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SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

P.O.BOX 5864 S-102 40 STOCKHOLM SWEDEN
PHONE +46 8 665 28 00 TELEX 13108 SKB
FAX +46 8 661 57 19

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TECHNICAL REPORT

COMPACTION OF BENTONITE BLOCKS

DEVELOPMENT OF TECHNIQUE FOR INDUSTRIAL PRODUCTION OF BLOCKS WHICH ARE MANAGEABLE BY MAN

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Keywords: Clay, bentonite, compaction, blocks of bentonite, compaction pressure, form geometry, granulometry, compaction technique

ABSTRACT

In this report a useful technique for producing compacted blocks of bentonite is described. The report only deals with the technique to produce uniaxially compacted blocks (weight of the blocks: 10-15 kg) which are manageable by man.

Tests for producing blocks with a weight of approximately 10 kg were carried out at Höganäs Bjuf AB in Bjuv. This industry is normally producing refractory bricks and other refractory products. The plant has facilities for handling large volumes of clay. Furthermore there are machines suitable for producing uniaxially compacted blocks. Performed tests at the plant show that it is possible to compact blocks with good quality. Best quality was reached with a coarsely ground bentonite at a water ratio of 20%. The compaction was performed with lubricated form and stepwise loading.

The tests at Höganäs Bjuf AB were preceded by tests in the laboratory. In these tests smaller samples were compacted for studying how different factors affect the quality of the samples (density, water ratio, homogeneity et cetera). The influence of following factors was studied:

- water ratio of bentonite
- bentonite type and granulometry
- compaction pressure
- compaction rate
- form geometry
- form lubrication
- form heating

The results from these tests were used to modify and optimize the technique in the factory.

SAMMANFATTNING

Denna rapport behandlar och beskriver framtagandet av en användbar teknik för framställning av kompakterade bentonitblock. Rapporten behandlar bara enaxiellt kompakterade block med en volym och vikt som möjliggör manuell hantering av blocken (vikt på blocken: 10-15 kg).

Tester för framtagande av block med en vikt på ca 10 kg har utförts på Höganäs Bjuf AB i Bjuv. Vid denna anläggning framställs normalt eldfast tegel och andra eldfasta produkter. Anläggningen har faciliteter som möjliggör en automatisk hantering av stora volymer lera. Vidare finns på anläggningen pressar som är lämpliga för framställning av enaxiellt kompakterade block. Utförda tester med befintlig utrustning visar att det är möjligt att framställa block av bentonit med god kvalité. Bäst resultat erhölls med granulerad bentonit med en vattenkvot på omkring 20%. Kompakteringen skedde med smord form och i flera laststeg för att undvika att sprickor uppstår i blocken.

Försöken i Bjuv föregicks av ett omfattande försöksprogram, innefattande kompaktering av mindre provkroppar i laboratoriet. Vid dessa försök studerades olika faktorers inverkan på de kompakterade kropparnas egenskaper, såsom densitet och vattenmättnadsgrad. Inverkan av följande faktorer studerades bl.a.:

- vattenkvot
- bentonittyp och granulstorlek
- kompakteringsspänning
- presshastighet
- formgeometri
- smörjning av formen
- uppvärmning av formen

Resultaten från laboratorieförsöken låg till grund för utformningen av de tester som utfördes på Höganäs Bjuf AB:s anläggning i Bjuv.

TABLE OF CONTENT

SUMMARY AND CONCLUSIONS

A technique has been developed for producing blocks with a weight of approximately 10 kg at Höganäs Bjuf AB in Bjuv. This industry is normally producing refractory bricks and other refractory products. The plant has facilities for handling large volumes of clay.

The tests at Höganäs Bjuf AB were preceded by tests in the laboratory. In these tests smaller samples were compacted for studying how different factors affect the quality of the samples (density, water ratio, homogeneity et cetera). The influence of following factors was studied:

- water ratio of bentonite
- bentonite type and granulometry
- compaction pressure
- compaction rate
- form geometry
- form lubrication
- form heating

The results from these tests were used to modify and optimize the technique in the factory.

