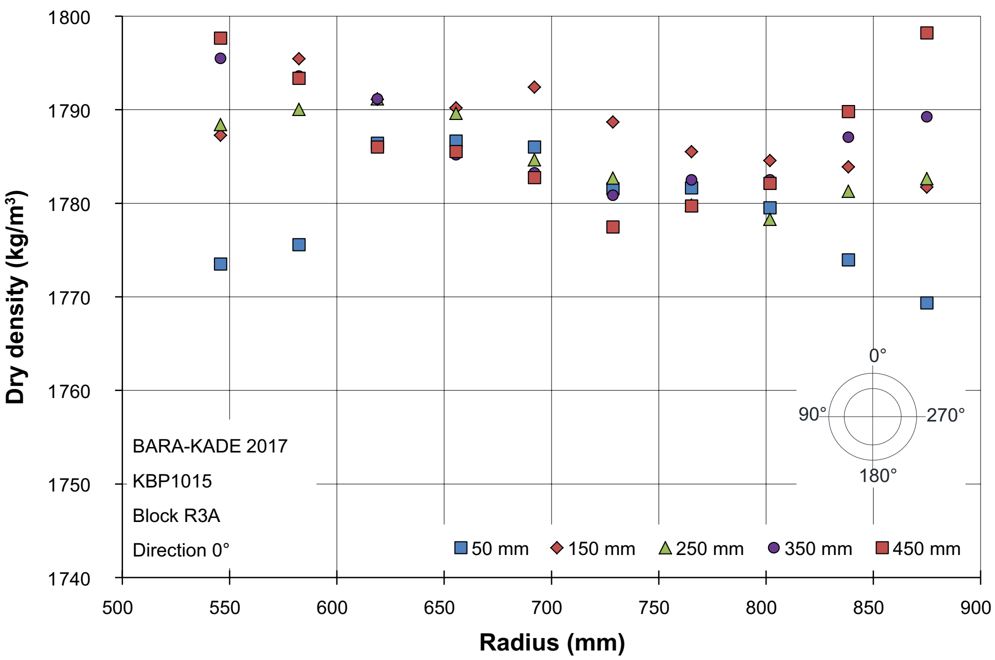


Figure 5-1. *The dry density of block R3A as function of the radial distance from the centre of the block. The determinations are made at five different heights from the bottom of the block. The block is compacted with the conical mould.*

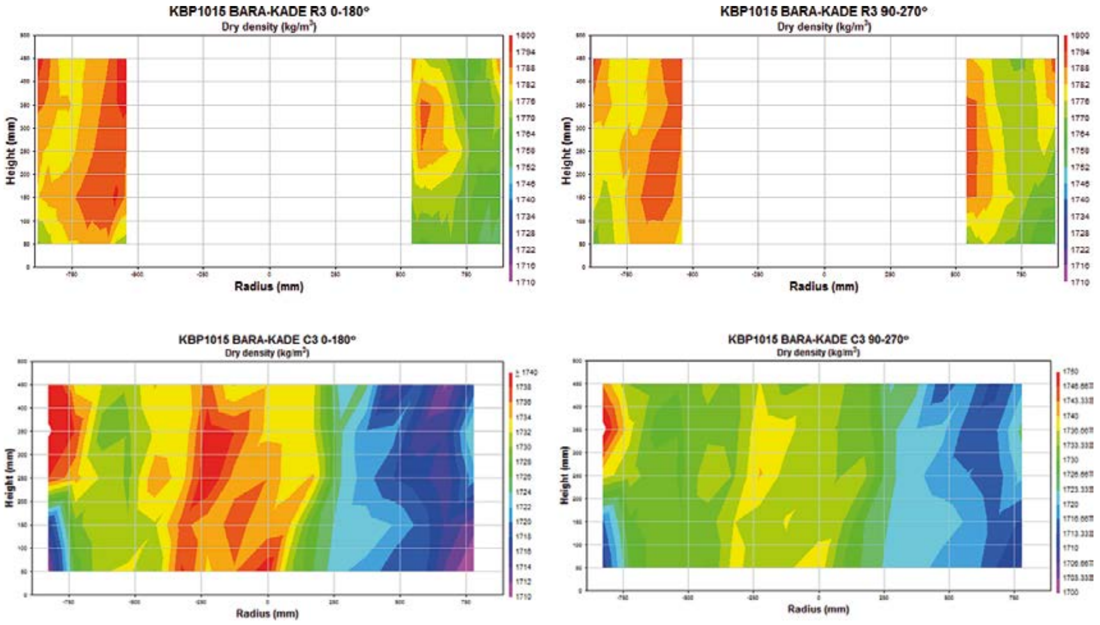


Figure 5-2. Contour plots of the dry density of block R3A and C3A.

5.2.2 India 2018

The bentonite India 2018 was purchased as a very fine powder. A first attempt to compact a solid block with the bentonite failed. After the block was pressed out from the mould, a crack about 10 cm from the top of the block was observed, see Figure 5-3. This crack was going through the entire block which made it impossible to handle it with the lifting device. The block was compacted in the same way as described in Section 4.1 including applying of vacuum in the mould during the compaction. One possible explanation to the failure is that due to the fine powder, it was not possible to evacuate all the air from the bentonite during compaction. After the compaction the entrapped air expanded and caused the crack. It was decided to compact another two solid block where the bentonite was vibrated in the mould before compaction in order to increase the initial density of the powder. Furthermore, the arrangement to evacuate the air from the mould during the compaction was made more efficient.

The examination of these blocks indicates that there were some minor cracks on the blocks. However, the cracks did not cause any problems to handle the blocks with the vacuum yoke and the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.

The measurements of the average densities are summarised in Table 5-2. When comparing this data with the data collected directly after compaction it is obvious that the blocks dimensions (C3B) have increased, about 1 mm in height and about 1 mm in outer diameter during storage, resulting in a decrease in density. Furthermore, the average density of the compacted block is about 100 kg/m^3 higher than the expected cf. Table 4-1 and Chapter 5.2.1.

Table 5-2. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the two compacted blocks (India 2018).

Block No.	σ_c (MPa)	D_{out1} (mm)	D_{out2} (mm)	D_{inner} (mm)	H (mm)	m (kg)	w* (-)	ρ_{bulk}** (kg/m^3)	ρ_{dry} (kg/m^3)
KBP1015_C2B	30	1779.7	1793.5	0.0	496.6	2546	0.175	2055	1749
KBP1015_C3B	30	1779.5	1793.1	0.0	494.9	2538	0.166	2056	1763
Measurements on the blocks made about two months after compaction									
KBP1015_C3B	30	1780.6	1796.25	0.0	496.0	2528	0.169	2039	1744

* The water content was determined on samples taken from the material at the compaction.

** At the calculation of the bulk density are the volumes of the blocks adjusted for the seals used at the manufacturing.

Samples were taken from block C3B, in total about 150, on which the water content and the density were determined. From the measurements it is possible to determine the dry density of the samples. An example of data from one profile in Block C3B is shown in Figure 5-4 and data from the rest of the investigated profiles are shown in Appendix 3. In Figure 5-5 are contour plots of the dry density block C3B shown, based on data in Appendix 3. The plots show the dry density in two perpendicular sections. The figure indicates that the solid block is fairly homogeneous except for the volumes close to the outer surface of the block. The dry density varies in the whole block between 1 730 and 1 780 kg/m^3 while the variation in density in the centre of the block is much smaller.

Figure 5-3. *A block compacted with the bentonite India 2018.*

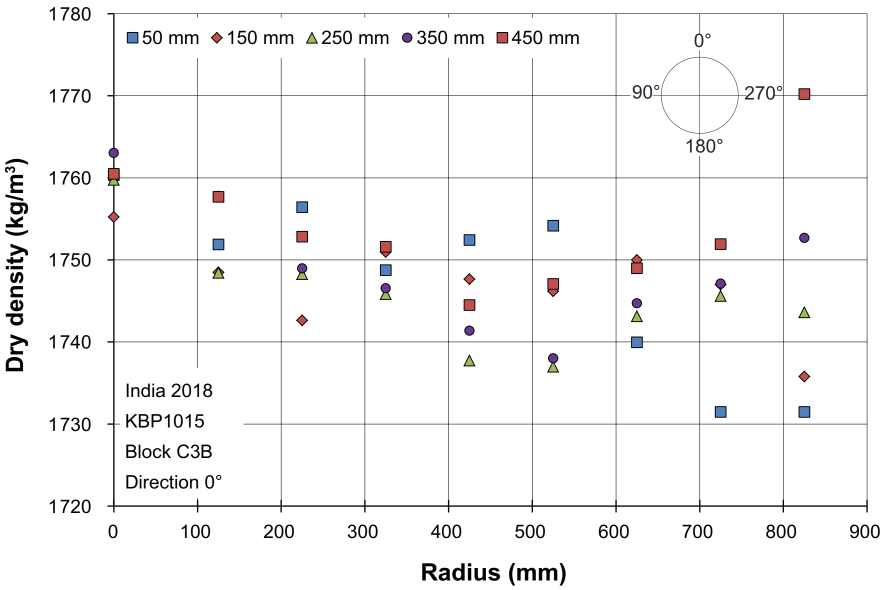


Figure 5-4. *The dry density of block C3B as function of the radial distance from the centre of the block. The determinations are made at five different heights from the bottom of the block. The block is compacted with the conical mould.*

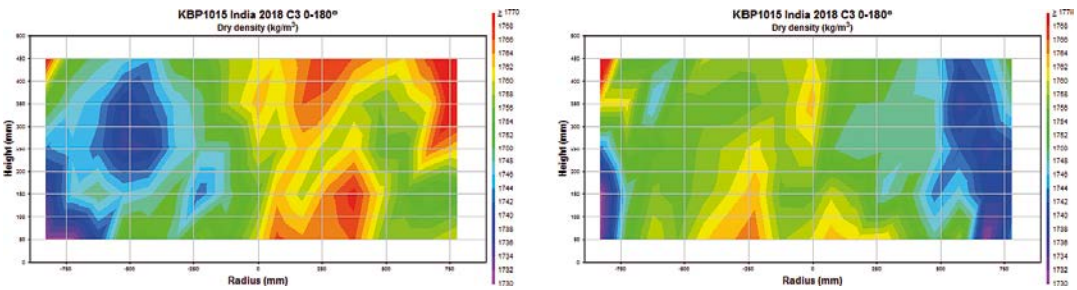


Figure 5-5. *Contour plots of the dry density of block C3B.*

5.2.3 Bulgaria 2017

The bentonite Bulgaria 2017 was delivered as a rather coarse material, compared to the other investigated bentonites. Its initial water content was also high, above 0.19 and consequently, no adjustment of the water content was made prior to compaction.

With the known dimensions and weight of the blocks it was possible to calculate the bulk densities of the blocks which are summarised in Table 5-3. All the blocks of the bentonite Bulgaria 2017 were compacted with the same compaction pressure, 30 MPa. When comparing the two types of blocks it is obvious the ring shape blocks had a significant lower density compared to the solid blocks, about 25 kg/m^3 lower. At the compaction of the ring shaped blocks there is friction between the bentonite and the mould both on the outside, as for the solid blocks, as well as on the inside and this is probably the reason for the lower average density on the ring shaped blocks although the compaction pressure is the same for both types of blocks.

Table 5-3. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the six compacted blocks (Bulgaria 2017).

Block No.	σ_c (MPa)	D_{out1} (mm)	D_{out2} (mm)	D_{inner} (mm)	H (mm)	m (kg)	w* (-)	ρ_{bulk}** (kg/m^3)	ρ_{dry} (kg/m^3)
KBP1015_C1C	30	1784.6	1798.9	-	496.1	2354	0.185	1891	1596
KBP1015_C2C	30	1784.3	1799.0	-	498.9	2380	0.189	1902	1599
KBP1015_C3C	30	1784.0	1799.5	-	497.8	2380	0.190	1906	1601
KBP1015_R1C	30	1782.4	1800.0	1058.0	508.3	1556	0.194	1883	1577
KBP1015_R2C	30	1783.1	1800.0	1052.5	512.1	1572	0.197	1876	1568
KBP1015_R3C	30	1783.0	1801.0	1057.0	514.7	1564	0.197	1864	1558
Measurements on the blocks made about two months after compaction									
KBP1015_C3C	30	1785.5	1798.0	-	499.4	2378	0.188	1898	1598
KBP1015_R3C	30	1785.5	1804.2	1059.0	517.1	1564	0.194	1850	1549

* The water content was determined on samples taken from the material at the compaction.

