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Compaction properties of bentonite clay

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Abstract

During test manufacturing of bentonite compaction a number of problems related to the material has been discovered. For example certain blocks have become brittle and there have also been differences in compaction properties between different deliveries of bentonite material. Earlier it has been found that the granule size distribution affects the strength and compaction properties of the material (Sandén et al. 2016). There have also been some material related issues related to the production of bentonite blocks that have not been tested before. Therefore a number of tests have been done to investigate these questions.

Form the work done in this report the following conclusions can be made:

- Models have been constructed that can predict most of the properties of bentonite during compaction. The models can also explain the problems that have been experienced during production. However, more testing is needed to verify the models.
- The constructed models predicts that the parameter affecting compaction properties of the material is the flow stress of the material, initial bulk dry density and water content. The friction between the mould and the material also affects the final density. The granule size distribution does not have a direct effect on the compaction properties of the material but the granule size distribution has an indirect effect since it affects the initial dry density.
- The model implies that the initial bulk dry density is probably a better way to specify the compaction properties of the material then the granule size distribution. This is because it is easier to measure and is less strict.
- The tensile strength seems to be dependent on the pore size and therefore enough fine material should be present in to reduce the pore size in the material to get a less brittle block.
- It is important to prevent the material from segregating during handling since segregation will affect the compaction properties. If the material is different in different parts of the block unnecessary stresses can arise in the block which could make them crack. If there is a difference in material between blocks it can be problematic to control the production process.
- Block quality does not seem to change very much when the crushed and reused material is used in the production. This means that discarded blocks and material machined away can be reused.
- It is most likely that blocks without lubrication can be produced. However, more work should be done in order to investigate how internal stresses affect the way that the block behaves when the block is subjected to drying or wetting environment. Internal stresses could change the time it takes for the block to crack at a certain relative humidity.

Sammanfattning

Under de tillverkningstester av bentonitblock som har gjorts så har ett antal materialrelaterade problem upptäckts. Till exempel så har vissa block blivit spröda, det har också upptäkts att materialens kompakteringsegenskaper har varierat mellan olika leveranser. Det har tidigare visats att granulstorleksfördelningen påverkar både hållfasthet och kompakteringsegenskaperna på materialet (Sandén et al. 2016). Det har också funnits ett antal osäkerheter relaterade till tillverkningsprocesserna som inte har testats tidigare. Därför har ett antal tester gjorts för att utreda dessa frågor närmare.

Utifrån det arbete som har gjorts i denna rapport så kan följande slutsatser dras:

- Modeller har skapats som kan förutse de flesta egenskaperna som uppmäts under testerna. Modellerna kan också förklara de svårigheter som har uppmärksammats vid provtillverkningar. Dock så behövs ytterligare tester för att verifiera att modellerna stämmer.
- De framtagna modellerna förutspår att de parametrar som påverkar kompakteringsegenskaperna är materialets flytspänning samt den initiala bulkdensiteten och vattenkvoten. Friktionen mellan pressformen och materialet påverkar också den slutliga densiteten. Granulstorleksfördelningen har ingen direkt påverkan på kompakteringsegenskaperna men den påverkar indirekt genom att den påverkar den initiala bulkdensiteten.
- Modellen antyder att initial bulkdensitet antagligen är bättre att använda i specifikationen på materialet än granulstorleksfördelning. Detta eftersom det är lättare att mäta och att uppfylla.
- Sträckgränsen verkar vara beroende på porstorleken och därför bör tillräckligt med finmaterial finnas för att undvika spröda block.
- Det är viktigt att hindra att materialet segregerar under hantering eftersom det kan påverka kompakteringsegenskaperna. Om kompakteringsegenskaperna är olika i olika delar av blocket så kan extra spänningar finnas i blocket vilket kan leda till sprickor. Olika kompakteringsegenskaper kan också leda till problem att kontrollera kompakteringtryck under tillverkningsprocessen.
- Blockkvaliteten verkar inte påverkas så mycket av att krossa och återanvändas för att pressa nya block. Det betyder att kasserade block och material från bearbetningen borde kunna återanvändas i tillverkningsprocessen.
- Det är troligt att buffertblock kan tillverkas utan smörjmedel. Dock bör mer arbete göras på hur de extra spänningar som blir i blocket påverkar hur fort blocken spricker vid olika relativa fuktigheter.

Contents

1 Introduction

Production of bentonite blocks and pellets is planned to be done close to the repository for spent fuel. The bentonite material will be stored in the harbour area before being crushed and dried. After crushing and drying the material will be delivered to the production building were the material will be mixed to the correct water content and compacted to blocks (Eriksson 2014a, b). During the years a large amount of manufacturing tests have been performed, during these tests some material related problems, which are described in Section 2.2, have been discovered which has not been fully understood. These problems can be avoided or reduced by adapting the process parameters, such as water content and compaction pressure. However, it has not been completely clear what causes these problems. Therefore a number of compaction tests have been carried out where the parameters have been varied and the effect on compaction properties and block strength has been measured.

The main focus of this report is to report the result from new tests and evaluate data that has been produced in this report and in older reports, especially data from Sandén et al. (2016). The purpose is mainly to try and find out which parameters that could influence the quality of bentonite blocks. This work could then be used to create better material specifications that would make block compaction process more stable and reliable.

2 Background

2.1 General

A large amount of manufacturing tests have been done both on backfill blocks and buffer blocks. However, there have been some questions regarding how the material behaves during the manufacturing process. The questions are related both to how the process is designed and to problems that has arisen during the manufacturing tests.

Some of the questions related to the process design have been:

- Can material be recycled, or will the block quality deteriorate when it's re-crushed and re-compacted?
- Does the time from mixing to compaction have an impact on the compaction process? This could have an effect if the water content does not have time to homogenize enough before block compaction. This is of importance at the designing of how large the storage capacity between the mixer and the compaction must be, which is not very large in current design.
- Does the buffer mould need to be lubricated? Currently a lubricant is used on the mould to reduce friction between the mould and the bentonite. The lubricant is then machined away after compaction. However, it would be an advantage to do the compaction without any lubricant because the material machined away from the block could then be reused.

To get a better understanding of these questions some new tests have been done. The tests are described and the results are presented in this report.

During manufacturing tests a few unsolved questions relating to the material during production have been identified. These are;

- Material from older batches need a higher compaction pressure compared to newer ones to reach the same dry density. It is not known what causes this change in compaction properties.
- Compaction of some materials results in brittle blocks. This mainly shows as very brittle edges that fall off when the blocks are handled and has been noticed in backfill block manufacturing.
- Compacted buffer blocks with dark stripes have been produced and cracking has sometimes occurred close to the stripes leading to the suspicion that the cracks are caused by phenomena linked to the stripes.

Some smaller tests have been done to answer these questions but the main work has been in developing models on how the material behaves. The models can thereafter be used to explain the problems seen in the manufacturing tests.

2.2 Problems experienced during production

2.2.1 Striped blocks

During assembly of the KBS-3H Multipurpose test it was noticed that the blocks had lighter and darker stripes, see Figure 2-1. When the blocks were handled they were subjected to a relative humidity in the air which was not in equilibrium with the water content in the blocks during the assembly. During this time the blocks cracked and it was observed that the blocks seemed more prone to crack close to the interface between the dark and the lighter area, see Figure 2-2. However, this is only observations and no data exists to support this observation.

Some investigations were made where cores were taken from a block. The cores were then cut to smaller samples, as shown in Figure 2-3: The water content and density were determined on the samples and the results are presented in Table 2-1. The results indicated that the difference in colour was caused by a difference in saturation, but no further conclusions could be made at that time regarding the cause of this.

Figure 2-1. *striping in compacted blocks.*

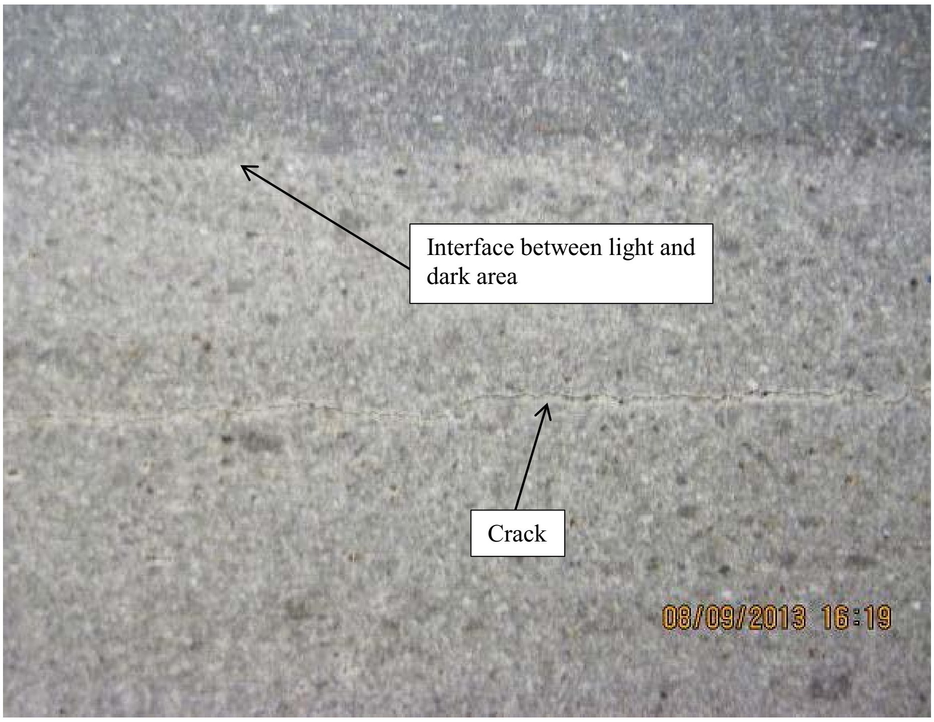

Figure 2-2. *Enlargement of the interface between darker and lighter area.*

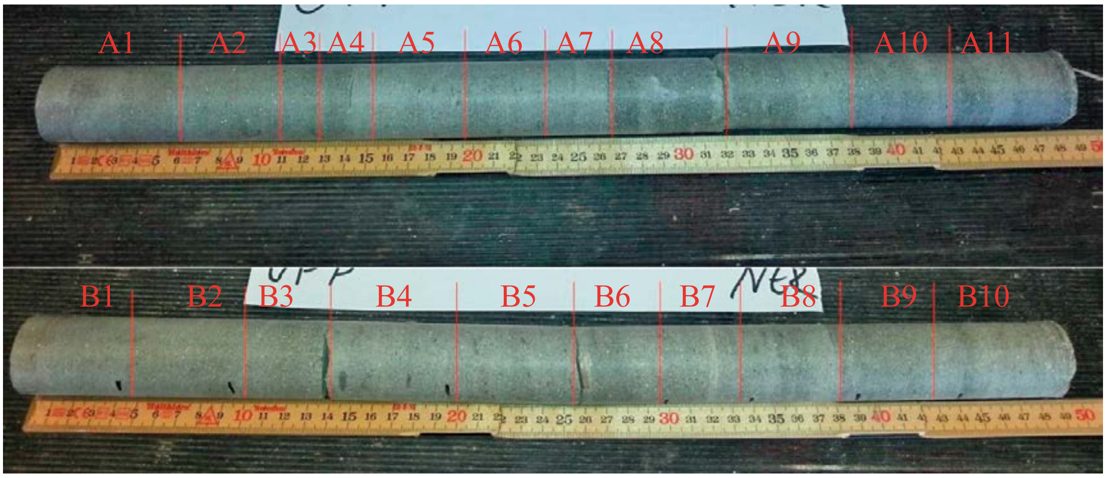

Figure 2-3. *Test cores taken from a striped block.*

Table 2-1. Test result from test cores.