Although the tests at Höganäs Bjuf AB were preceded by tests in the laboratory several problems with the quality of the blocks occurred. The problems were mainly of two types, viz. damage appearing at compaction and damage occurring during storage of the compacted blocks. The first type of damage consisted of different types of cracks in the blocks. The observed cracks were essentially of four types:

1. Cracks due to the friction between the form and bentonite
2. Cracks caused by air that was entrapped in the blocks at the compaction
3. Cracks due to the elastic swelling at unloading and removal of the block from the form
4. Cracks caused by brittle edges of the blocks

Other types of damages and problems were the following:

1. Damage due to sticking of the bentonite to the form and pistons.
2. Desiccation of the blocks during storage.
3. Appearance of mould on the blocks during storage.

The problems were discovered and solved in the course of the test series.

An optimum technique that yields blocks of good quality at the desired density and degree of saturation implies that the following steps are taken:

- In order to minimize the air entrapped in the blocks during compaction the following steps are proposed

    1. Use coarsely ground bentonite of the type IBECO C or similar
    2. Use stepwise compaction
    3. Use fairly large gaps between the pistons and the form
    4. Make blocks with the height/diameter ratio not larger than 0.4

- In order to prevent damage of the blocks due to friction between the bentonite and the form the form should be lubricated with oil before the bentonite is poured into the form. The lubricating oil also prevents damages on the blocks due to sticking of bentonite to the form and pistons.

- In order to prevent damage of the block due to the expansion during removal of the block from the form, the block should be compacted to a high degree of saturation. For a compaction pressure of 100 MPa the water ratio of the bentonite should not be less than 18%. The damages could also be prevented by making the form somewhat conical.

- To prevent desiccation the blocks must be wrapped in plastic sheeting after compaction. The plastic tested so far did not prevent the bentonite from desiccation. More tests are required for finding suitable sheet material.

- To prevent moulds from growing during storage the water ratio of the bentonite should not exceed 20%.

SYMBOLS

e	=	void ratio
E	=	Young´s modulus
S_r	=	degree of saturation
w	=	water ratio
w_L	=	liquid limit
W	=	moment of resistance
ε_f	=	maximum tensile strain
ρ	=	density
ρ_d	=	dry density
ρ_m	=	density at saturation
ρ_s	=	density of the particles
ρ_w	=	density of water
σ_t	=	maximum tensile strain
τ_f	=	maximum shear stress

1 INTRODUCTION

The Swedish KBS3 concept for disposal of nuclear waste implies that the bentonite barrier around the waste canisters is composed of blocks of highly compacted bentonite, which, after replacement swell and homogenize to yield a uniform buffer mass. The requirements respecting shape, void ratio, and homogeneity of the blocks are very strict and there may also be a desire to make blocks with a high and uniform degree of water saturation. The techniques for compacting blocks of bentonite are mainly two; isostatic compaction and uniaxial compaction. This project deals with development and testing of a technique for uniaxial compaction.

The volume and weight of the blocks can roughly be divided into two groups:

1. Blocks of brick size that are manageable by hand. They are termed ”brick blocks” in this report.
2. Blocks of ”magnum” type that need tools to be handled. They are termed ”magnum blocks” in this report.

For the first group of blocks the upper weight limit is 10-15 kg. The weight of the second group of blocks is limited by the compaction devise but also by the capacity of the tools for handling the blocks. The brick-size blocks need to be compacted at a high rate for obtaining an acceptable production capacity, and common techniques for manufacturing refractory bricks appears to be suitable. Magnum blocks require a very large compaction device (form and press) that can exert big loads. For this type of blocks one can accept low compaction rates and individual handling. The report only with brick-size blocks.