** At the calculation of the bulk density are the volumes of the blocks adjusted for the seals used at the manufacturing.

The examination of these blocks indicates that there were some minor cracks on the ring shaped blocks. However, the cracks did not cause any problems to handle the blocks with the vacuum yoke and the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.

Samples were taken from two blocks, block C3C and block R3C,in the same way as described in Section 5.2.1, on which the water content and the density were determined. An example of data from one profile in Block R3C is shown in Figure 5-6. Data from the rest of the investigated profiles for both block R3C and C3C are shown in Appendix 4–5. In Figure 5-7 are contour plots of the dry density of both block R3C and C3C shown, based on data in Appendix 4–5. The plots show the dry density in two perpendicular sections of the blocks. They indicate that the solid block is rather homogenous except for the area close to the outer surface of the block. The dry density varies in the block between 1 570 and 1 625 kg/m^3 while variation in density in the centre of the block is much smaller. Furthermore, the figure is indicating that for block R3C the dry density varies between 1 530 and 1 620 kg/m^3. The lowest densities were measured close to the bottom of the block, see also Figure 5-6. It is obvious that the variation in density for block R3 is not just limited to the peripheral of it, see also Chapter 5.2.1.

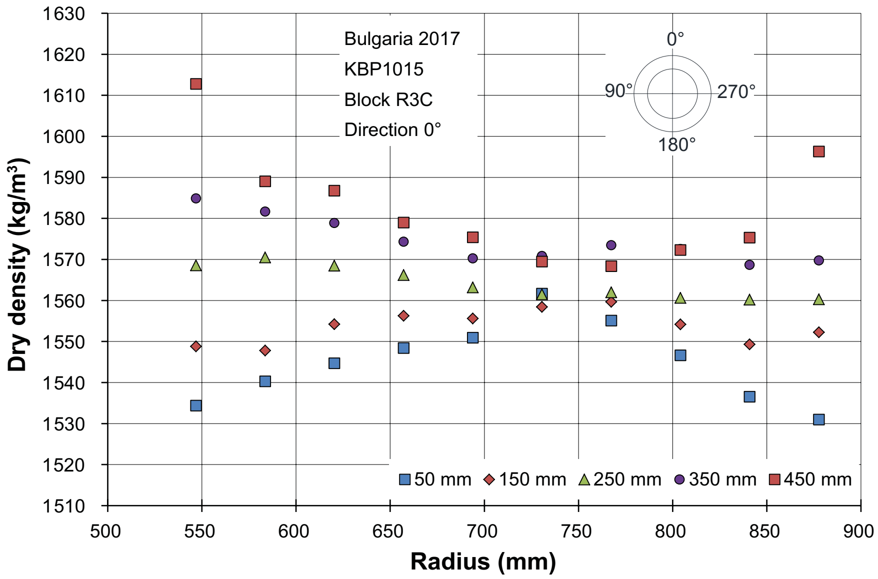


***Figure 5-6.** The dry density of block R3C as function of the radial distance from the centre of the block. The determinations are made at five different heights from the bottom of the block. The block is compacted with the conical mould.*

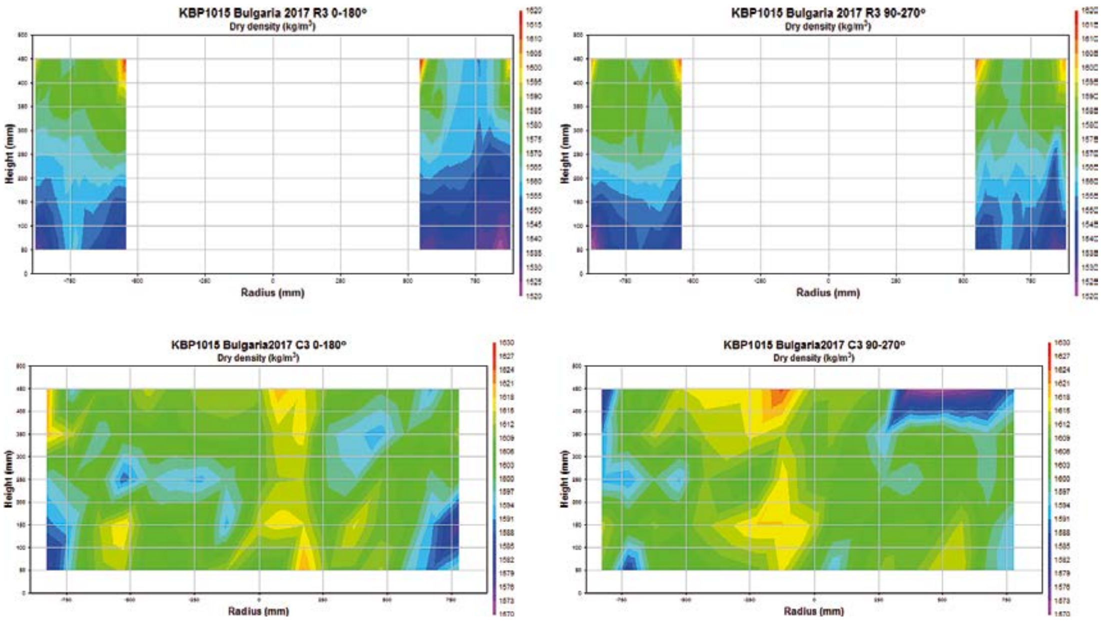


***Figure 5-7.** Contour plots of the dry density of block R3C and C3C.*

5.3 The cylindrical blocks

The data from the investigations of the compacted blocks collected immediately after compaction is summarised in Table 5-4. Due to malfunction of the press, blocks C1A and C2A were compacted with a somewhat lower compaction pressure than planned, which was 30 MPa. Also block R1A was compacted with a lower compaction pressure than planned, 22 MPa instead of 53 MPa. The reason for this was that the mould began to move upwards during the compression, i.e. the mould was lifted from the bottom plate and at that stage the press stopped. A sliding of the mould on the conical outer surface of the liner occurred. This phenomenon was avoided by not using any lubricant between the mould and the liner. The expected bulk density for the two types of blocks is shown in Table 4-1 and is thus for the ring shaped blocks 2 024 kg/m^3 and for the cylindrical blocks 1 989 kg/m^3. Blocks which were compacted with the right compaction pressure and with lubricant on the mould, i.e. blocks C3A and R3A, had somewhat higher density than expected.

The examination of the blocks indicates that there were some minor cracks on all of the compacted blocks. The cracks did not cause any problems to handle the blocks with the vacuum yoke and the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.

Two blocks, C3A and R3A, were examined after the storage period including measurements of the average density and the variation of the density within the blocks, see Section 5.1.

The measurements of the average densities are summarised in Table 5-4 below. When comparing the data obtained immediately after compaction with the data after two months of storage a small increase in dimensions (less than 1 mm) was observed for block C3A. Corresponding comparison made for block R3 show an increase in the outer diameter of about 1 mm and an increase of the height of about 2.5 mm.

Table 5-4. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the six compacted blocks. (BARA-KADE 2017).

Block No.	σ_c (MPa)	D_{out1} (mm)	D_{out2} (mm)	D_{inner} (mm)	H (mm)	m (kg)	w** (-)	ρ_{bulk}*** (kg/m^3)	ρ_{dry} (kg/m^3)
KBP1017_C1A	28.3	1 632.0	1 632.4	-	513.8	2 131	0.166	1 986	1 703
KBP1017_C2A	28.3	1 633.0	1 633.3	-	515.1	2 138	0.170	1 985	1 697
KBP1017_C3A	30	1 632.9	1 632.6	-	508.9	2 138	0.165	2 011	1 726
KBP1017_R1A	22	1 637.5	1 639.1	1 070.0	540.2	1 233	0.167	1 898	1 627
KBP1017_R2A*	53	1 632.6	1 632.6	1 070.0	508.5	1 232	0.169	2 041	1 746
KBP1017_R3A	53	1 631.6	1 632.1	1 070.0	505.9	1 234	0.170	2 058	1 759
Measurements on the blocks made about two months after compaction									
KBP1017_C3A	30	1 633.6	1 634.5	-	508.3	2 130	0.168	2 002	1 714
KBP1017_R3A	53	1 632.5	1 632.1	1 071.0	508.8	1 234	0.167	2 047	1 754

* No lubricant was used on the mould.

** The water content was determined on samples taken from the material at the compaction.

*** At the calculation of the bulk density are the volumes of the blocks adjusted for the seals used at the manufacturing.

Samples were taken from two blocks, block C3A and block R3A,in the same way as described in Chapter 5.2.1, on which the water content and the density were determined. An example of data from one section in Block R3A is shown in Figure 5-8. The data from the rest of the investigated profiles for both block R3A and C3A are shown in Appendix 6–7. In Figure 5-9 are contour plots of the dry density of both block R3A and C3A shown, based on data in Appendix 6–7. These plots show the dry density in two perpendicular sections of the blocks and indicate that the solid block is rather homogenous except for the area close to the outer surface of it with a variation in density between 1 650 and 1 750 kg/m^3 although the variation in the centre of the block is much smaller. Furthermore, the figure is indicating that for block R3 varies the dry density between 1 720 and 1 790 kg/m^3 with the lowest densities close to the upper surface of the block, see also Figure 5-8. There are also variations between the investigated sections of the block. Furthermore, it is obvious that the variation in density for block R3 is not just limited to the peripheral of it. The explanation for this is that the friction both on the inside and the outside of the mould is affecting the density of the block.

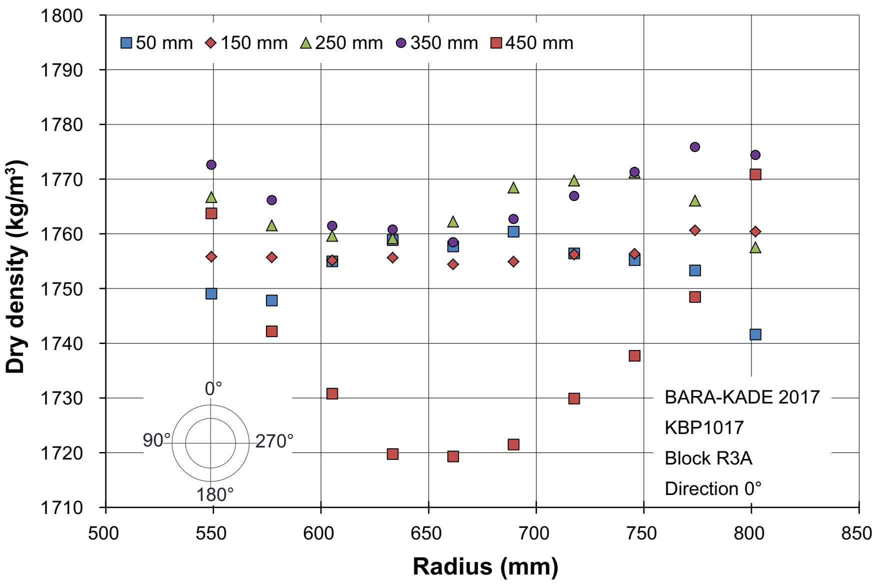


Figure 5-8. *The dry density of block R3A as function of the radial distance from the centre of the block. The determinations are made at five different heights from the bottom of the block.*