Sample	Color	Water content	Density	Degree of saturation (%)
A1	Dark	21	2088	95.56
A2	Dark	21	2090	95.80
A3	Dark	20.9	2090	95.59
A4	Medium	–	–	–
A5	Light	20.3	2078	92.54
A6	Light	–	–	–
A7	Light	20.3	2076	92.46
A8	Dark	21	2080	94.53
A9	Dark	20.9	2083	94.74
A10	Medium	–	–	–
A11	Medium	20.6	2084	94.11
A12	Medium	20.6	2079	93.53
B1	Dark	21.1	2087	95.78
B2	Dark	21	2090	95.82
B3	Dark	–	–	–
B4	Medium	20.3	2081	92.99
B5	Light	–	–	–
B6	Medium	20.5	2080	93.46
B7	Light	20.5	2075	92.67
B8	Light	–	–	–
B9	Dark	20.7	2085	94.32
B10	Light/Medium	20.5	2076	92.80

2.2.2 Different compaction properties

The compaction properties of the material, MX-80 clay, that has been used for production of buffer blocks has changed over the years. A large change in compaction properties was noticed somewhere around 2008 when the material suddenly became much easier to compact. It was also noticed that the bulk density of the powder had gone up and thus the mould did not have to be filled as high as earlier. The difference in compaction properties between material delivered 1993 and material delivered 2012 is shown in Figure 2-4 and Figure 2-5. It can be noticed that for the material delivered 1993 it was difficulty to reach a dry density of 1769 kg/m^3, even at very high compaction pressures, which is the block dry density for the buffer rings according to the reference design. Note that the water content is different in Figure 2-4 this would likely make the difference even larger then seen in the graph since higher density is normally achieved with lower water content. It is important to understand why there is such a big difference between the materials to avoid the situation where blocks cannot be compacted to the correct density.

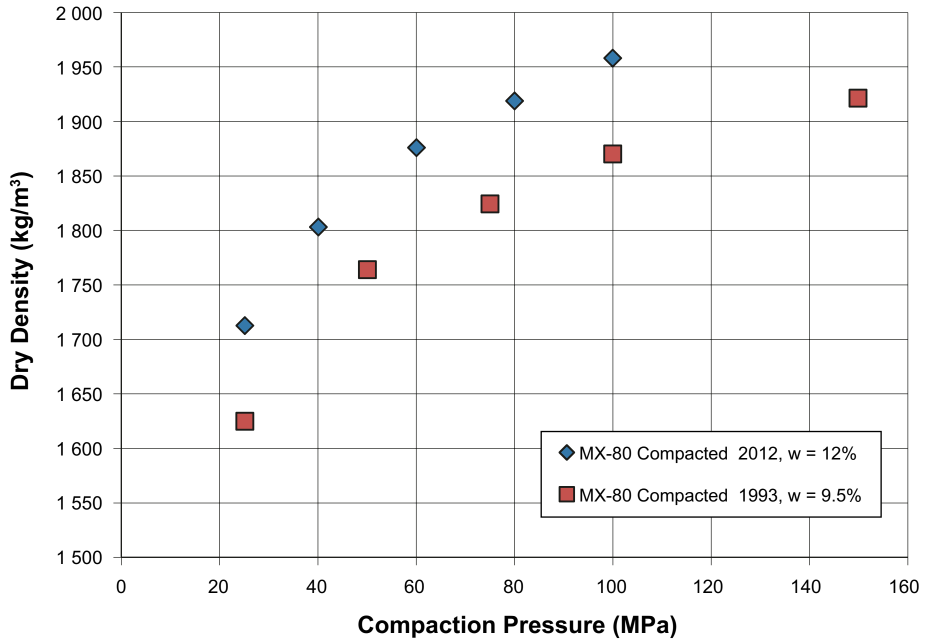

Figure 2-4. *Compaction curves of MX-80 from 2012 and 1993.*

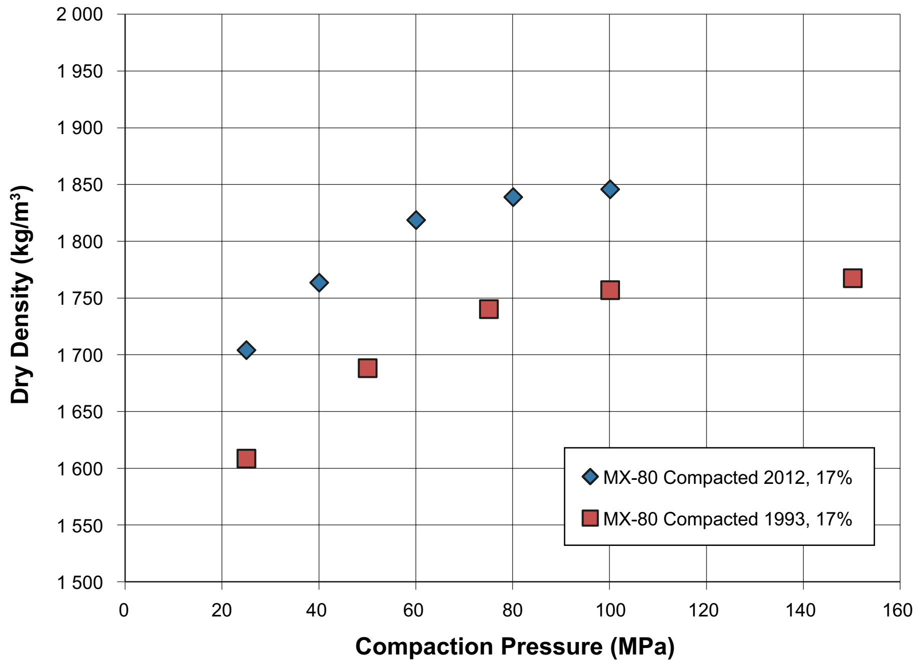

Figure 2-5. *Compaction curves of MX-80 from 2012 and 1993.*

2.2.3 Brittle blocks

During full scale manufacturing tests of backfill blocks (Sandén et al. 2015) some blocks had very brittle edges and this resulted in edges that fell off the blocks, see Figure 2-6. The quality of the block was improved when the material was crushed and after some adjustments to the process parameters, water content and compaction pressure. However, no good explanation on why the crushed materials produced less brittle blocks was found.

Figure 2-6. *Brittle edges on a backfill block.*

3 Method and description of performed tests

3.1 Motivation to complementary tests

A number of new test were performed to get data and to explain the problems discussed in Chapter 2. To try and find out how the granule size distribution affects the block quality the test described in Section 3.2 was done.

There were also a couple of production related questions needed to be answered. In the production the material will be compacted a short time after mixing which has never been done in the test production, therefore these tests, Section 3.3, are needed find out if this potentially could be a problem. During the production of bentonite blocks there will be some material waste, most of which comes from the machining of the buffer blocks and discarded blocks. If the material could be reused in the process it would reduce the amount of waste. However, it is not known if the recycled material will affect the quality of the blocks since this has not been tested before. To find out if the recycled material would behave different from blocks compacted with virgin material some small scale test were performed, see Section 3.4.

3.2 Influence of granule size

3.2.1 General

Tests have been performed earlier in order to find out how the granule size distribution affects the compaction properties of the material and the strength of the block (Sandén et al. 2016). The tests showed that there were some differences in the compaction properties when the granule size distribution was varied. However, several variables were changed between the different compaction tests and therefore it is difficult to know which variables are the most important. In an attempt to reduce the number of variables a new test series was performed. These new tests were designed to find out what influence the granule size has on the compaction properties of the bentonite material. Therefore, the material was sieved to obtain different granule fractions. These fractions could then be compacted and strength and density could be determined afterwards. In Sandén et al. (2014) it was shown that the coarser granules in the Asha 2010 material contained more material with swelling properties then the fine granules. In order to find out if this difference in properties result in any effect on the compaction properties the coarsest fraction was milled and sieved again. This material could now be compared with the material that was first sieved from the original material. The quality of the compacted blocks were evaluated by measuring the tensile strength, in the same way as it has been done in previous tests (Sandén et al. 2016).

3.2.2 Test setup

The material used for the test was an Indian bentonite delivered to SKB in 2010, at SKB called Asha 2010. This material was chosen because there are coarse granules in this material and therefore a large interval of granule sizes could be achieved. The material was then sieved into the fraction sizes shown in Table 3-1. After the sieving the different materials were compacted with the goal to reach the same dry density for all the compacted blocks. To evaluate the tensile strength of the blocks, beams were sawed from the compacted block and the block tensile strength was measured

The test was done in the following steps:

- The material was sieved to different fractions.
- Blocks were compacted (approx. Ø 100 mm, h 20 mm). From each block two beams were cut with the dimensions ($a \times b \times c \sim 20 \times 20 \times 80\ mm^3$).
- The beams were bent until failure by applying a force with a constant velocity of 0.1 mm/min at the centre of the beam. Load and displacement was measured continuously. Beams were bended both in the compaction direction and perpendicular to the compaction direction to see if there was any anisotropy in tensile strength.

Figure 3-1. *The different fractions used in the compaction tests.*

Table 3-1. Different fractions of granules from ASHA 2010 tested. Each fraction is then compacted separately.

Fraction size used in the test (mm)	In the test denoted as	Comment
< 0.25	0.25	
0.25–0.5	0.5	
0.5–1	1	
1–2	2	
2–4	4	
4–8	8	
> 8	16	
< 0.25	16 milled	Granule size > 8 mm milled and resieved

3.2.3 Three point bending test

The tensile strength of the compacted blocks was measured through a three point bending test, which is shown in Figure 3-2 and Figure 3-3.

The force and displacement is recorded and the ultimate tensile strength (σ_t) and the strain at failure (ε_t) were evaluated according to Equation 3-1 and Equation 3-2.

$$\sigma_t = \frac{6Qc}{4ba^2}$$ Equation 3-1

$$\varepsilon_t = \frac{a\omega 6}{c^2}$$ Equation 3-2

Where:

Q = vertical load

a = sample height

b = sample width

c = distance between the supports

ω = vertical displacement in the centre

3.2.4 Results

Generally the failure surface seems to follow the granule boundaries, at least when the granules are large, see Figure 3-4 and Figure 3-5. This indicates that the granule boundaries act as weak spots. When the granules are large the failure also tends to happen eccentric from the point where the load is applied. When finer granules are used the failure is more centric. The results from the tests can be seen in Table 3-2 to Table 3-4. The material seems to have a higher tensile strength the smaller granules the material has, See Figure 4-13.