In order to investigate the factors that affect the properties of the compacted blocks, many test series have been carried out in the laboratory. Factors that have been studied are:

- compaction pressure
- compaction rate
- water ratio
- form geometry
- bentonite type and granulometry

The results from the laboratory tests were used for optimizing the technique for the tests at compaction of larger by hand manageable blocks. These tests were carried out at Höganäs Bjuf AB in Bjuv.

2 MATERIALS

Two different bentonite types have been used for the tests, one sodium-converted Ca-bentonite from Greece (IBECO) and one naturally occurring bentonite with Na as major adsorbed cation from Wyoming, USA. Two different forms of the natural Na-bentonite were used. One of them has coarse granules (MX-80) and the other one has been ground to a fine powder (SPV200). The sodium-converted bentonite was used in the form of a fine powder and three different granule size distributions.

Typical chemical analyze results of the bentonites are shown in Table 2-1.

Table 2-1. Results from chemical analyses of the different bentonites.

Sample	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)
IBEC0-Na*)	63.8	19.8	5.0	0.8	3.2	3.1	1.0	2.8	0.2
MX-80**)	66.9	20.8	4.7	0.2	3.1	1.9	0.6	2.8	0.1
SPV200***)	64.6	23.3	3.7		3.4	0.4	0.5	2.6	

*) Karnland et al 1992
**) Karnland et al 1994
***) according to the data sheet from the deliverer of the bentonite

The grain size distributions of the bentonites are shown in Figs 2-1 and 2-2. In Fig 2-1 the grain size distribution of the bentonites in dispersed form are plotted. The diagram shows that more than 80% of the dispersed grains are smaller than 0.002 mm and thus belong to the clay fraction. The granule size distributions of the bulk materials with their natural content of water of the two types of the natural Na-bentonites and the three types of coarsely ground sodium converted bentonites (IBECO) are shown in Fig 2-2. For the coarsely ground bentonite MX-80 more than 50% of the granules in the bulk material are larger than 0.2 mm, while for the same bentonite in powder form (SPV200) only approximately 5% of the granules in the bulk material are larger than 0.2 mm. The granule size distribution of the coarsely ground IBECO-bentonites varies a lot. The most coarsely ground bentonite (IBECO-C) has almost no granules smaller than 0.5 mm while the most finely ground IBECO bentonite is somewhat coarser than MX-80.

The fall-cone liquid limit determined according to standard geotechnical procedures is shown in Table 2-2. The two natural occurring bentonites (MX-80 and SPV200) have liquid limits in the same range while the liquid limit for of the sodium-converted bentonites is lower.