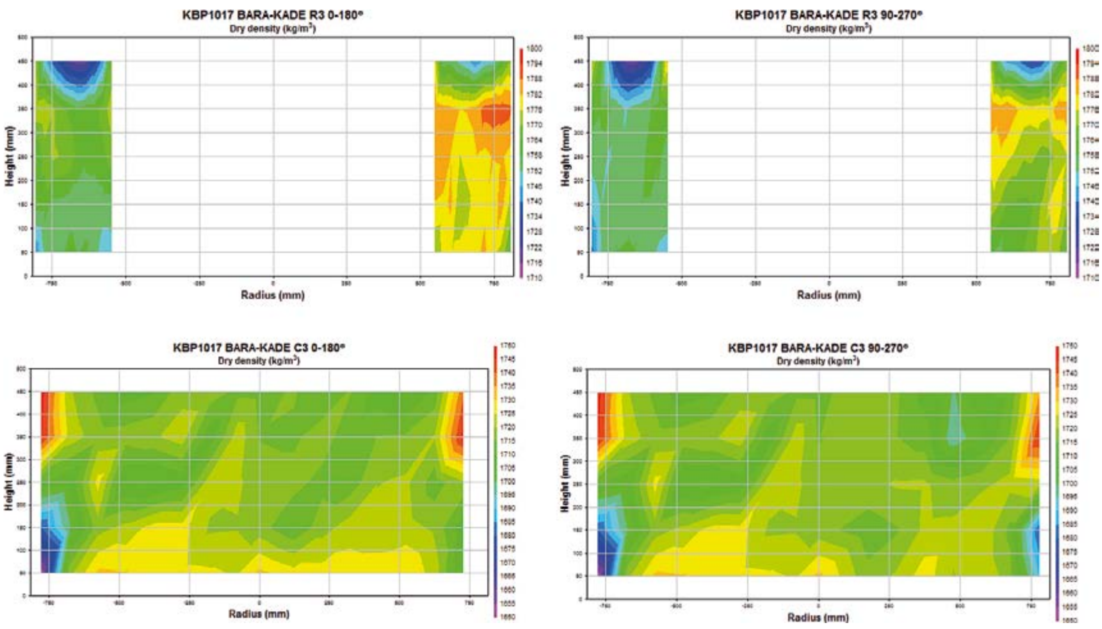


Figure 5-9. *Contour plots of the dry density of block R3A and C3A.*

6 Comparison with conical and cylindrical shaped blocks

The test made with the bentonite BARA-KADE 2017 both with the conical and the cylindrical mould is summarised in Table 6-1. The data is indicating that the blocks made with the conical shaped mould have somewhat higher average dry density compared with those compacted with the cylindrical mould. In Figure 6-1 are the contour plots of the blocks with the two different moulds compared. Also this figure shows that the blocks compacted with the conical mould have a somewhat higher density. Furthermore, the figure is also showing that the blocks compacted with the conical mould are more homogeneous. The most obvious differences between the conical and cylindrical shaped blocks can be seen when comparing the ring shaped blocks (cf. Figure 6-1 c and d). The ring shaped block has anomalies in the dry density close to the top of the block, which is not the case for the conical block.

Both the higher density and the more homogeneous blocks made with the conical mould are indicating that the friction between the mould and the bentonite at the compaction is smaller compared to the compaction with a cylindrical mould. However, the judgement is that the observed variation in density is not affecting the possibility to use the blocks as buffer.

Table 6-1. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for two blocks compacted with the cylindrical mould (KBP1017_C3A and KBP1017_R3A) and two blocks compacted with a conical mould (KBP1015_C3A and KBP1015_R3A).

Block No.*	σ_c (MPa)	D_{out1} (mm)	D_{out2} (mm)	D_{inner} (mm)	H (mm)	M (kg)	w** (-)	ρ_{bulk}*** (kg/m^3)	ρ_{dry} (kg/m^3)
KBP1017_C3A	30	1633.6	1634.5	-	508.3	2130	0.168	2002	1714
KBP1017_R3A	53	1632.5	1632.1	1071.0	508.8	1234	0.167	2047	1754
KBP1015_C3A	30	1780.5	1797.1	-	504.4	2544	0.169	2017	1725
KBP1015_R3A	53	1780.2	1795.5	1055.0	512.1	1723	0.169	2075	1775

* A lubricant was used at the compaction.

** The water content was determined on samples taken from the compacted blocks (average water content)

*** At the calculation of the bulk density are the volumes of the blocks adjusted for the seals used at the manufacturing.

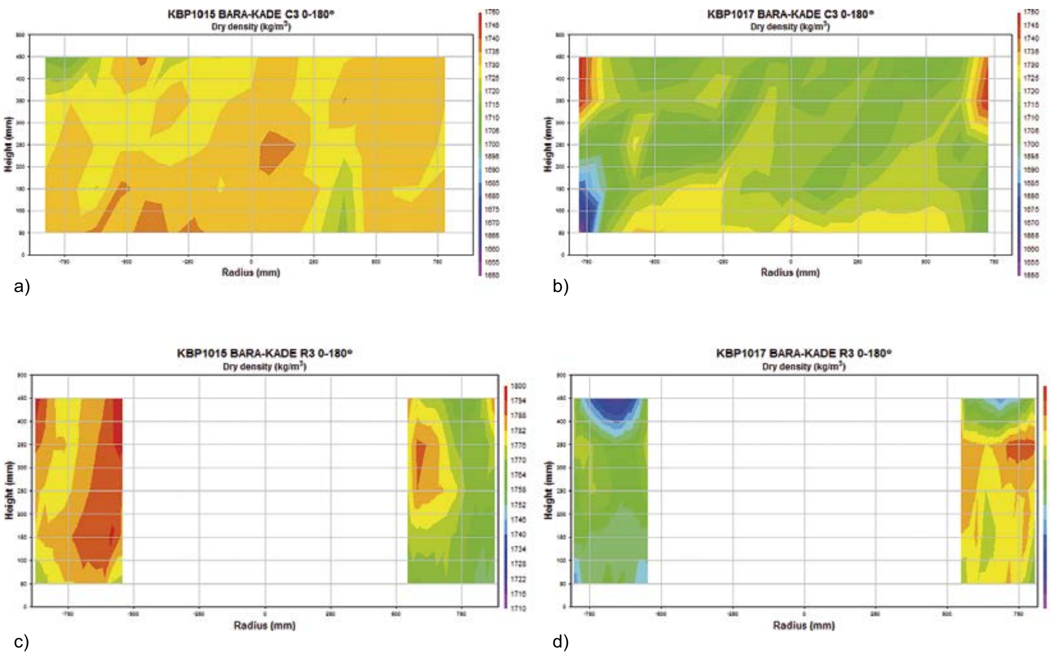


Figure 6-1. *Contour plots of the dry density of block a) KBP1015_C3A, b) KBP1017_C3A, c) KBP1015_R3A and d) KBP1017_R3A.*

7 Conclusions and recommendations

Compaction of large scale blocks was made with three bentonites BARA-KADE, India 2018 and Bulgaria 2017 as a part of the project KBP1015. The test was made with a conical shaped mould. A lubricant was used on the mould at the compaction. The following conclusions can be drawn from the tests:

- The compaction of the bentonites turned out well except for the bentonite India 2018. The reason for the failure with this material was that, it was purchased as a fine powder, which resulted in cracks in the blocks due to entrapped air in the block. After adjustment of compaction procedure, it was possible to compact acceptable blocks also with this material. It is expected that the issue could be avoided by using a granular size distribution with less fine material.
- A swelling of the blocks after compaction was observed for all blocks. The swelling was in the order of 1–2 mm both in radial and axial direction. This is in accordance with previous made investigations (Eriksson 2014).
- Some variation in dry density within the blocks could be observed. The largest variation was found for the material Bulgaria 2017, up to 90 kg/m^3. The judgement is however that the observed variation in density is not affecting the possibility to use the blocks as buffer as the requirements are set on the average dry density in a deposition hole.
- Although the statistical data is limited, tests made at the same conditions that are with the same material and compaction load ended up with small variation in the average dry density for the blocks i.e. a good repeatability.
- Small cracks were observed in most of the compacted blocks. However, the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.
- Previous compactions with this technique were done with the bentonite MX-80. The compaction tests reported here show that it is possible to compact blocks with different types of bentonites.
- The performed tests show that it is advantageous to avoid the material as a fine powder.

The technique to compact cylindrical blocks involves a lining inside a conical shaped mould and this was tested in full scale production where altogether six blocks with cylindrical outer surface have been compacted with a rebuilt mould, three solid blocks and three ring shaped blocks. The following conclusions can be drawn from the tests:

- The construction and the rebuilding of the mould worked as planned.
- The compaction of the six blocks largely worked according to plan.
- The compacted blocks had an average dry density in accordance with what was expected.
- There were some variations of the dry density within the blocks which were larger compared to blocks compacted with a conical shaped mould, see also above.
- The compacted blocks had some minor damages and cracks but not so severe that they jeopardize the possibility to handle, store and install them.
- This project uses a rebuilt form that is therefore not optimized for large-scale production of buffer blocks. The test performed still indicates that the proposed technique is feasible. However, there is great potential for optimization of both the equipment and the technique.
- The reported compaction tests made with the cylindrical mould were done with only one bentonite type, BARA-KADE 2017, which was mixed to specific water content. It is essential that additional test should be done with other bentonite types and at different water content of the material.
- Only one block was compacted without use of a lubricant (KBP1017_R2A). The judgement is that more blocks should be produced without lubricant in order to get more information if this is feasible.

Compaction of both ring shaped blocks and cylindrical blocks with the bentonite BARA-KADE 2017 was made both with a conical and a cylindrical mould. Comparisons between the compacted blocks indicate the following:

- The blocks compacted with the conical mould are more homogeneous.
- The blocks compacted with the conical mould have a somewhat higher density.
- The results from laboratory compactions in a smaller cylindrical mould, i.e. the dry density, which are used for deciding the compaction pressure at the production of large scale blocks is more in accordance with the cylindrical mould.

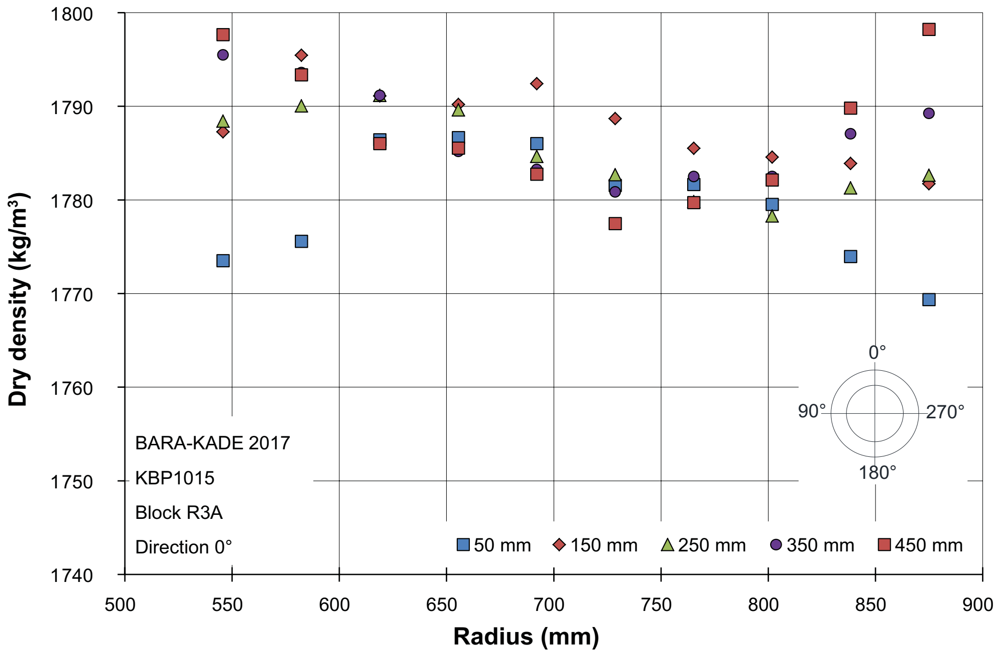
References

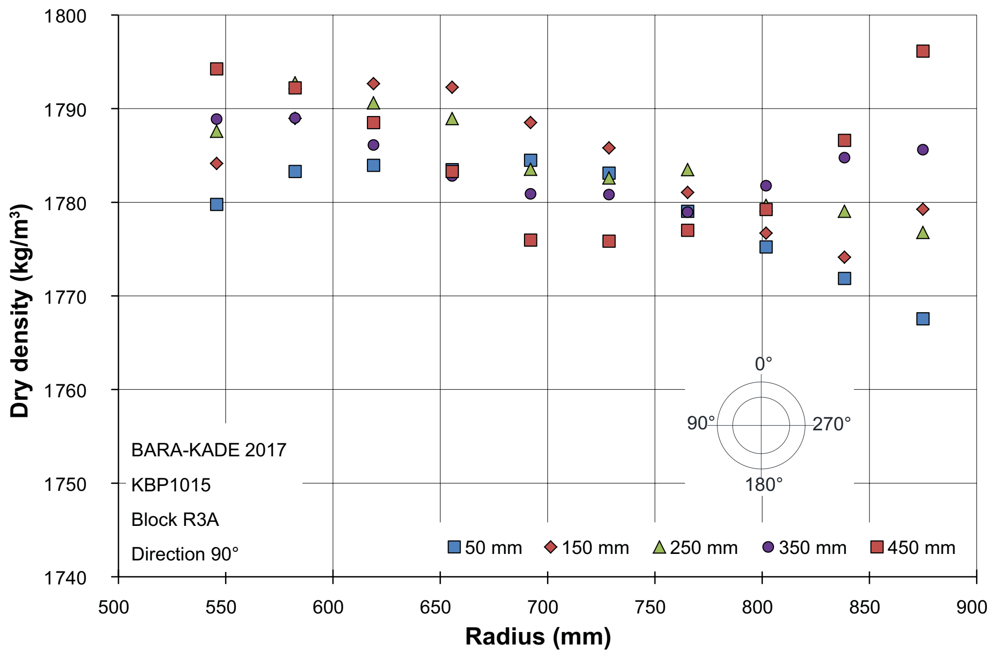
SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