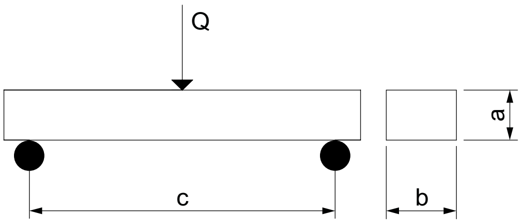

Figure 3-2. *Tensile strength measurement setup.*

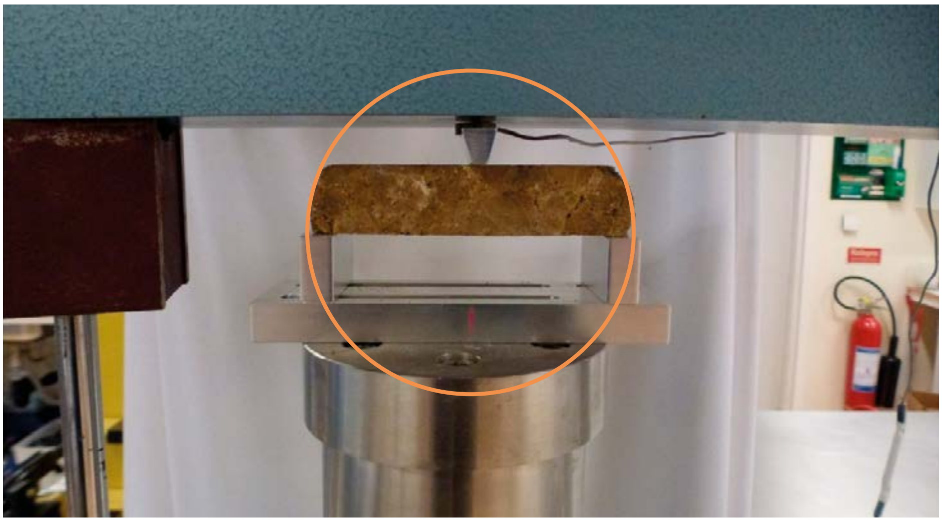

Figure 3-3. *Test sample during strength measurement, the circle shows the original block from which the beam is taken.*

Figure 3-4. *Image of beam after failure, the beam has failed in the centre. The specific granule size for this sample is < 0.25 mm.*

***Figure 3-5.** Example of a test sample with a coarse fraction. The failure surface is not in the centre and tend to follow the granule boundaries.*

Table 3-2. General data from the tests.

Granule size mm	Denoted as	Mould filling height mm	Compaction ratio	Water content %	Share fraction in Asha 2010 %	Compaction force kN
< 0.25	0.25	37	1.85	15.1	12.44	200
0.25–0.5	0.5	37	1.85	15.9	7.88	200
0.5–1	1	37	1.85	16.3	10.32	200
1–2	2	38	1.9	16.6	19.25	200
2–4	4	39	1.95	16.7	20.72	220
4–8	8	40	2	16.4	15.37	200
> 8	16	36	1.8	17.0	14.02	200
0.25	16 milled	37	1.85		na	200

Table 3-3. Test result from the tests.

Test ID	Water content %	Dry density kg/m³	Void ratio	Max. Tensile stress kPa	Strain at failure %
0.25 H 1	15.0	1707	0.699	1374	0.440
0.25 H 2	15.0	1738	0.668	1644	0.472
0.25 V 1	14.9	1729	0.677	1383	0.354
0.25 V 2	14.9	1730	0.676	1473	0.379
0.5 H 1	15.7	1717	0.689	1100	0.513
0.5 H 2	15.7	1715	0.691	985	0.387
0.5 V 1	15.6	1704	0.702	874	0.380
0.5 V 2	15.6	1735	0.672	971	0.400
1 H 1	16.0	1725	0.682	909	0.437
1 H 2	16.0	1758	0.649	935	0.415
1 V 1	15.8	1711	0.694	690	0.368
1 V 2	15.2	1746	0.661	808	0.463
2 H 1	16.3	1733	0.674	627	0.321
2 H 2	16.6	1712	0.694	693	0.311
2 V 1	16.2	1709	0.697	470	0.433
2 V 2	16.3	1736	0.671	541	0.300
4 H 1	16.4	1750	0.657	543	0.324
4 H 2	16.5	1744	0.663	476	0.345
4 V 1	15.9	1745	0.662	422	0.336
4 V 2	16.4	1751	0.656	474	0.417
8 H 1	16.1	1742	0.664	444	0.581
8 H 2	15.9	1749	0.658	438	0.310
8 V 1	16.2	1735	0.671	372	0.621
8 V 2	16.4	1751	0.656	350	0.406
16 H 1	16.1	1748	0.659	476	0.112
16 H 2	16.1	1737	0.670	399	0.283
16 V 1	16.0	1788	0.622	702	0.337
16 V 2	16.8	1747	0.660	183	0.270

Table 3-4. Test Result from test series 2.

Test ID	Water content %	Dry density kg/m³	Void ratio	Max. Tensile stress kPa	Strain at failure %
16 H 3	16.7	1741	0.666	568	0.405
16 H 4	15.9	1748	0.659	728	0.373
16 V 3	16.6	1766	0.642	464	0.322
16 V 4	16.3	1759	0.649	293	0.304
16 milled H 5	16.4	1731	0.675	1254	0.451
16 milled H 6	16.3	1727	0.679	1368	0.408
16 milled V 5	16.1	1737	0.670	1262	0.284
16 milled V 6	16.1	1728	0.679	1052	0.337

3.3 Homogenisation tests

The main reason for these tests is to find out if water in the material needs to homogenise between the mixing and the compaction. The current plan for the production facility is that the compaction of the blocks will take place rather short time after the mixing of the bentonite. Therefore it is important to show that homogenisation is quick enough to not influence the compaction process. The material chosen is Asha 2010 material with all granules smaller than 1 mm sieved away. The test was done in the following steps:

- The material was mixed with water to the right water content, 20.5 %.
- At specified times after mixing the blocks were compacted (approx. Ø 100 mm, h 20 mm). From each block two beams were cut with the dimensions ($a \times b \times c \sim 20 \times 20 \times 80$ mm^3).
- The beams were bent until failure by applying a force at the centre of the beam at a constant velocity of 0.1 mm/min. Load and displacement was measured continuously in the same way as described in Section 3.2.2.

The compactions of blocks were made directly after mixing thereafter at 1, 2, 4 and 8 days after mixing.

3.3.1 Results

No significant difference could be noticed between the samples. The difference in behaviour can mainly be attributed to the difference in water content and density. This suggests that the homogenisation within the granules is quite fast and that the compaction is not significantly affected by the time between the mixing and the compaction. This means that there is no need for an intermediate storage between mixing and compaction and the time between mixing and compaction does not need to be considered. The results show that no significant difference in density or strength can be seen, see Table 3-5.

Table 3-5. Test results from the homogenisation test.

Sample	Time after mixing (Days)	Water content (%)	Density (kg/m³)	Void ratio	Tensile strength (kPa)	Strain at faliure (%)
0d H 1	0	20.3	1748	0.659	1560	0.494
0d H 2	0	20.3	1737	0.670	1391	0.392
1d H 1	1	20.7	1732	0.674	1584	0.489
1d H 2	1	20.7	1729	0.677	1465	0.551
2d H 1	2	20.65	1716	0.690	1584	0.482
2d H 2	2	20.6	1738	0.669	na	na
4d H 1	4	20.6	1721	0.685	1236	0.701
4d H 2	4	20.7	1737	0.669	1371	0.595
8d H 1	8	20.4	1740	0.667	1538	0.586
8d H 2	8	20.4	1727	0.679	1269	0.556

3.4 Recycling of the material

At the production of buffer block in a future repository for spent fuel the buffer blocks likely need to be machined to get the correct dimensions. This machining will create some waste and it would be advantageous if this material could be recycled and put back in to the production process. In order to see if this recycling of material could influence the strength of the compacted blocks, a small test series was done by compaction small blocks and then mill them and recompact the material again. This process was repeated and after each recompaction the strength was measured. In total 5 recompactions were made. Unfortunately the milling of the material caused the material to dry and therefore changed the compaction properties and also the strength which decreases with decreased water content (Sandén et al. 2016). In Table 3-6 the data from the test is shown and in Figure 3-6 the data is compared to data from Sandén et al. (2016) for similar material. The data suggests that the block strength does not degrade during milling and recompaction. However, there is a very big scatter in the data and the change in the water content makes the results even more uncertain.

Table 3-6. Test result from recompaction test.

Test ID	Number of recompactions	Water content (%)	Dry density (kg/m³)	Max. tensile stress (kPa)	Strain at failure (%)
A11	1	16.824	1774.345	962	0.463
A12	1	16.930	1765.505	1322	0.525
B11	2	16.112	1784.113	2048	0.707
B12	2	16.076	1783.620	1654	0.626
C11	3	15.256	1796.222	1654	0.757
C12	3	15.168	1798.897	1401	0.538
D11	4	14.282	1813.339	1769	0.412
D12	4	14.403	1804.634	2241	0.544
E11	5	13.932	1815.502	1459	0.549
E12	5	13.930	1812.088	1793	0.860

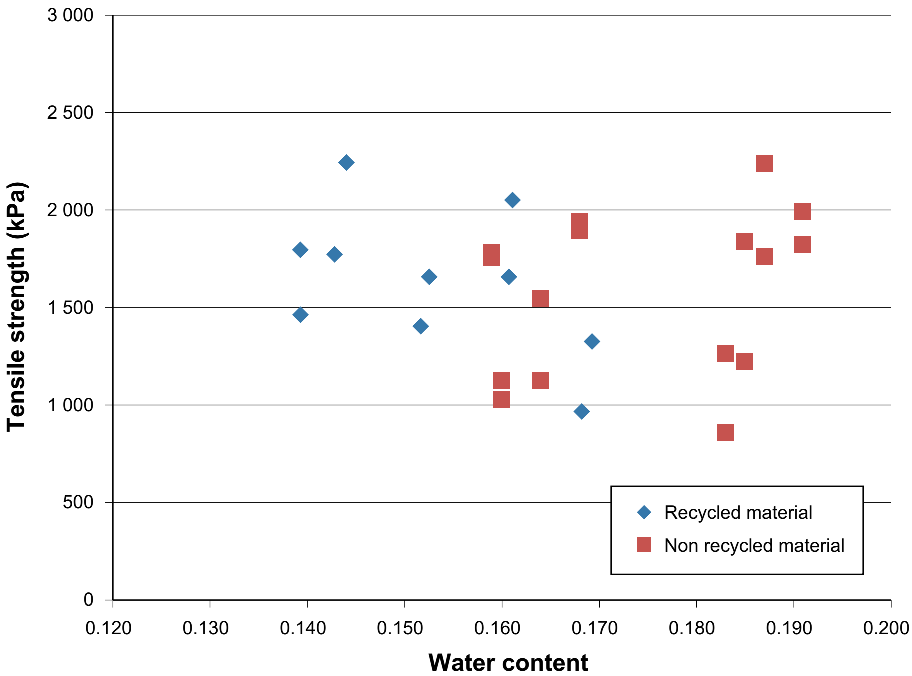

Figure 3-6. Comparison between results of tensile strength tests for recycled and non-recycled material. Red dots shows virgin material, data taken from Sandén et al. (2016). Blue diamonds are data from recycled material in this report.