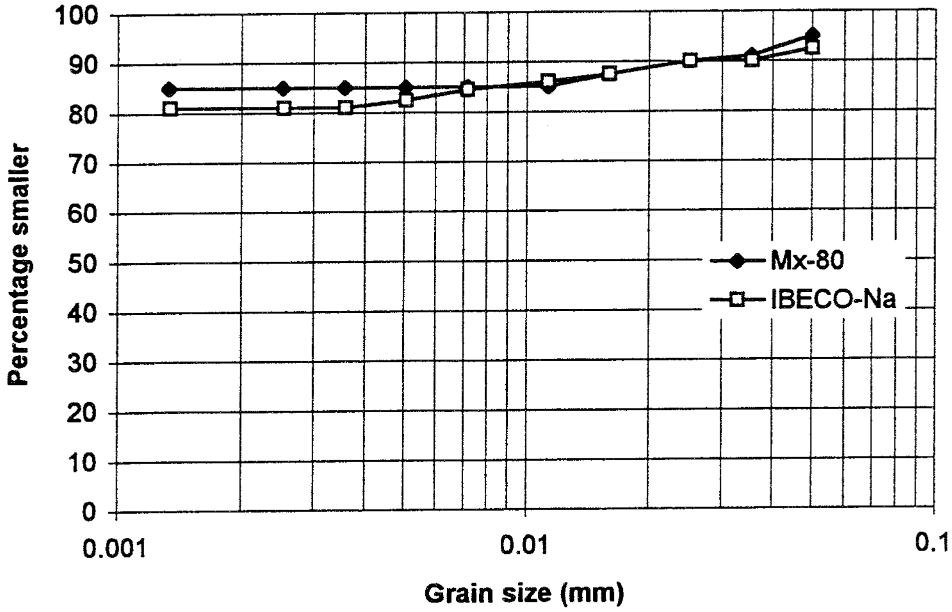


Figure 2-1. *Grain size distribution of dispersed MX-80 and IBECO-Na.*

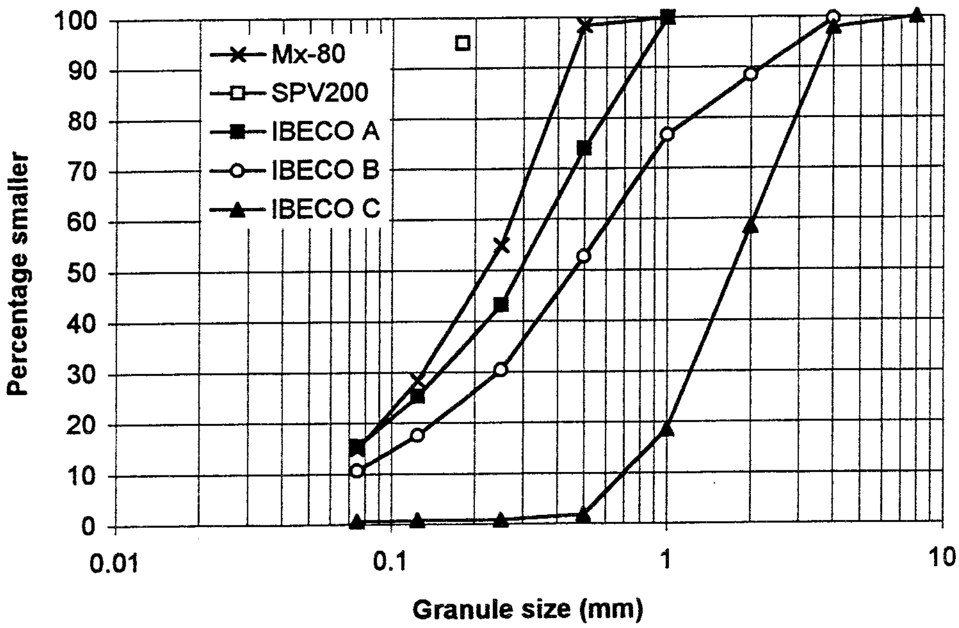


Figure 2-2. *Granule size distribution of the bentonites in bulk form.*

Table 2-2. Liquid limit w_L of the bentonites.

Type	w_L, % (%)
IBECO-Na	400
IBECO A	393
IBECO-B	410
IBECO C	340
MX-80	518
SPV 200	484

3 TECHNIQUES

3.1 GENERAL

Tests have been carried out both in laboratory scale and in an industrial scale. In the laboratory tests only small samples were used. The compaction and mixing of the bentonites were made manually and the forms and other equipment used for the compaction were designed and constructed for these tests. The tests on an industrial scale were performed with available outfit for compacting firebricks. Only small modifications of the equipment and the technique to suit the present materials were made.

3.2 AVAILABLE COMPACTION TECHNIQUES

Available techniques for compacting bentonite blocks are mainly two, isostatical compaction and uniaxial compaction. The blocks made for the Buffer Mass Test in Stripa in 1981 were isostatically compacted.