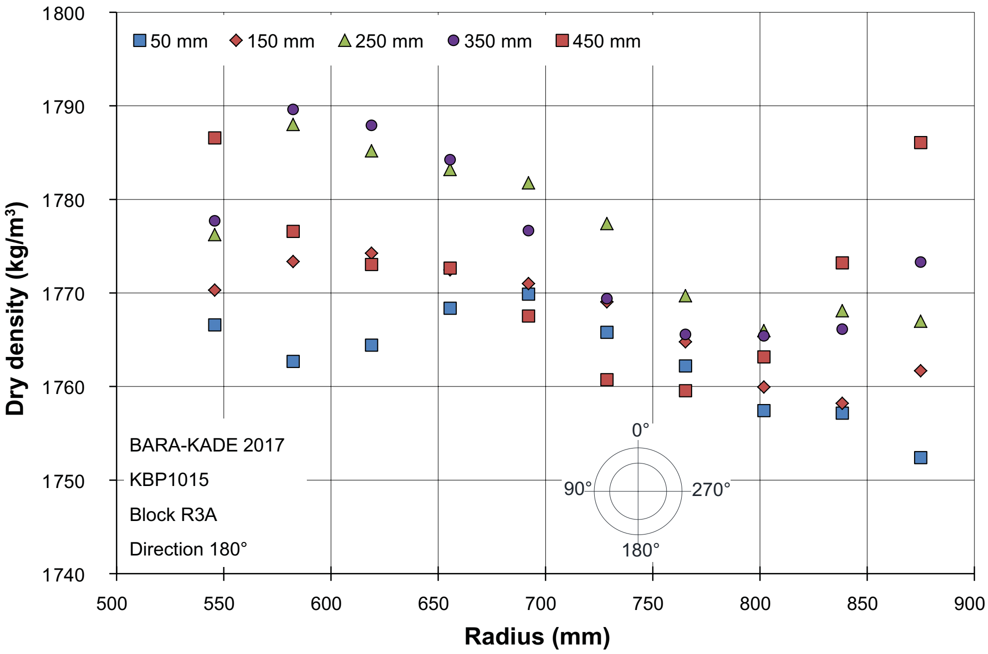
Eriksson P, 2014. Basic engineering of buffer production system. SKB P-14-11, Svensk Kärnbränslehantering AB.

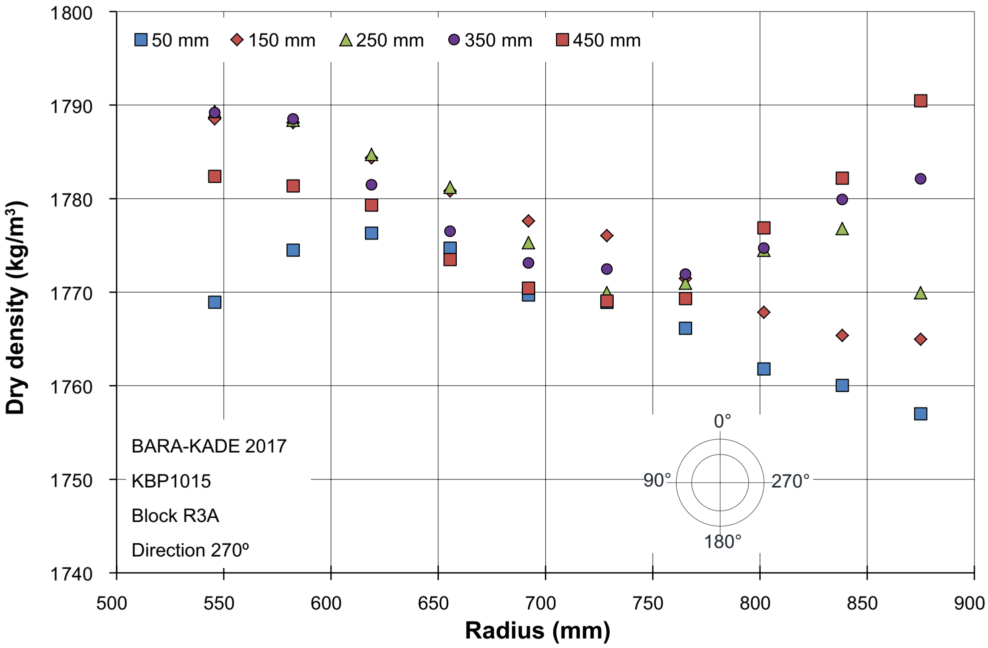
Svensson D, Eriksson P, Johannesson L-E, Lundgren C, Bladström T, 2019. Development and testing of methods suitable for quality control of bentonite as KBS-3 buffer and backfill. SKB TR-19-25, Svensk Kärnbränslehantering AB.

Dry density of block R3A BARA-KADE 2017 conical shape

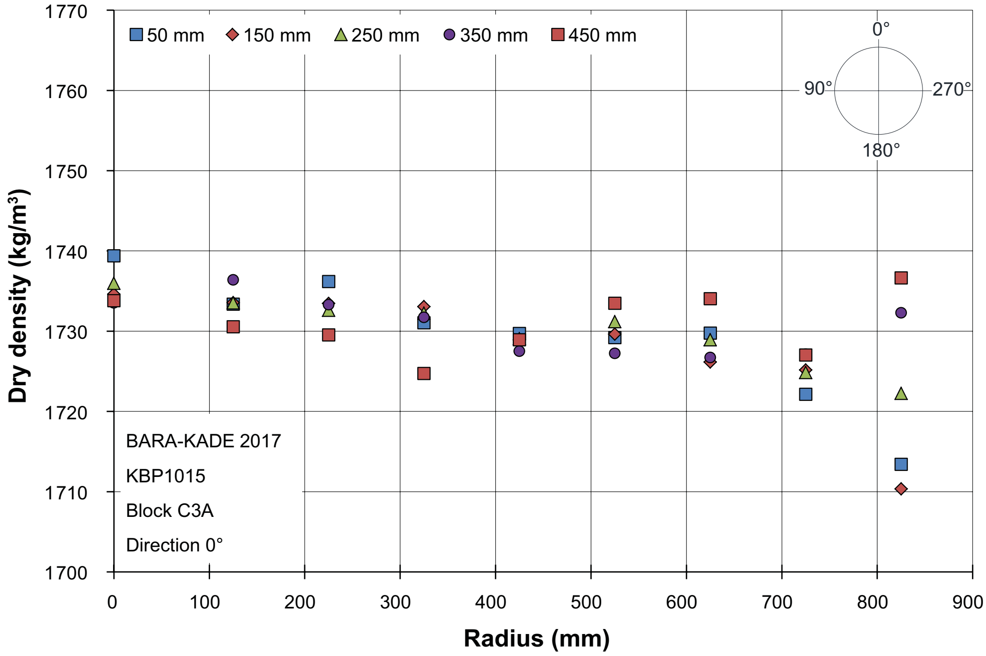


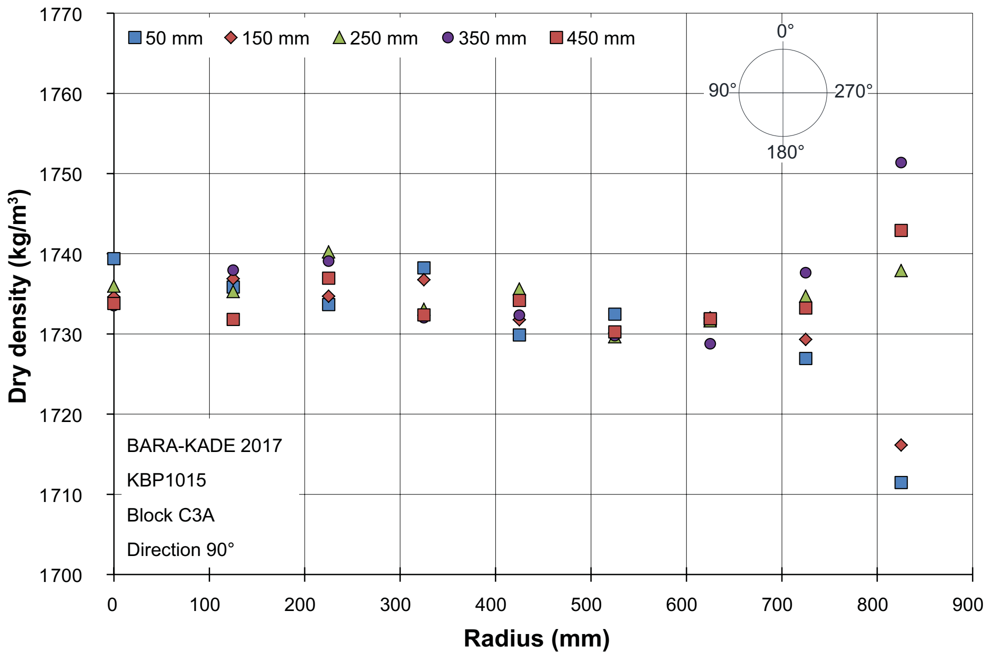


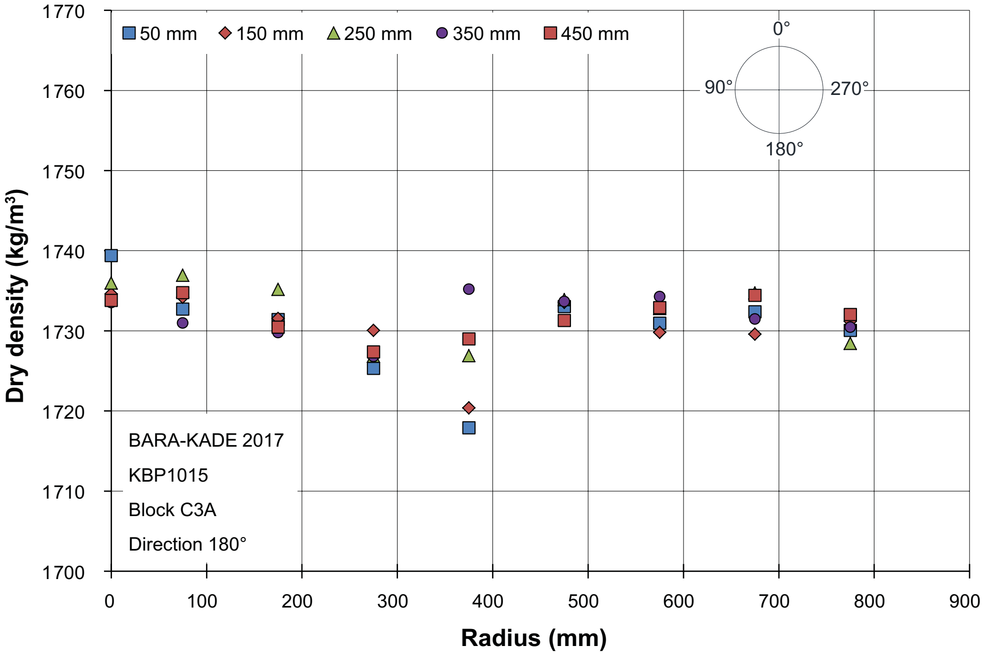

50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
BARA-KADE 2017
KBP1015
Block R3A
Direction 180°
0°
90°
270°
180°