3.5 Lubricant free block

3.5.1 Description of production

In order to evaluate how well it would work to compact blocks without using lubrication on the mould a test was done were two full scale blocks were compacted. One of the blocks was compacted with lubrication and one without lubrication. The other process parameters were kept constant. Ring shaped blocks were selected for the comparison because they are more affected by the difference in friction due to the lower diameter to height ratio than the solid blocks.

The compaction process starts with the preparation of the mould. The mould is cleaned and for the case where lubrication is used the lubrication is applied on the vertical surfaces of the mould. After the mould has been prepared it is filled with the correct weight of bentonite clay from a big bag, see Figure 3-7. The clay used in this case was MX-80 which was delivered during 2015. The filled mould is then placed in the press, Figure 3-8, and vacuum is applied to the mould to evacuate excess air from the bentonite material. The compaction pressure is then applied and increased during ten minutes until the desired compaction pressure is reached. Then the compaction pressure is kept constant for another ten minutes before the pressure is slowly released during ten minutes. This means that the total compaction time is approximately 30 minutes. More details about the manufacturing process in general can be found in Johannesson (2014). The data from the manufacturing is shown in Table 3-7.

Table 3-7. Data from the manufacturing of blocks.

Block ID	KBS3V15R3 (lubricated)	KBS3V15R13 (unlubricated)
Compaction pressure	46 MPa	51 MPa
Water content	17%	16.6%
Dry density	1767	1781

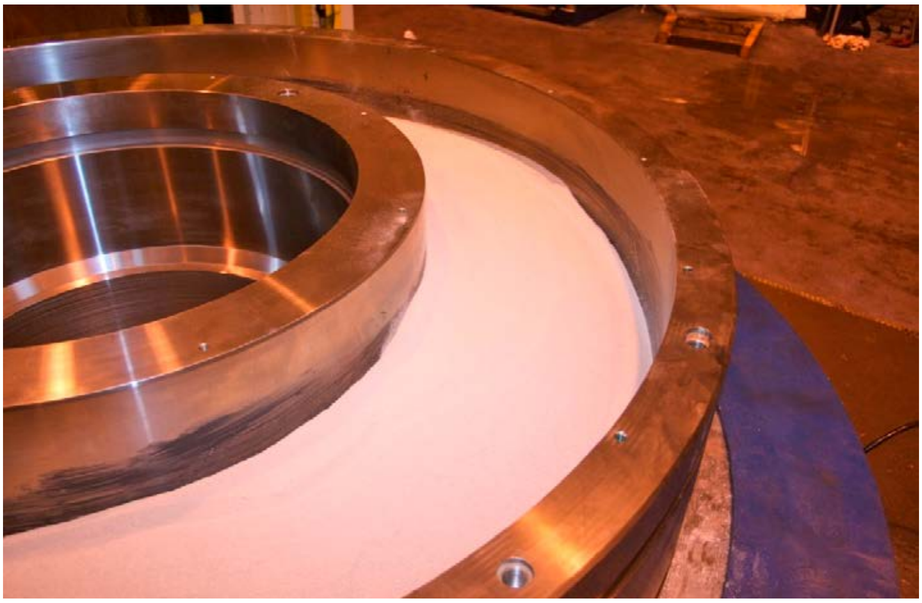

Figure 3-7. *Mould filled with bentonite.*

Figure 3-8. *Compaction press.*

3.5.2 Comparison between lubricated and unlubricated blocks

The water content and the density of the blocks were determined after compaction. This was done by cutting 4 slices in four directions with 90 degrees between them. Each slice was then cut in 50 pieces with a band saw, 5 pieces in the height direction and 10 in the radial direction, according to Figure 3-9. In each of these pieces the water content and the density were measured.

The result from the measurements can be seen in Figure 3-10 and Figure 3-11. The figures show that the lubricated block has a better homogeneity in density than the unlubricated block. The biggest difference in the two blocks is close to the outer surface where the influence of the friction can be clearly seen. However, there is no requirement on the homogeneity of density within the block. The requirement on the blocks is only on the average bulk density.

One interesting thing that can be noticed is that the variation in water content is quite big inside the blocks. This indicates that there are residual stresses inside the blocks since the blocks were stored for approximately 3 months before the testing was done. Therefore any differences from the compaction or filling should have evened out if there were no internal stresses that could keep the gradients in water content over time. The water content distribution indicates that there are compressive stresses in the surface of the unlubricated block because it has a lower water content. This is likely because friction has caused the density to be higher there and therefore the elastic expansion should be higher close to the surface.