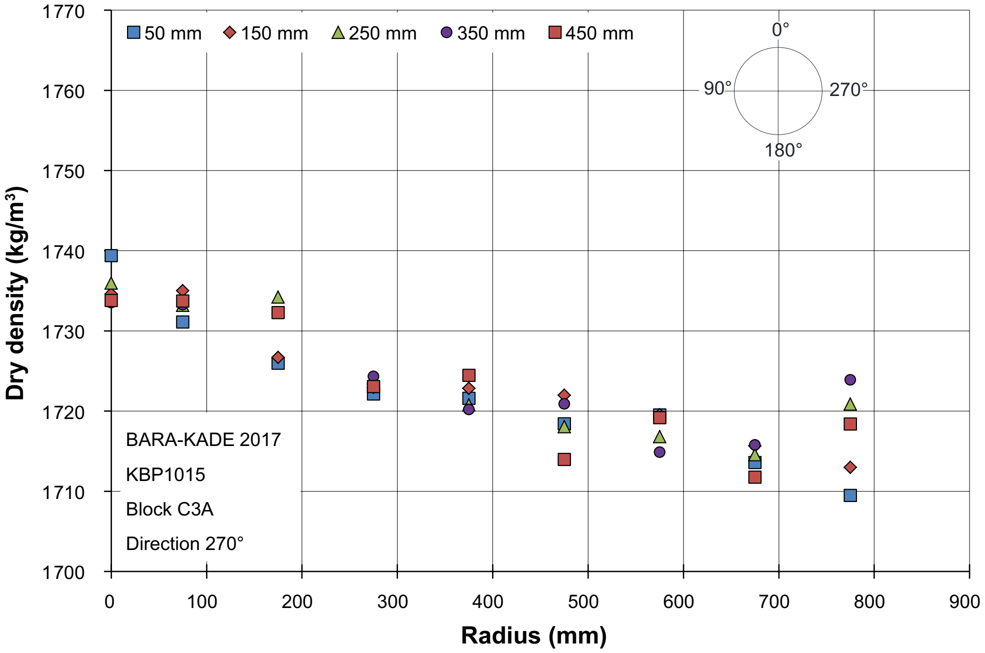

50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
BARA-KADE 2017
KBP1015
Block R3A
Direction 270º
0°
90°
270°
180°

Dry density of block C3A BARA-KADE 2017 conical shape

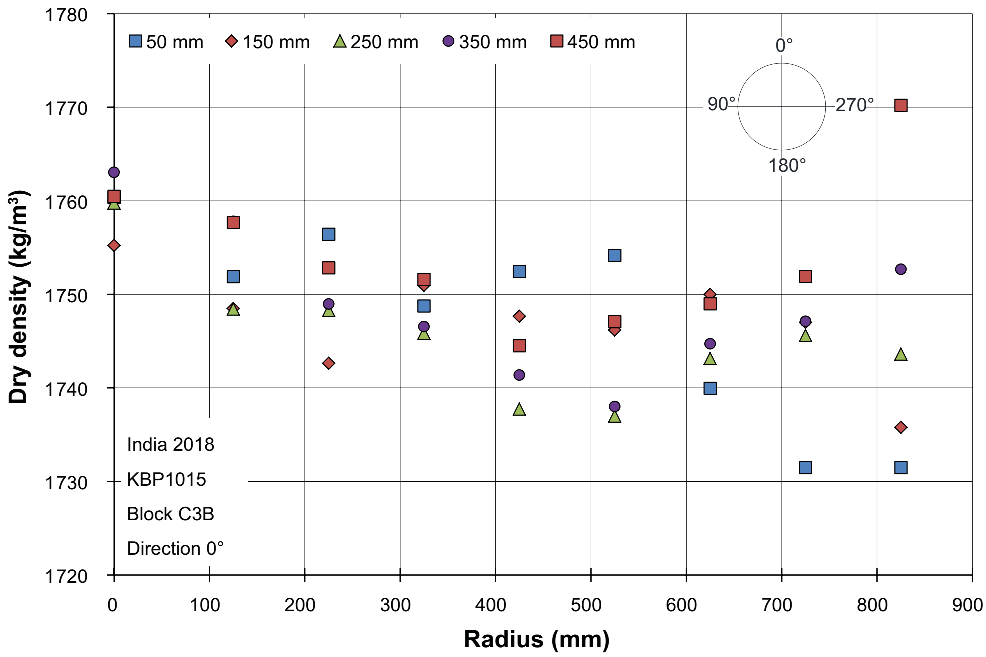


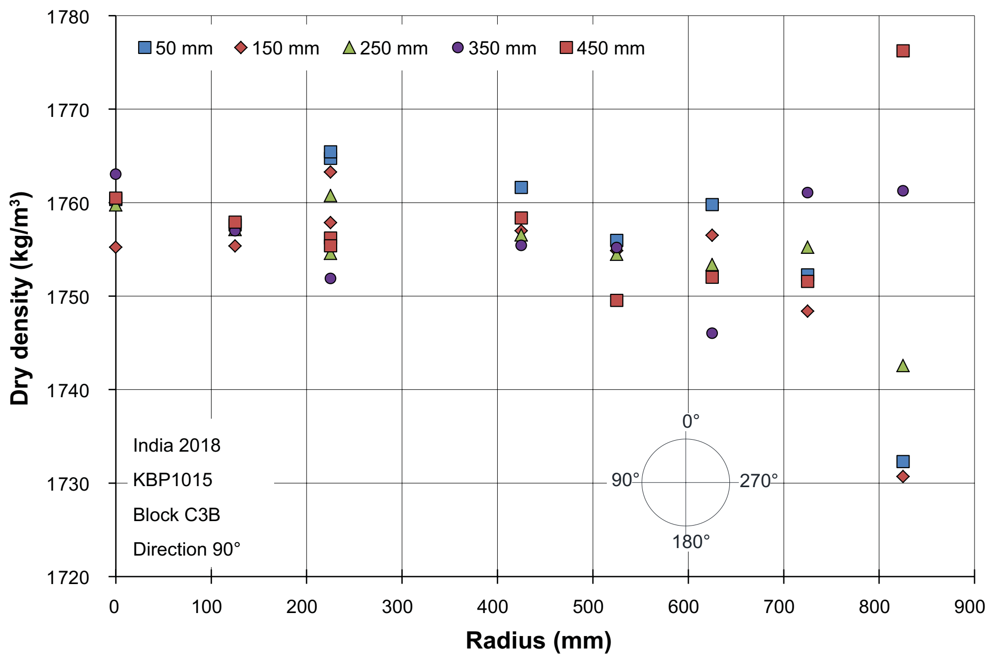


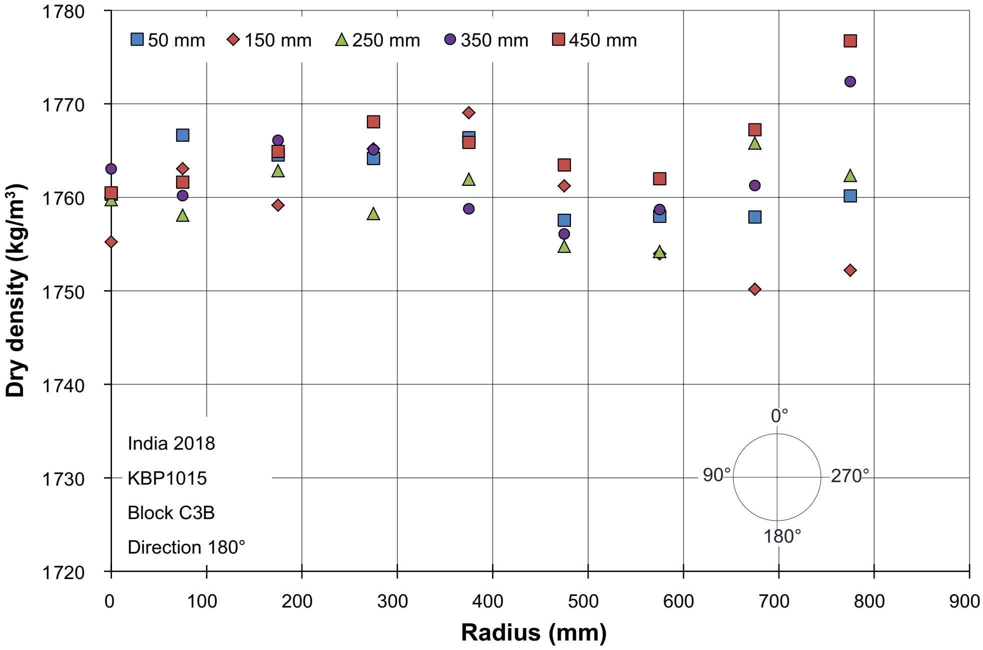

50 mm
150 mm
250 mm
350 mm
450 mm
0°
90°
270°
180°
BARA-KADE 2017
KBP1015
Block C3A
Direction 180°
Dry density (kg/m³)
Radius (mm)
1770
1760
1750
1740
1730
1720
1710
1700
0
100
200
300
400
500
600
700
800
900

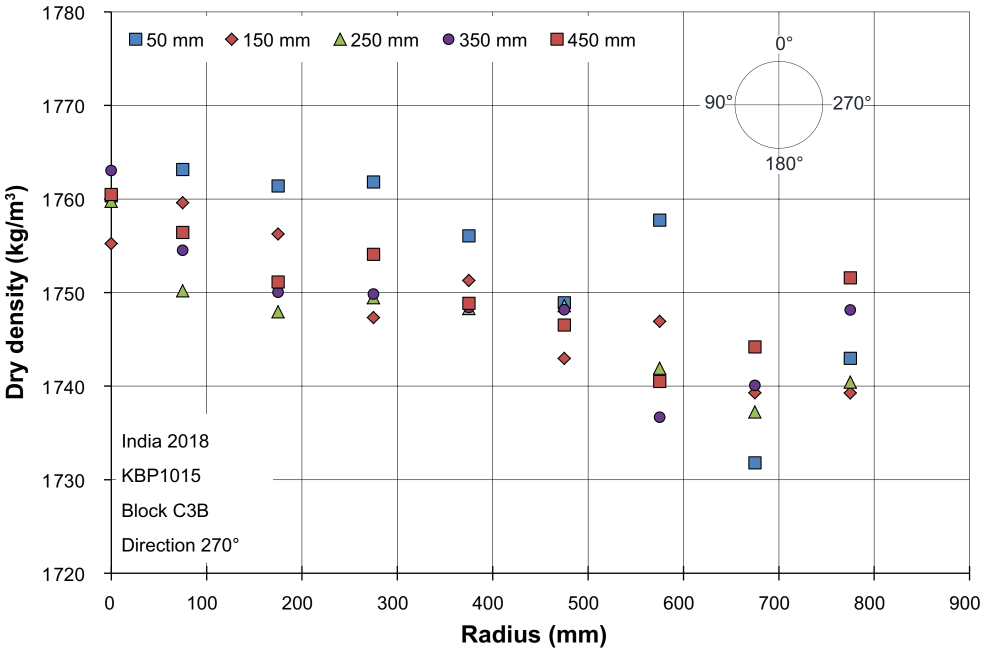

50 mm
150 mm
250 mm
350 mm
450 mm
0°
90°
270°
180°
BARA-KADE 2017
KBP1015
Block C3A
Direction 270°
Dry density (kg/m³)
Radius (mm)
1770
1760
1750
1740
1730
1720
1710
1700
0
100
200
300
400
500
600
700
800
900

Dry density of block C3B India 2018 conical shape

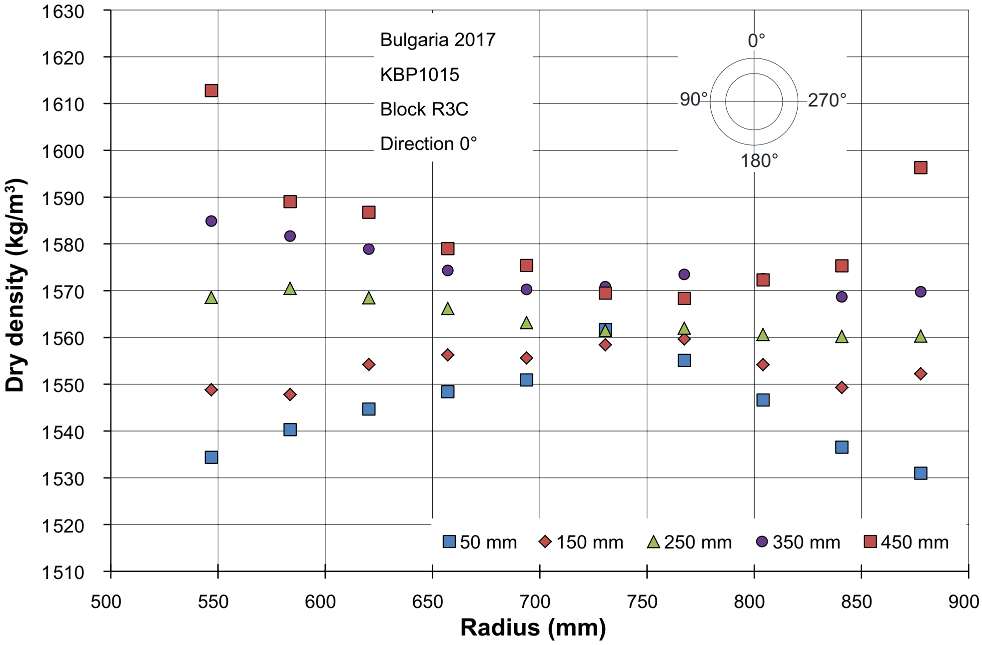


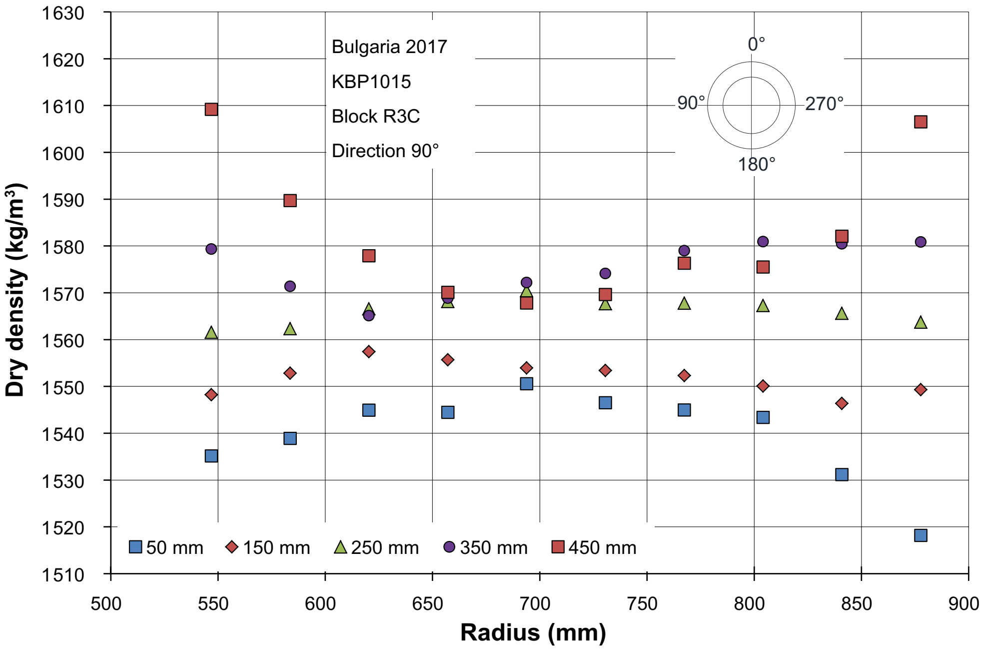


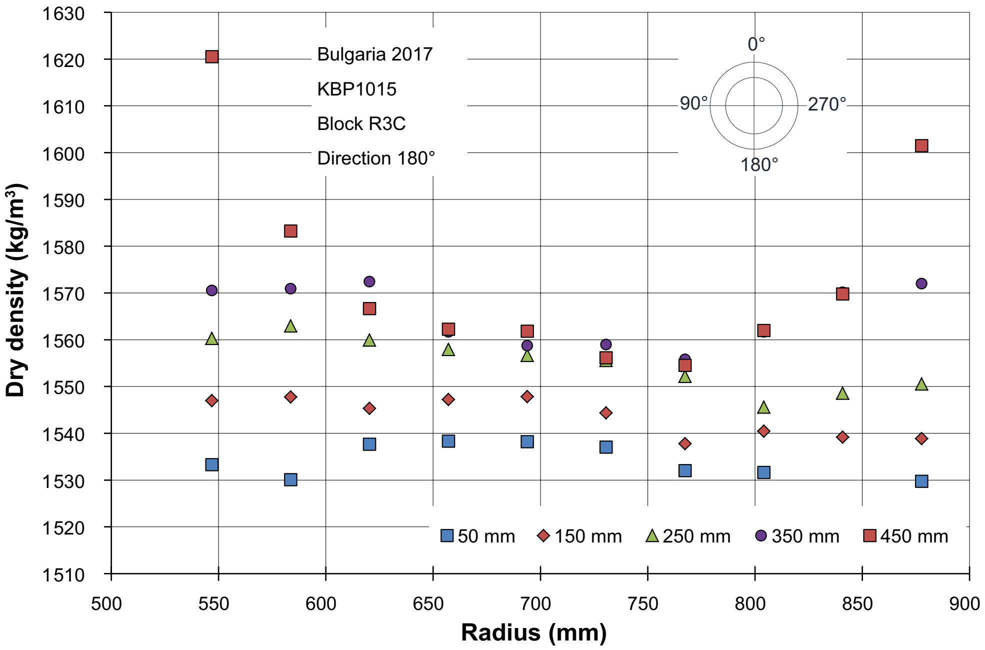

50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
India 2018
KBP1015
Block C3B
Direction 180°
0°
90°
270°
180°

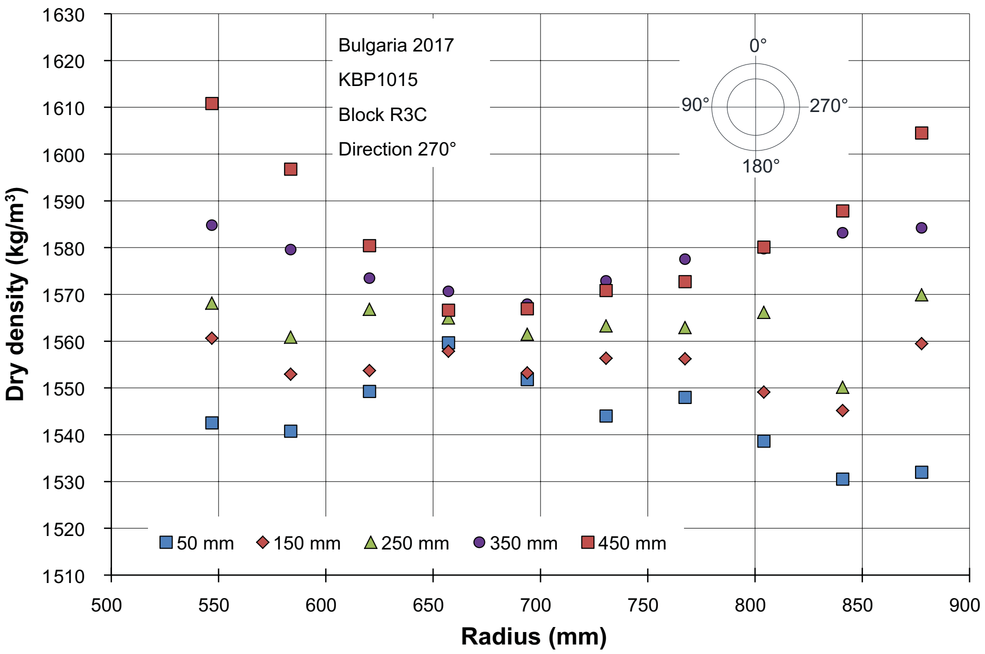

50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
India 2018
KBP1015
Block C3B
Direction 270°
0°
90°
270°
180°