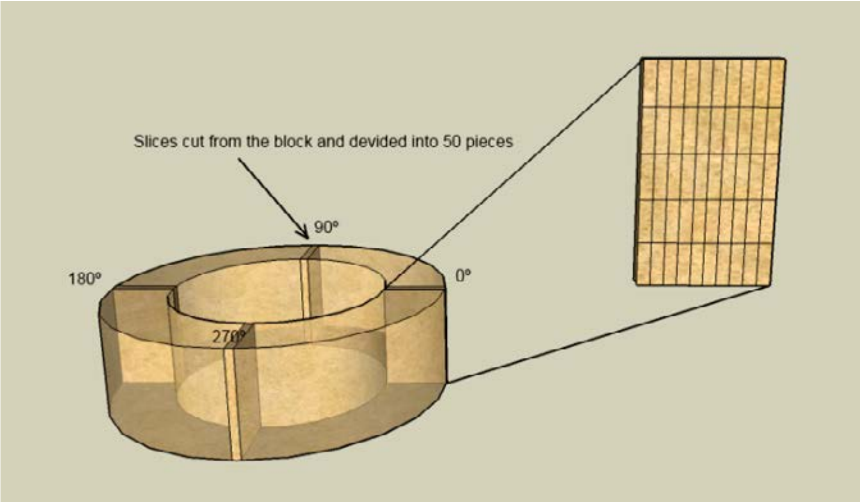

Figure 3-9. *Sketch showing were test sample are taken out.*

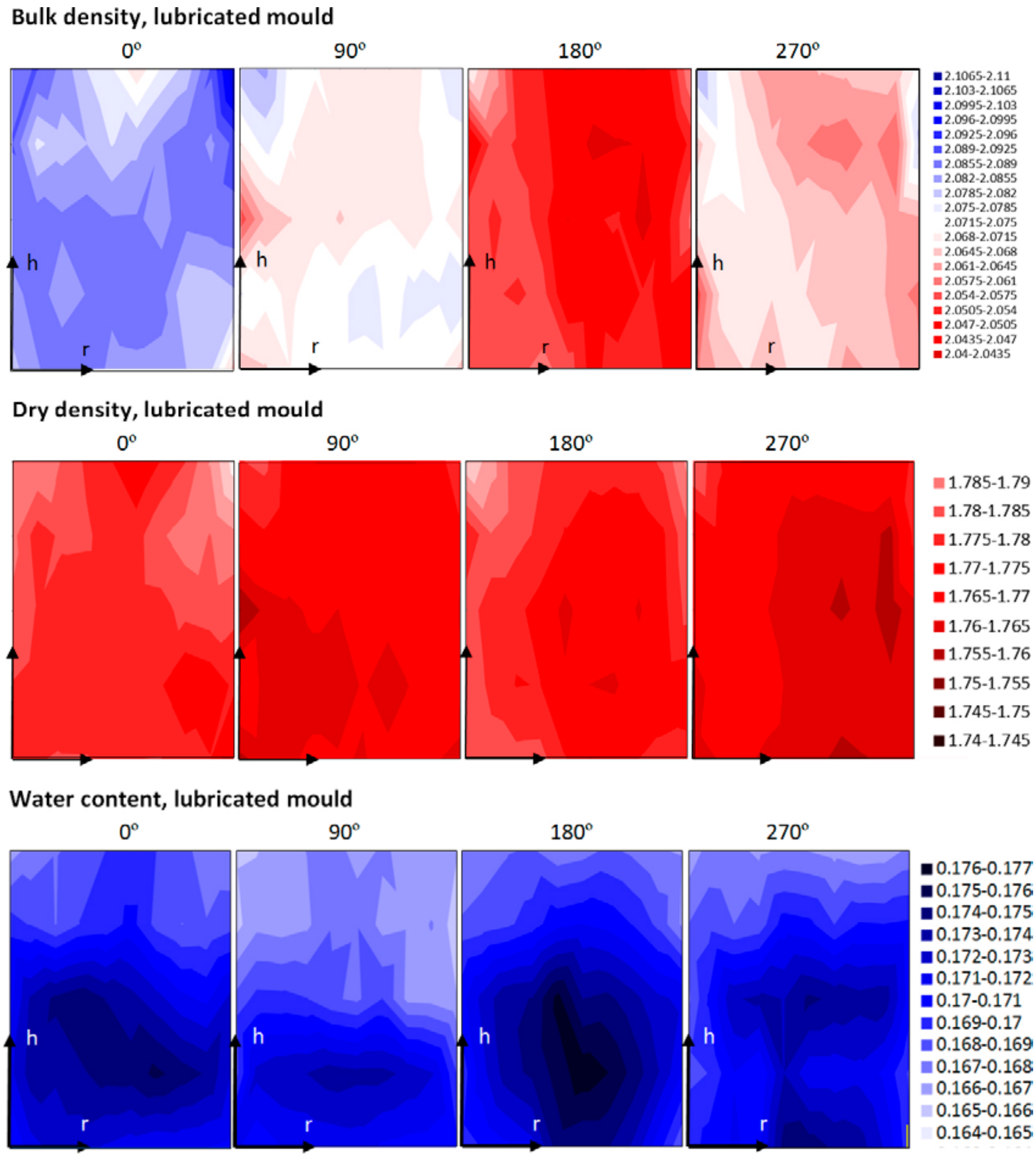

Figure 3-10. *Result for the lubricated block.*

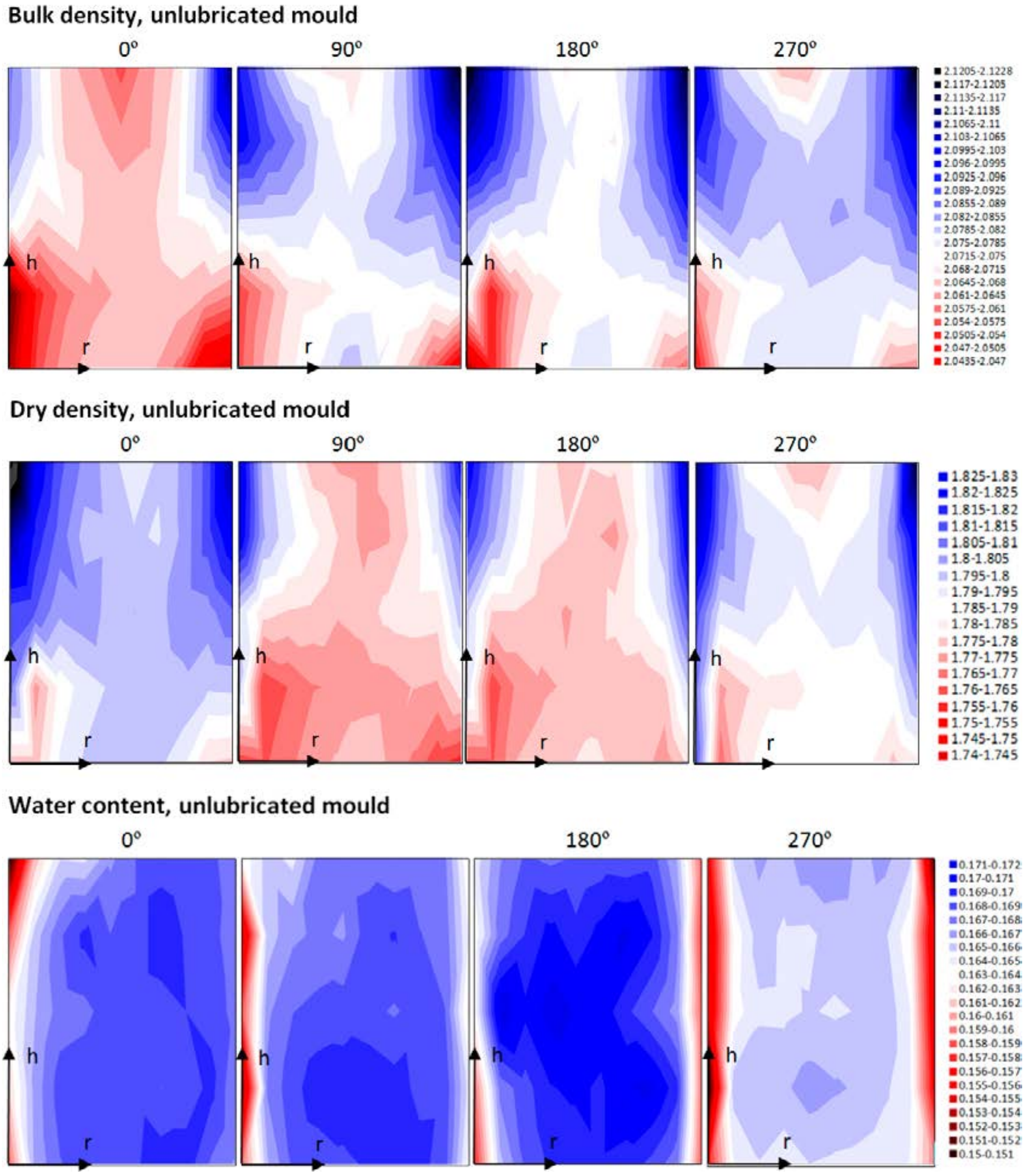

Figure 3-11. *Result for the unlubricated block.*

4 Theory and models

4.1 Axial pressure vs radial

In uniaxial compaction the material is compacted in the mould by applying an external axial pressure. Due the axial pressure applied there will also be a radial pressure. This radial pressure affects the compaction as it governs, together with the friction coefficient, how large the friction forces will be. The forming of a radial pressure will also affect the demoulding because a high radial pressure will increase the swelling of the block in the radial direction. To predict how the radial pressure evolves as a function of axial pressure in a uniaxial compaction process a model suggested by Long (1960) is used. In this model the compaction of a body can be described by four steps:

1. Elastic loading, $\sigma_r = \sigma_a \nu/(1-\nu)$ $(\sigma_a - \sigma_r)_{\geq}\sigma_0$
2. Plastic loading, $\sigma_r = \sigma_a - \sigma_0$
3. Elastic releasing, $\sigma_r = \sigma_a \nu/(1-\nu) + k$ $(\sigma_a - \sigma_r)_{\geq}\sigma_0$
4. Plastic releasing, $\sigma_r = \sigma_a + \sigma_0$

Where σ_a is the axial stress, σ_r is the radial stress, ν is the poisons ratio and σ_0 is the flow stress of the material.

The model can be extended by adding friction. The axial pressure is then $\sigma_a = P_a \pm \mu c P_r$, where μ is the friction coefficient and c is a constant to describe diameter to height ratio.

1. Elastic loading, $\sigma_r = P_a \nu/(1-\nu-c\mu\nu)$
2. Plastic loading, $\sigma_r = (P_a - \sigma_0)/(1+c\mu)$
3. Elastic releasing, $\sigma_r = P_a \nu/(1-\nu+c\mu\nu) + k$
4. Plastic releasing, $\sigma_r = (P_a + \sigma_0)/(1-c\mu)$

Where P_a is the applied axial stress.

From this model it can be seen that a higher flow stress will give a higher radial stress in the block when the axial pressure is released, also an increased friction will increase the residual radial stress, Figure 4-1. When the block later is extruded from the mould the external radial pressure will disappear and the block will swell. This swelling will cause shearing stresses in the block at the edge of the mould and they become too high cracks can appear.

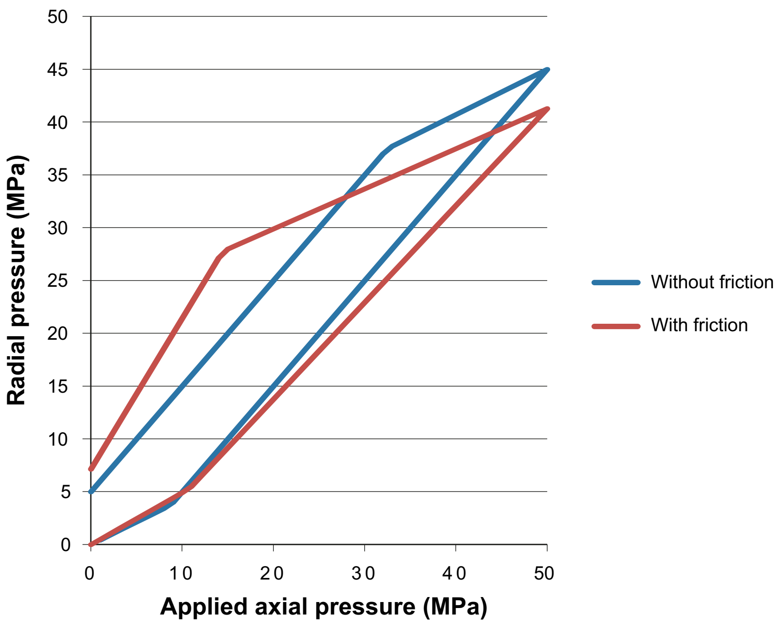

Figure 4-1. *Radial pressure vs axial pressure calculated with equations above with c = 1. σ_0 = 5MPa, μ = 0.3.*

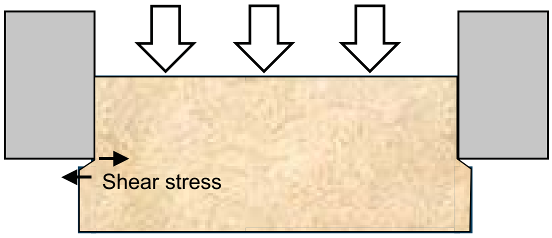

Figure 4-2. *Sketch of the demoulding of a block.*

4.2 Minimum solid area model

Since compacted bentonite is a porous material made up from granules that are pressed together, a model to describe the contact area between the granules are needed to predict the compaction properties. The main idea of the minimum solid area model (MSA-model) is to predict the area in which the granules are in contact with each other. The contact surface between the granules will have the smallest area which will affect the compaction properties of the material because the most deformation will take place here.

To create this model we consider two spherical granules which are placed beside each other, see Figure 4-3. Since no compaction has taken place the contact area between the spheres is zero. When the material starts to compact the contact area increases as shown in Figure 4-4.

This can be described mathematically. First we define that the mass or if the granules have constant density the volume of the granules should be constant according to Equation 4-1.

$$\frac{4\pi R^3}{3} - \pi n\left(d^2 R - \frac{d^3}{3}\right) = \frac{4\pi R_0^3}{3} \quad \text{Equation 4-1}$$

Where R is the radius of the sphere, R_0 is the initial radius of the sphere, n is the number of contact points or closest neighbours to the sphere and d is a distance to measure how far the spheres has been compressed into each other, see Figure 4-5.

To calculate the number of contact points, n, and the surface area of the volume are assumed to be equal to that of a sphere with the radius R at full compaction here denoted R_m.

$$2\pi n R_m \sqrt{2 d_m R_m - d_m^2} = 4\pi R_m^2 \quad \text{Equation 4-2}$$

$$\pi n\left(dm^2 R_m - \frac{dm^3}{3}\right) = \frac{\varphi_{g0}}{1-\varphi_{g0}} \frac{4\pi R_0^3}{3} \quad \text{Equation 4-3}$$

It should be noted that φ_{g0} which is the initial gas intergranular porosity is not the same porosity as used in soil science. Instead it is defined as the ratio between the volume of the granules to total volume ratio, see Eq. 4-4.

$$\varphi_g = 1 - \frac{\rho_b}{\rho_g} \quad \text{Equation 4-4}$$

Where ρ_g is the granule dry density and ρ_b is the bulk dry density.

By combining Equation 4-1 and Equation 4-3 R_m can be calculated. d_m can be calculated by combining Equation 4-1 and Equation 4-2 and d can then be derived from Equation 4-1.

The relative area, A_r, which is the contact area compared to the maximum contact area at full compaction, between the granules can then be calculated according to Equation 4-5. This equation is plotted in Figure 4-6 and from this plot it can be seen that the relative area increases with a higher initial porosity for the same density. This suggests that one of the properties that control the strength of the material will be the degree of compaction.

$$A_r = \frac{(2dR - d^2)}{(2d_m R_m - {d_m}^2)} \quad \text{Equation 4-5}$$

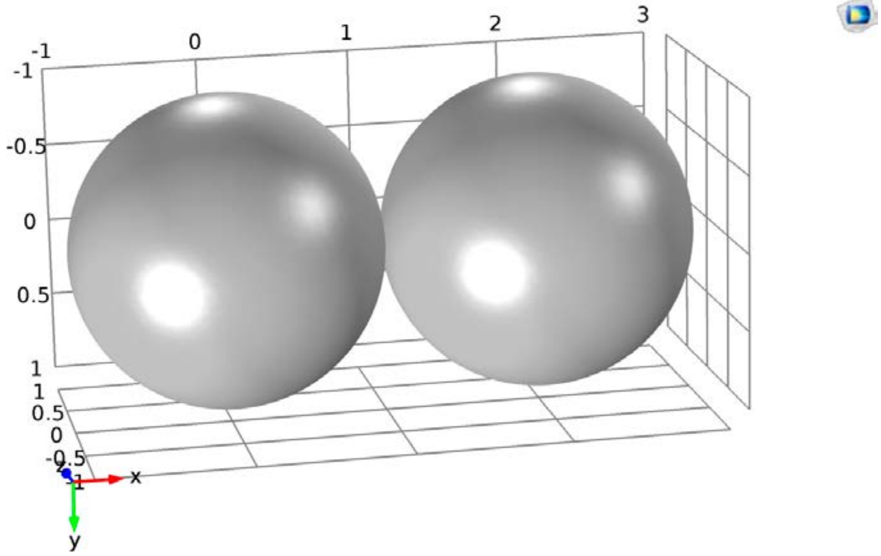

Figure 4-3. *Spheres in initial state.*

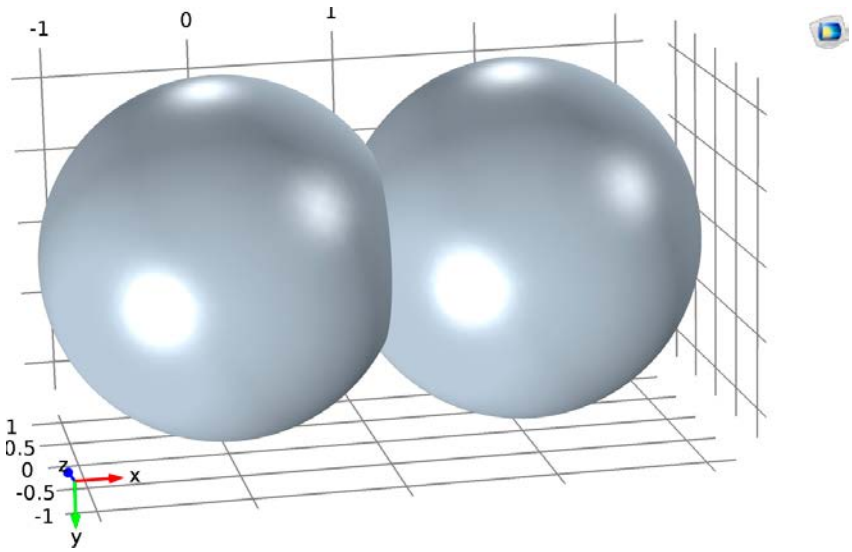

Figure 4-4. *Spheres compacted.*

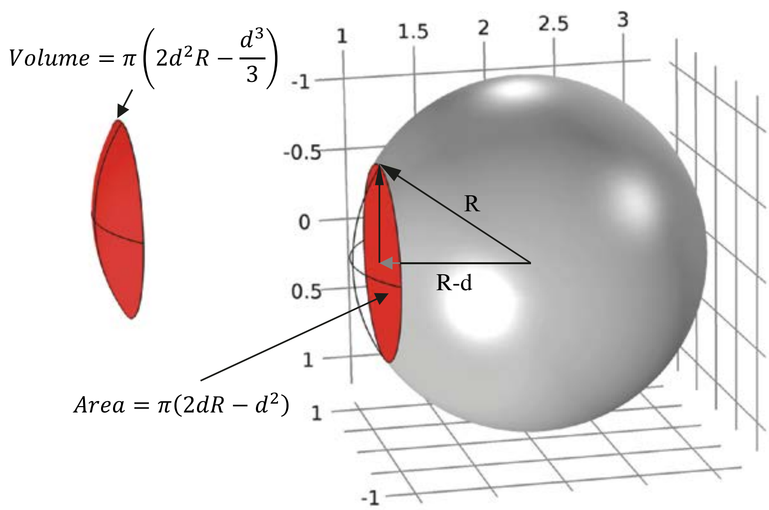

Figure 4-5. *Sketch showing the area which is in contact with other granules.*

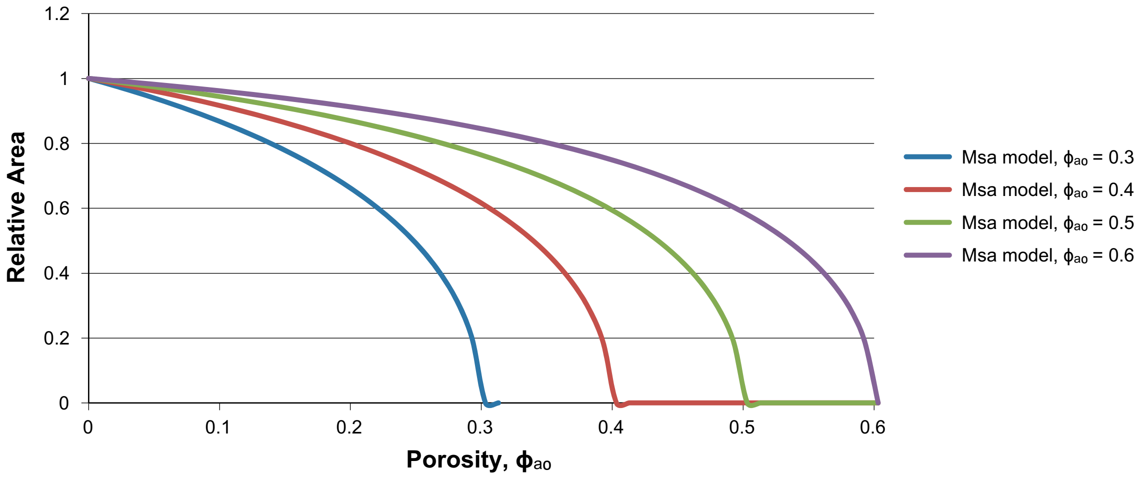

Figure 4-6. *Relative area for different initial intergranular porosity.*

4.3 Basic compaction model

To try and predict how the density is related to the compaction pressure a "hollow sphere model" is used. This model basically approximates the material as hollow spheres instead of seeing the material as pores between particles. If an external pressure, p in Figure 4-7, is applied and if it is big enough the sphere it will be compacted.

By solving the equilibrium equation (Equation 4-6) together with the elastic equations it can be shown that the material will start to plasticize at the inner radius of the sphere and at what pressure this will happen. It is also assumed that the material behaves perfectly plastic.

$$\frac{d\sigma_r}{dr} + \frac{2}{r}(\sigma_r - \sigma_\theta) = 0 \qquad \text{Equation 4-6}$$

The condition when this plasticization will start can be calculated and is shown in Equation 4-7. If it is assumed that there will be no hardening mechanism in the clay then the sphere will continue to deform according to this equation.

$$P \geq \frac{2}{3}\sigma(w)\left(\frac{R^3 - r^3}{r^3}\right) = \frac{2}{3}\sigma(w)\left(\frac{1-\varphi_s}{\varphi_s}\right) \qquad \text{Equation 4-7}$$

Where σ(w) is the flow stress which is dependent on the water constant, w.

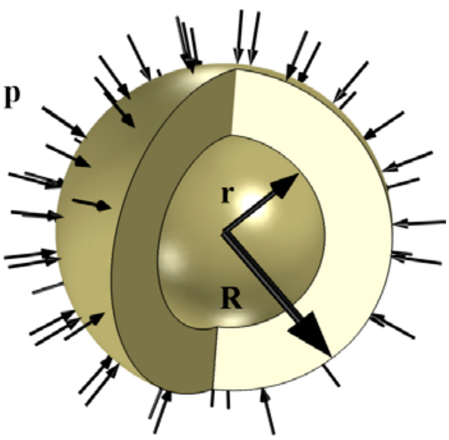

Figure 4-7. *Spherical model.*

With help of Equation 4-6 the density can be calculated as a function of pressure, Equation 4-8.

$$\rho = \frac{m}{V_{tot}} = \frac{\rho_s(1+w)}{(V_s+V_w)\left(1+\frac{\varphi_g}{1-\varphi_g}\right)} = \frac{\rho_s(1+w)}{\left(1+\frac{\rho_s w}{\rho_w}\right)\left(\frac{\frac{2}{3}\sigma(w)+P}{P}\right)} \qquad \text{Equation 4-8}$$

However, the cross section area of the hollow sphere is different from that calculated with the MSA model. Therefore the two models are combined and the area for the spherical model set to be the same as for the MSA model to compensate for the difference in cross section area according to Equation 4-9. The differences between the two models are shown in Figure 4-8.

$$\varphi_s = 1 - A_r \qquad \text{Equation 4-9}$$

Where φ_s is the air to clay material for the spherical model, see Equation 4-11. The pressure needed to compact to a specific density can then be calculated from Equation 4-10.

$$P = \frac{2}{3}\sigma(w)\frac{A_r}{1-A_r} \qquad \text{Equation 4-10}$$

$$\varphi_s = \frac{V_w+V_c}{V_{tot}} \qquad \text{Equation 4-11}$$

Where V_w is the volume of water, V_c is the volume of clay and V_{tot} is the total volume.

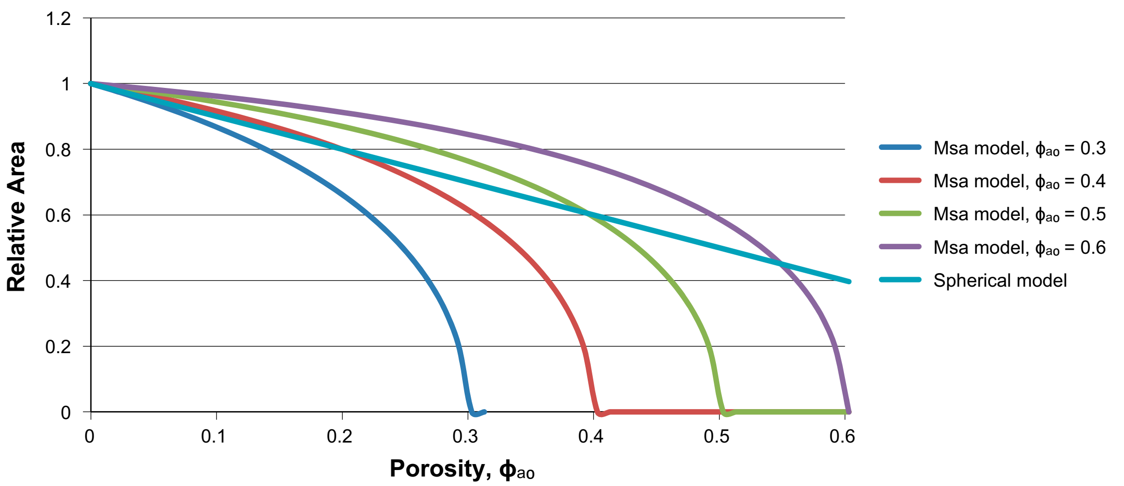

Figure 4-8. *Relative area of the solid area model compared to the relative area of the spherical model.*