Dry density of block R3C Bulgaria 2017 conical shape

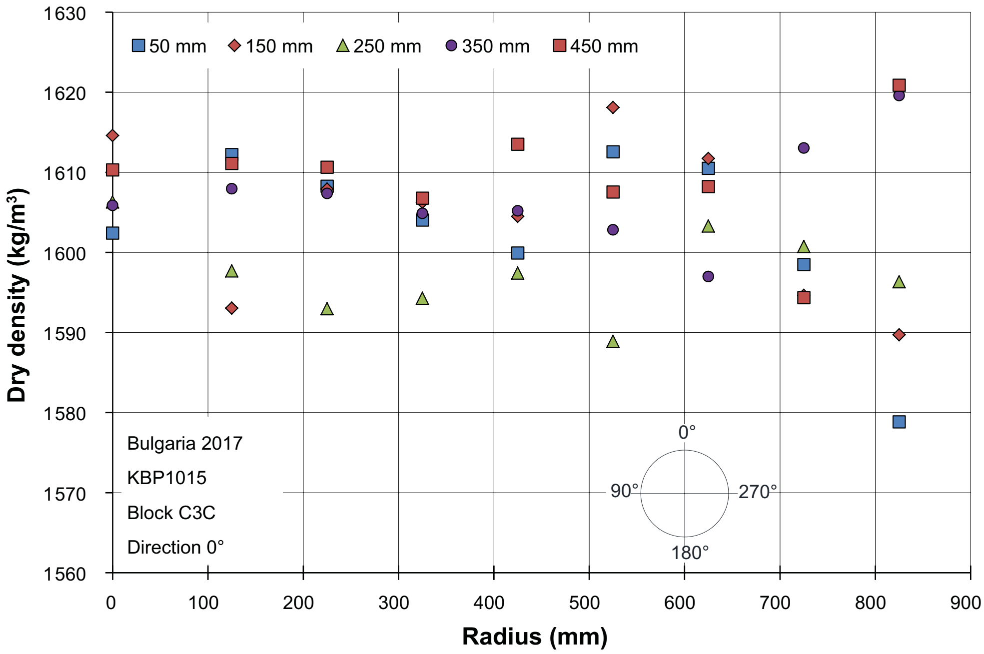


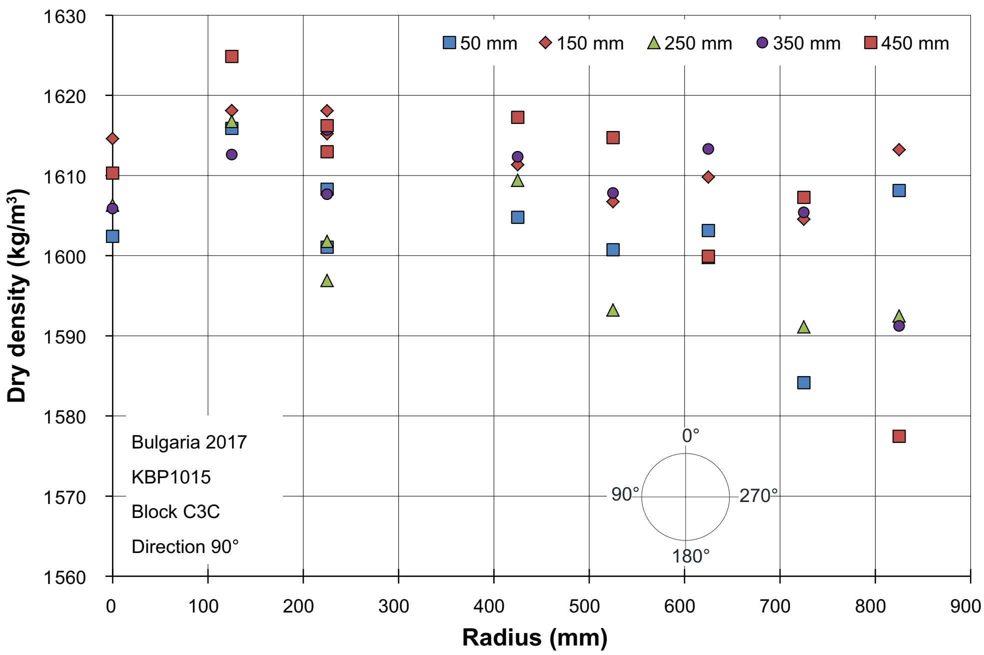


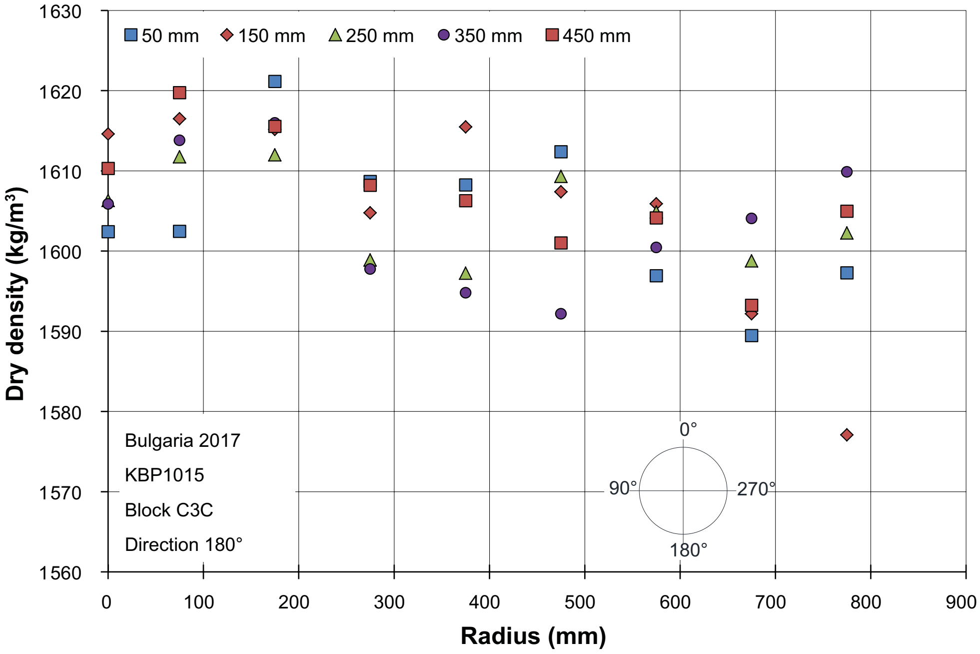

Bulgaria 2017
KBP1015
Block R3C
Direction 180°
0°
90°
270°
180°
Dry density (kg/m³)
Radius (mm)
50 mm
150 mm
250 mm
350 mm
450 mm


Bulgaria 2017
KBP1015
Block R3C
Direction 270°
0°
90°
270°
180°
Dry density (kg/m³)
Radius (mm)
50 mm
150 mm
250 mm
350 mm
450 mm

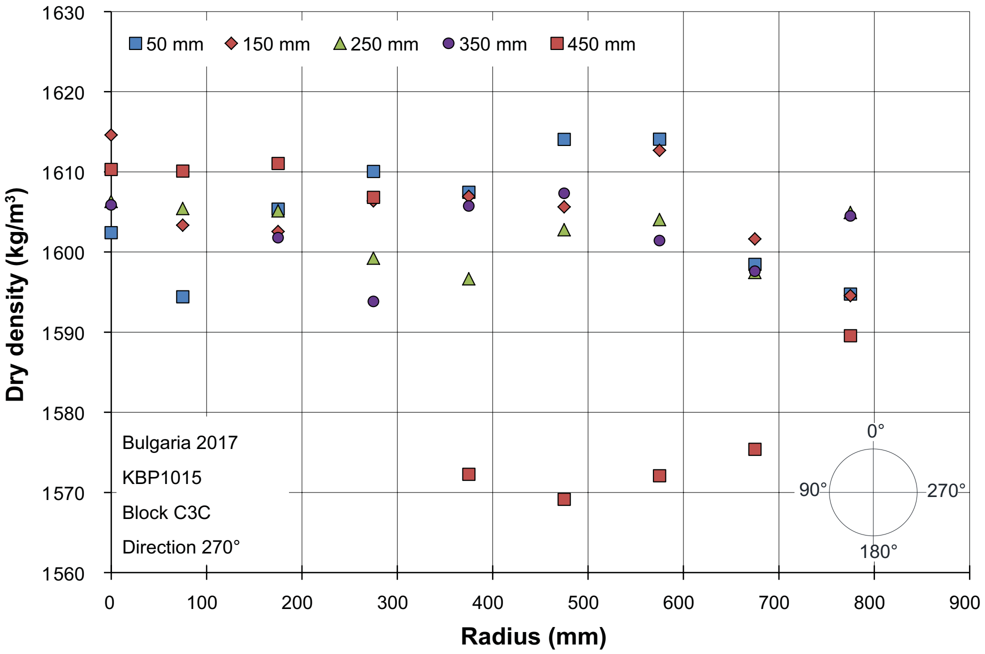
Dry density of block C3C Bulgaria 2017 conical shape







1630
1620
1610
1600
1590
1580
1570
1560
Dry density (kg/m³)
50 mm
150 mm
250 mm
350 mm
450 mm
Bulgaria 2017
KBP1015
Block C3C
Direction 180°
0°
90°
270°
180°
0
100
200
300
400
500
600
700
800
900
Radius (mm)



1630
1620
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Dry density (kg/m³)
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Bulgaria 2017
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Block C3C
Direction 270°
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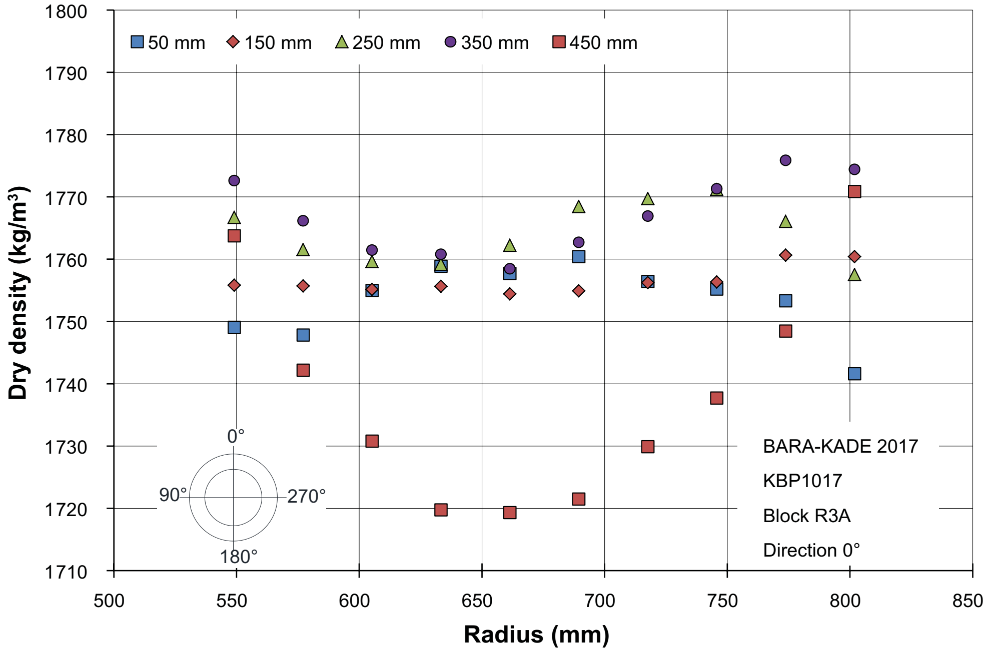
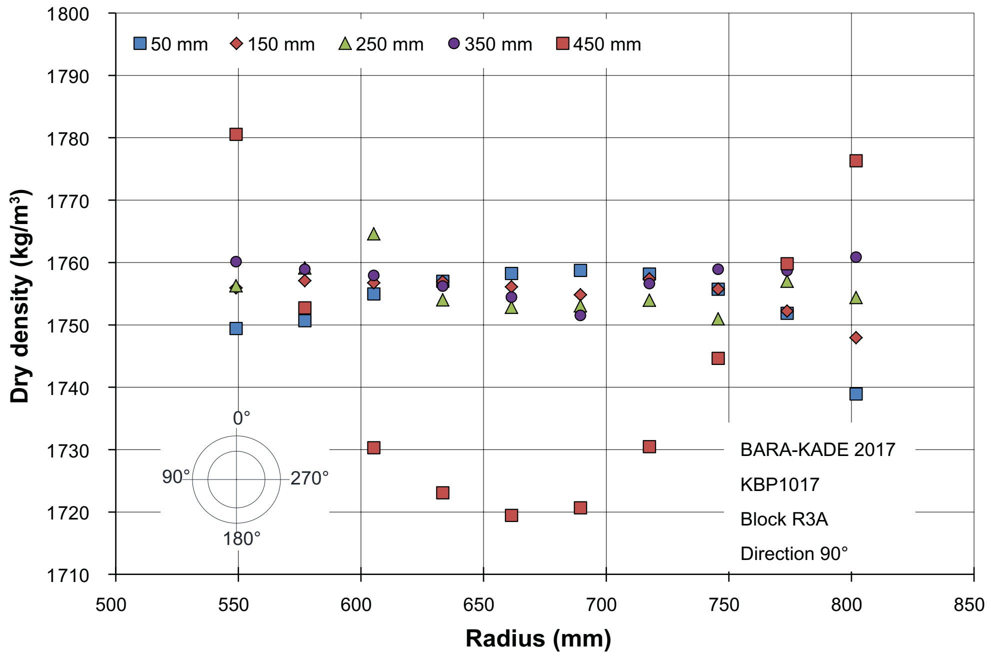
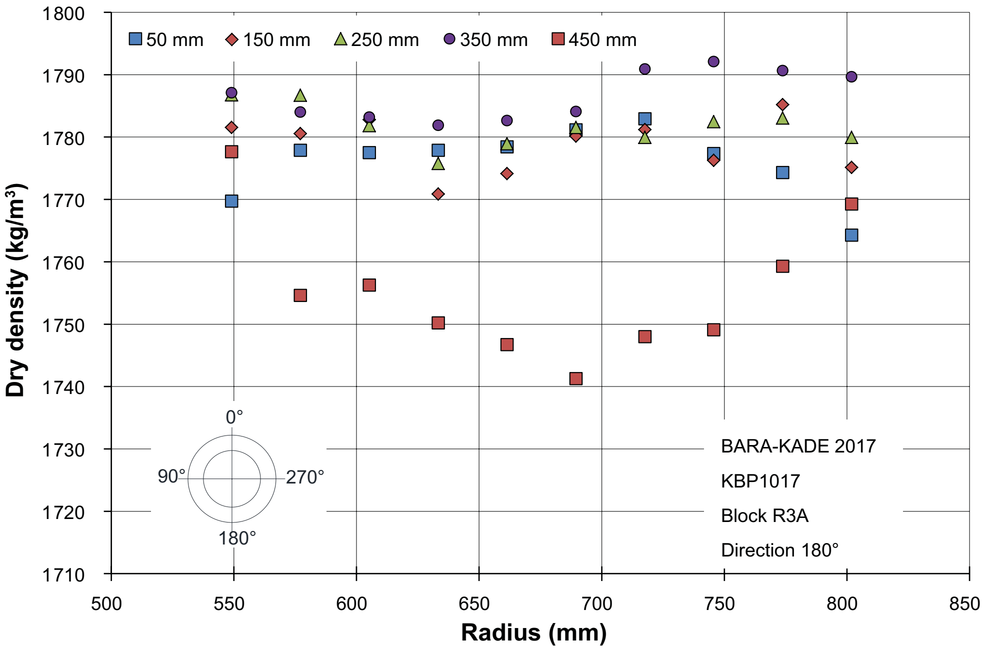
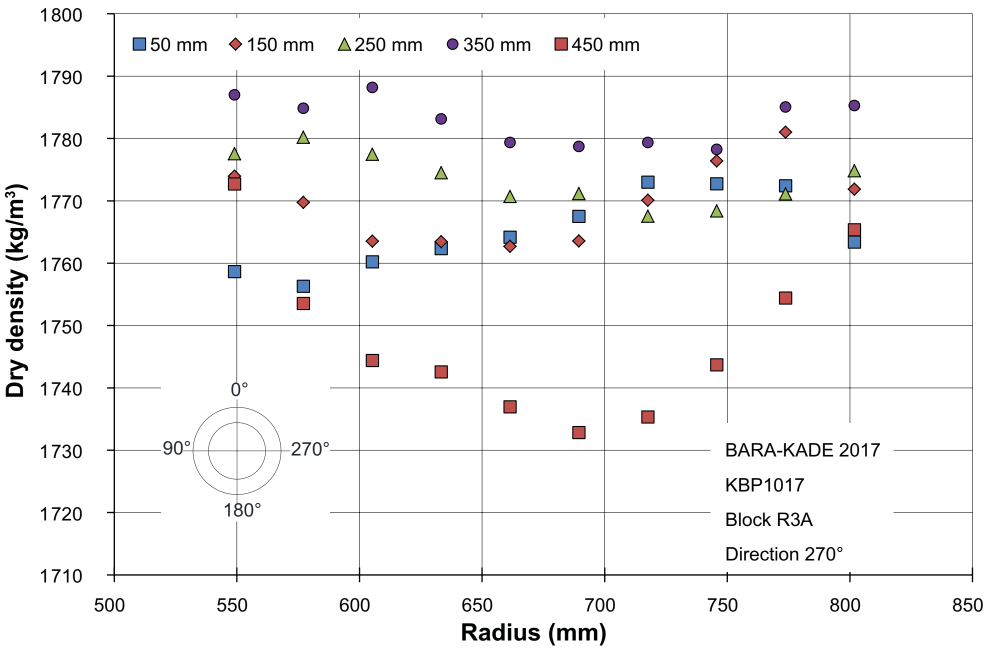
90°
270°
180°
0
100
200
300
400
500
600
700
800
900
Radius (mm)