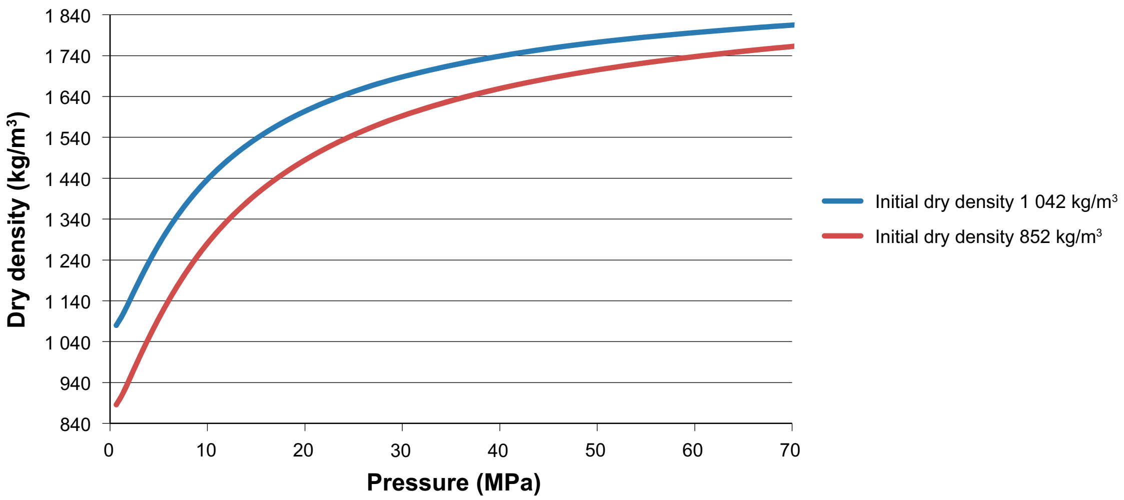

Figure 4-9. *Illustration of the influence of initial density.*

According to Equation 4-10 compaction pressure is dependent on the initial density which in turn depends on granule density and granule size distribution. This difference in compaction pressure can be seen in Figure 4-9 if a water content of 17% and a flow stress of 4.6 MPa is used. It can be noted that a higher initial density compacts easier than a material with lower initial dry density. At higher compaction pressure the two curves converges and the density is practically the same for the two materials. The pressure where the compaction curve converge point is dependent on the flow stress of the material.

To get a realistic value of the flow stress compaction data from Johannesson (2014) is used. From Equation 4-12 flow stress can be calculated when the porosity, water content and compaction pressure is known. The major force acting in clays are electrostatic forces or more specifically Van der Waals forces. Therefore we assume that the flow stress should be equal to the Van der Waals force. The Van der Waals force between two sheets of montmorillonite can be described according to Equation 4-10 (Jönsson et al. 2009).

$$\sigma(w) = \frac{A}{6\pi}\left(\frac{1}{{d_s}^3} + \frac{1}{(2h+d_s)^3} - \frac{2}{(h+d_s)^3}\right) \qquad \text{Equation 4-12}$$

$$d_s = h\frac{\rho_s}{\rho_w}w \qquad \text{Equation 4-13}$$

Where A is the Hamaker constant and h is the thickness of the montmorillonite sheet and d_s is the distance between the montmorillonite sheets. The distance, d_s is a function of water content and is calculated according to Equation 4-13. When the flow stress calculated from data with the MSA model is plotted together with the Van der Waals force, see Figure 4-10, a good agreement is found when a Hamaker constant of $3.5\cdot10^{-21}$ J is used and a sheet thickness of $8\cdot10^{-10}$ m. However, the expression seems to overestimate the flow stress at high water content therefore a simpler exponential expression, Equation 4-14, is used instead.

$$\sigma(w) = ae^{-bw} \qquad \text{Equation 4-14}$$

The calculations are quite sensitive to changes in initial dry density and this has not been measured except for in the test done on Asha material described in Section 3.1. To get a value on the initial density compaction data from Sandén et al. (2015) is used. The values used are shown in Table 4-1 but are not very certain. The initial densities from this data seem to give high values maybe because the material is compacted little bit during the mould filling. If the values of the initial density are measured the result would be more accurate. Changes in initial density could make large changes in the curves.

The model can now be compared with compaction curve and it fits rather well with experimental data, shown in Figure 4-11 and Figure 4-12.

Table 4-1 Initial intergranular porosityfor different materials.

Material	Intergranular porocity, φ_g	Comment
Crushed Asha	0.33	Calculated from Sandén et al. 2015
Asha 2010	0.4	Calculated from Sandén et al. 2015
Asha 2012	0.33	Calculated from Sandén et al. 2015
Asha > 1 mm	0.4	Assumed value
SPV200	0.33	Assumed value
MX-80 2012	0.38	Calculated from Sandén et al. 2015
MX-80 2002	0.38	Assumed to be the same as for MX-80 2012
MX-80 > 1 mm	0.4	Same as Asha > 1 mm

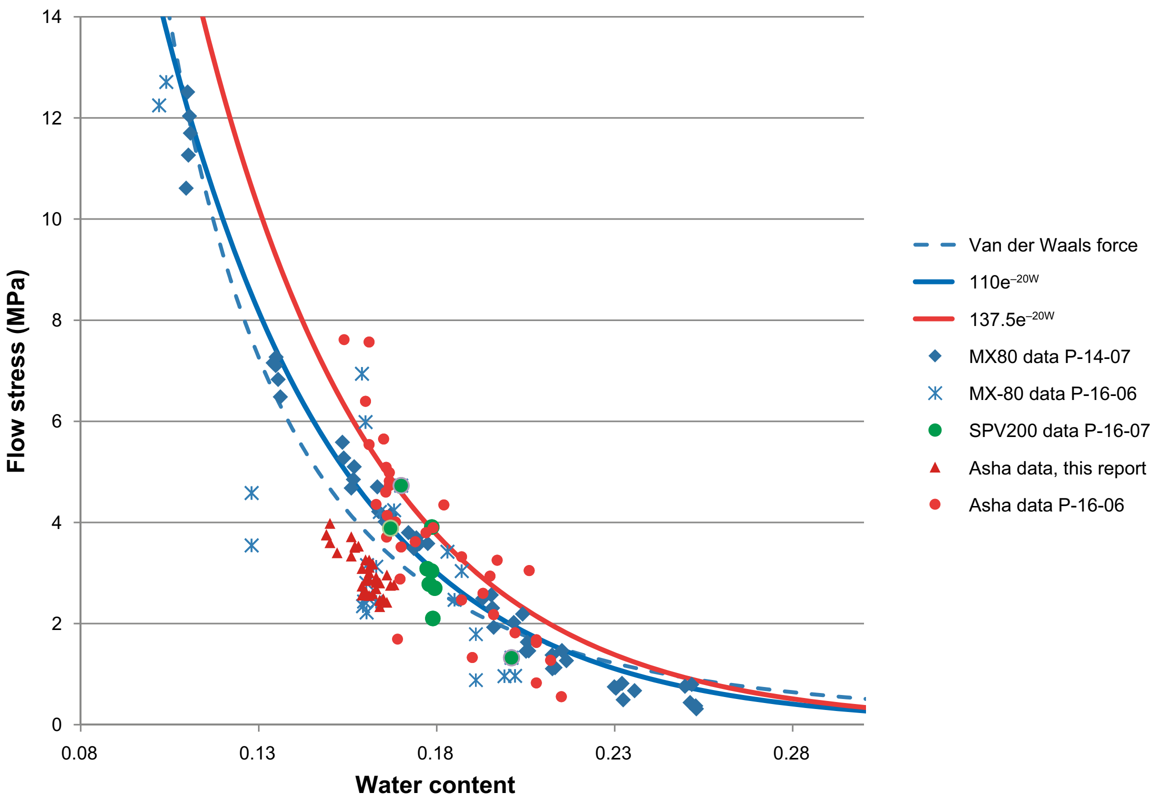

Figure 4-10. *Flow stress calculated from compaction data with help of the model described in this chapter.*

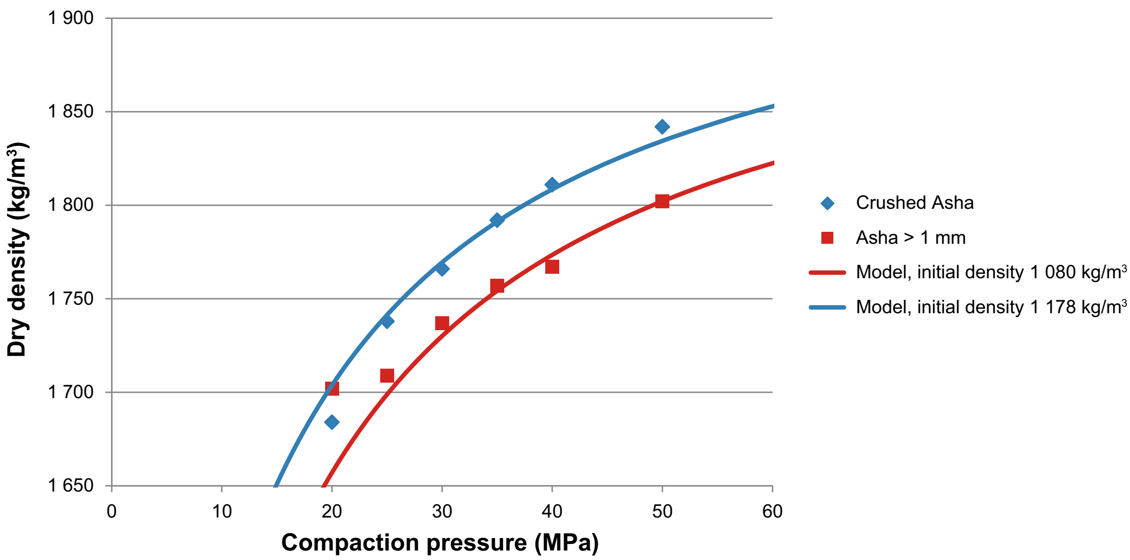

Figure 4-11. *Model compared to compactions with Asha clay.*

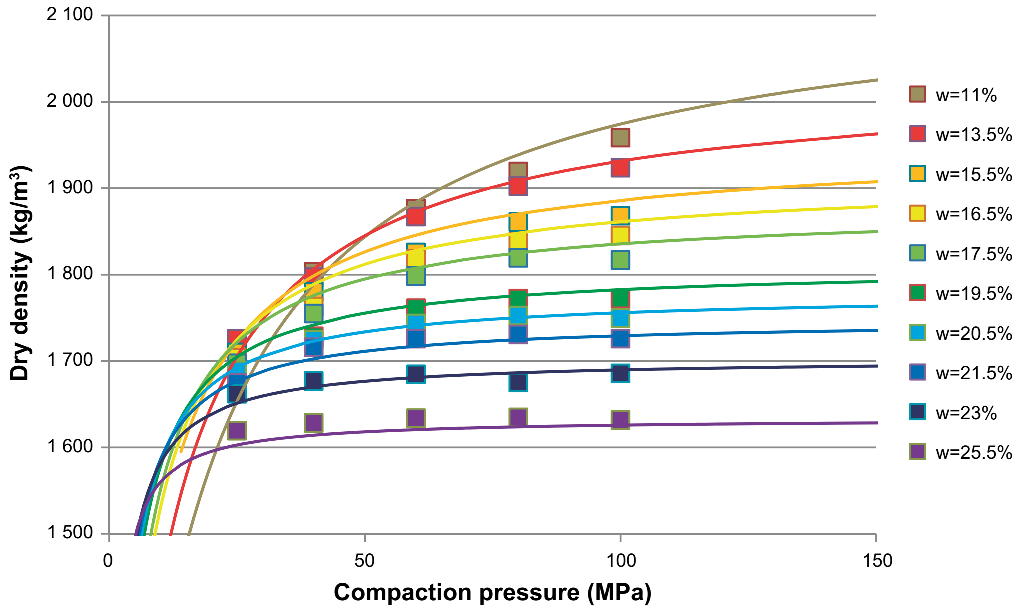

Figure 4-12. *Model compared to compaction data for MX-80 delivered 2012 taken from Johannesson (2014).*

4.4 Block strength

Material with different size fractions were compacted as described in Chapter 3 and the result is shown in Figure 4-13. Unfortunately the water content was not kept constant and it is not obvious which variable is responsible for the reduced strength of the material compacted with the coarse granules. However, it is known that increased water content for a specific material should cause an increased strength (Sanden et al. 2016). Therefore the difference in strength should be even larger than what is shown in Figure 4-13. The MSA model suggests that the strength should be proportional to the minimum cross section area calculated with Equation 4-4 but this does not seem to be the case. Instead, the data suggests that there is a dependency on granule size. In ceramic materials there is a correlation between strength and pore size. This would mean if the material does not have any fine material then large pores can be present which will cause a low tensile strength of the block. If the bentonite block behaves like a ceramic material then the strength of the material should be a function of porosity and pore size. More work is needed to find out exactly how the pore size influences the tensile strength of the material.

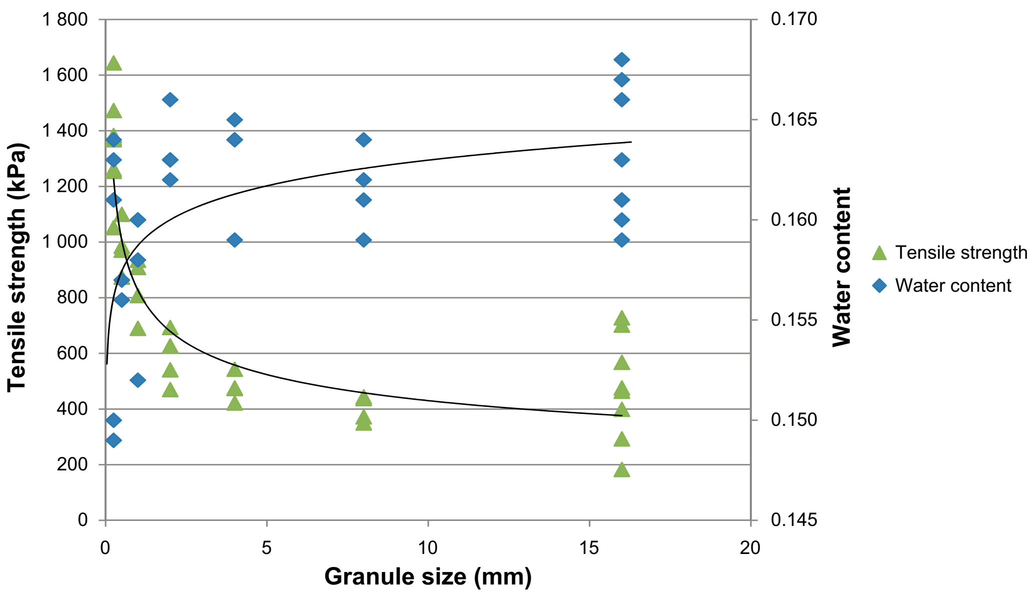

Figure 4-13. *Tensile strength vs granule size.*

5 Possible explanations for compaction problems

In Chapter 2 a number of problems encountered during production of blocks that could not be explained in a quantitative way. In this report models have been developed in order to explain these different problems. Since not all data is available to fully use the models, assumptions are sometimes used to conceptually explain the mechanisms predicted by the models.

5.1 Striped blocks

During the assembly of the Multi-Purpose test it was noticed that the block were striped and that cracks seamed be more prone to form close to the interface between the dark and light areas. Cores were taken from a block and the section from the light and dark areas were cut out. Water content and density were measured and the data is shown in Table 2-1. The degree of saturation shows a clear correlation with the colour of the bentonite.

During the mould filling the material to be compacted is poured into the mould. When the material starts to flow it segregates and coarser granules are placed in layers. This can be seen during production. This layering of coarse and fine material is likely to have different initial density and therefore the compaction properties will be different. Finer material that has a higher initial density compacts easier and therefore gets a higher saturation (dark area). Since these areas with finer material have higher density the elastic expansion is expected larger in these areas. The volume with coarser material which will have a lower density due to that the material is harder to compact. This lower density should result in a lower tensile strength and this should suggest that the cracking would appear on the lighter side, which can be seen in Figure 2-2, if tensile stresses form close to the surface due to for example drying.

5.2 Different compaction properties

In the models in Chapter 4 it is predicted that the compaction properties are affected by initial density of the bentonite. In Figure 5-1 and Figure 5-2 experimental values from bentonite delivered 1993 and 2012 can be seen compared to modelled values (Equation 4-4). Difference in initial dry density cannot fully account for the big difference and to get a good fit the flow stress of the granules or the grain density needs to be changed.

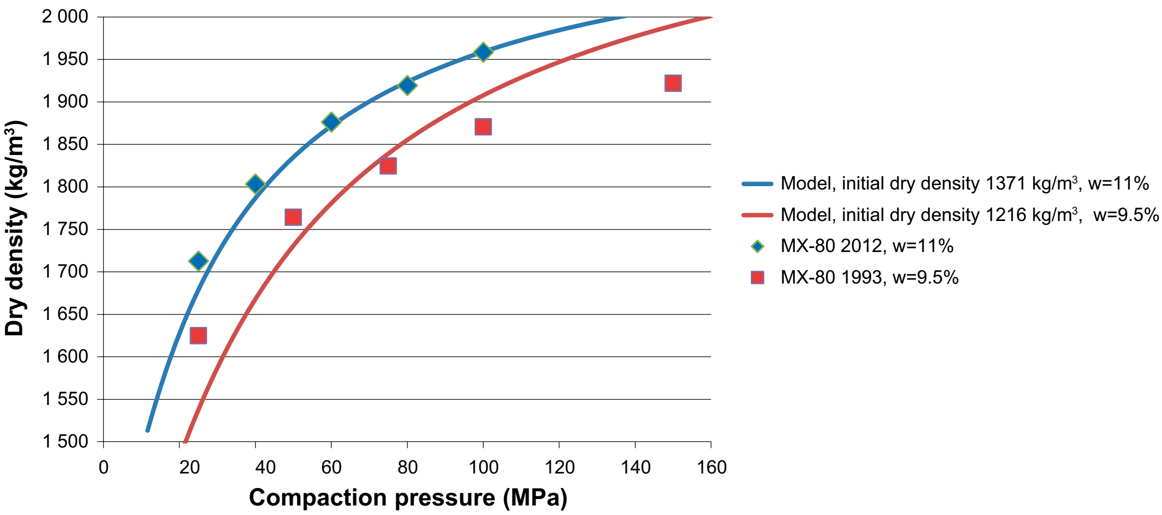

Figure 5-1. *Modelled values compared to the data from 2012 and 1993. In the model different densities have been used. No data for initial density was available and therefore initial densities are fitted to the data.*

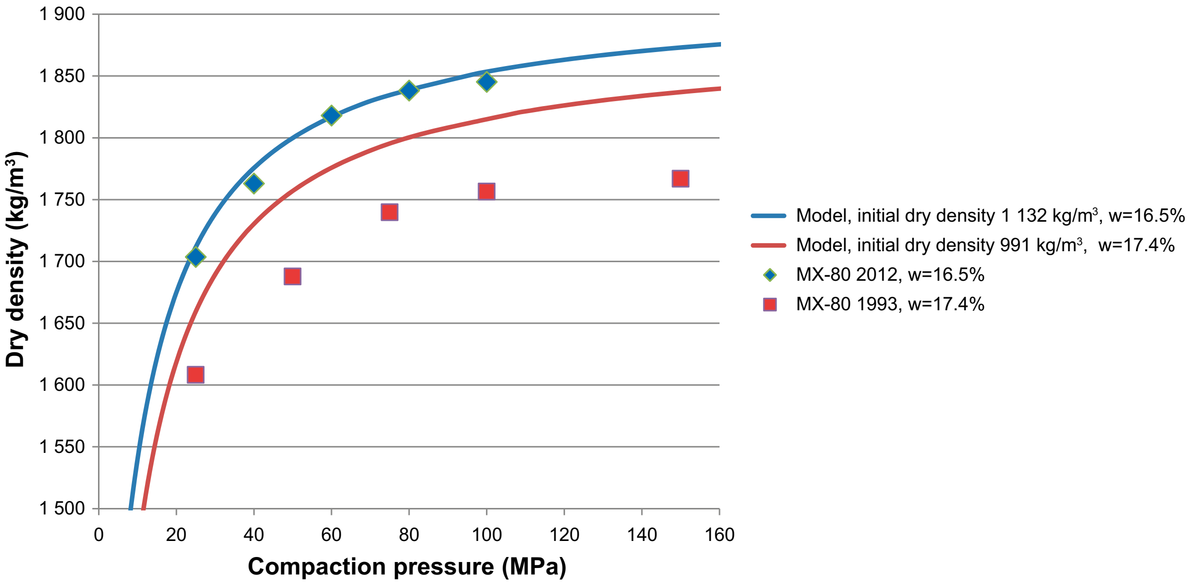

Figure 5-2. *Modelled values compared to the data from 2012 and 1993.*

6 Conclusions

In this work models have been created in order to predict the compaction behaviour of bentonite. The models could quite well describe the available data from compaction tests. However, more work should be done to verify that the models are correct. From the work done in this report the following conclusions can be made:

- Models have been constructed that can predict most of the properties of bentonite during compaction. The models can also explain the problems that have been experienced during production. However, more testing is needed to verify the models.
- The constructed models predicts that the parameter affecting compaction properties of the material is the flow stress of the material, initial bulk dry density and water content. The friction between the mould and the material also affects the final density. The granule size distribution does not have a direct effect on the compaction properties of the material but the granule size distribution has an indirect effect since it affects the initial dry density.
- The model implies that the initial bulk dry density is probably a better way to specify the compaction properties of the material then the granule size distribution. This is because it is easier to measure and is less strict.
- The tensile strength seems to be dependent on the pore size and therefore enough fine material should be present in to reduce the pore size in the material to get a less brittle block.
- It is important to prevent the material from segregating during handling since segregation will affect the compaction properties. If the material is different in different parts of the block unnecessary stresses can arise in the block which could make them crack. If there is a difference in material between blocks it can be problematic to control the production process.
- Block quality does not seem to change very much when the crushed and reused material is used in the production. This means that discarded blocks and material machined away can be reused.
- It is most likely that blocks without lubrication can be produced. However, more work should be done in order to investigate how internal stresses affect the way that the block behaves when the block is subjected to drying or wetting environment. Internal stresses could change the time it takes for the block to crack at a certain relative humidity.

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