Dry density of block R3A BARA-KADE 2017cylindrical shape

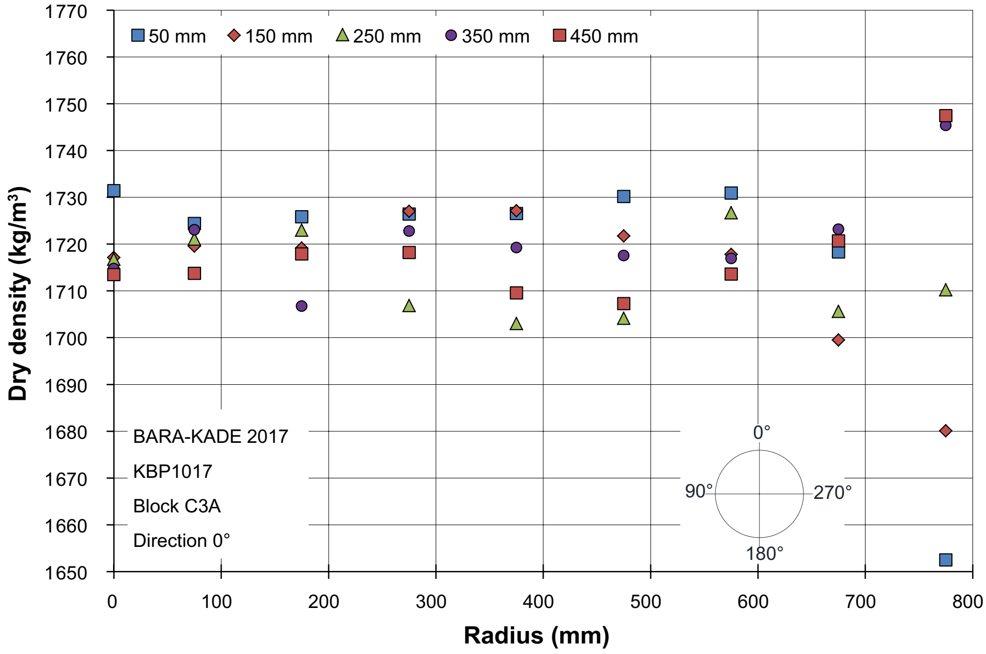


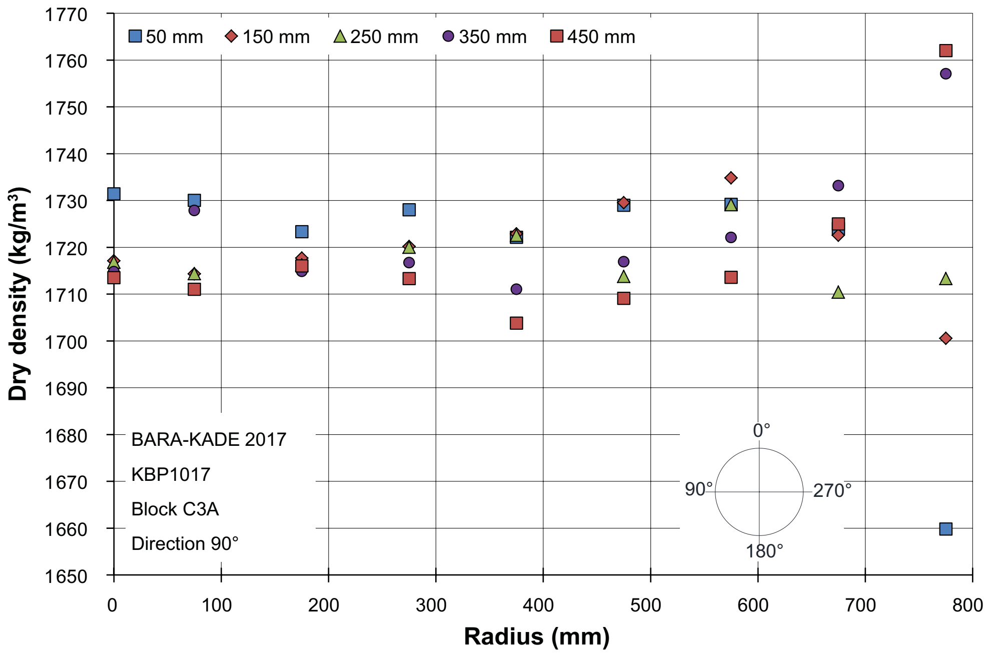


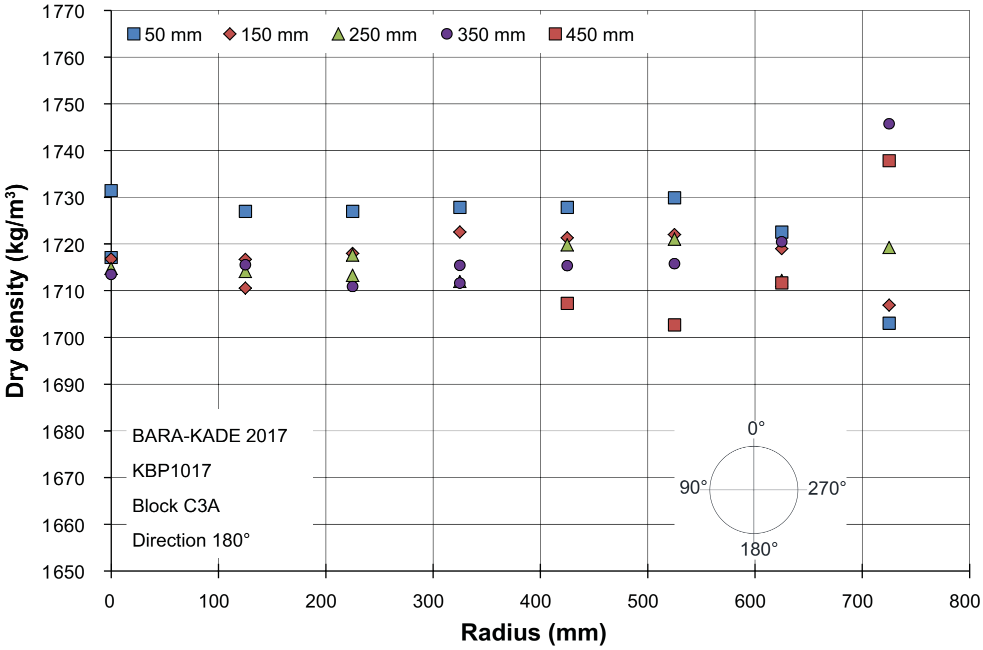

50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
0°
90°
270°
180°
BARA-KADE 2017
KBP1017
Block R3A
Direction 180°


50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
0°
90°
270°
180°
BARA-KADE 2017
KBP1017
Block R3A
Direction 270°

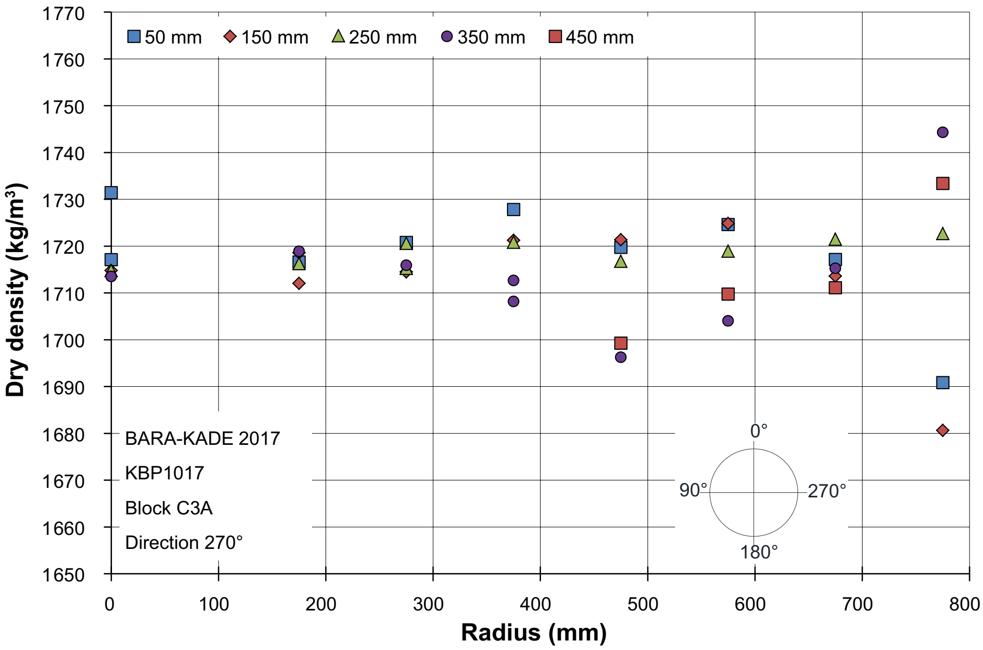
Dry density of block C3A BARA-KADE 2017 cylindrical shape







50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
BARA-KADE 2017
KBP1017
Block C3A
Direction 180°
0°
90°
270°
180°



50 mm
150 mm
250 mm
350 mm
450 mm
Dry density (kg/m³)
Radius (mm)
BARA-KADE 2017
KBP1017
Block C3A
Direction 270°
0°
90°
270°
180°

Arkitektkopia AB, Bromma, 2020

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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