The bentonite to be compacted isostatically is enclosed in a membrane which is surrounded by a liquid pressure medium, which is pressurised. The pressure acts uniformly over the entire area of the form. The advantage with isostatic compaction is that there is no form that may cause problems with friction, which means that the blocks become homogenous even if the height-diameter ratio is high. However, this technique also has two major drawbacks. One is that the production of each block requires much preparative work and is time-consuming which means that it is impractical and expensive unless very large blocks are made. The other drawback is that the shape of the block may deviate from the required. In order to get the required geometry it may be necessary to shape the block with a saw after compaction. If long time is required for preparation and sawing, the surface of blocks with a high degree of water saturation will dry.

When uniaxial compaction technique is used the bentonite is poured in a rigid form and a piston placed on the surface of the bentonite. The piston is pushed into the form by a press device so that the bentonite is compacted uniaxially. The disadvantage of this technique is that the blocks may become inhomogenous if the material close to the piston gets more compacted than other parts of the block due to the friction between the bentonite and the form. This disadvantage can be minimized by the following considerings:

- Keep the ratio between the height and diameter of the sample down
- Use both an upper and a lower piston at the compaction
- Compact blocks to a high degree of saturation

In this report only uniaxial compaction technique is treated.

3.3 LABORATORY COMPACTION

Most of the samples in the laboratory tests were compacted in a cylinder of steel (see Fig 3-1). The cylinder was attached to a bottom plate which had a small hole in the center covered by a steel filter. The hole and the filter allowed air in the sample to dissipate out during the compaction. The mixture of bentonite and water was poured into the cylinder and a steel piston applied on the sample. The sample was compacted in a press at a constant rate of strain. After compaction, the bottom plate was released from the cylinder and the sample pushed out from the cylinder by use of the piston.

In some of the tests the load and displacement of the sample were measured during the compaction.

Some tests were carried out in a compaction cylinder with a diameter of ≈ 35 mm. The height of the samples was 2/5 of the diameter of the compaction cylinder (≈ 14 mm) in most tests. Compaction cylinders with a diameter of ≈50 mm were also used and in these tests the height of the samples was varied between 5 - 100 mm in order to investigate the influence of the height/diameter ratio.

After compaction, the bulk density (ρ) and the water ratio (w) of the samples were determined. The water ratio is defined as the loss in weight of the sample after 24 hours drying in an oven at 105 °C, divided by the weight of the dry sample. The bulk density of the samples was determined by using the paraffin method. In some cases the sample was cut in 10 mm slices and each slice investigated separately in order to study the homogeneity of the sample.

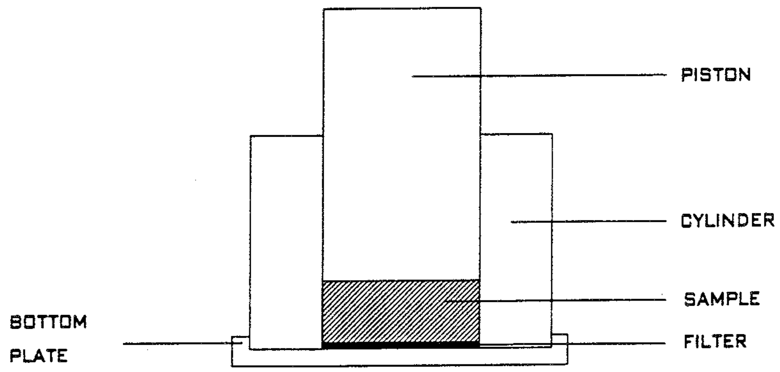


Figure 3-1. Schematic drawing of the compaction cylinder.

3.4 INDUSTRIAL COMPACTION

The production of brick blocks of bentonite on an industrial scale was made in the factory of Höganäs Bjuf AB in Bjuv, using equipment that is normally used for making refractory bricks. The compaction process and managing of both the clay material and the bricks are automatic. At first a box with the same volume as the form is filled with bentonite material which is poured into the form and compacted by use of both an upper and a lower piston. After compaction the brick is pushed out from the form by the lower piston. The form has an area of about $4.8 \cdot 10^{-2}$ m^2. The ordinary automatic managing of the clay was not used but the bentonite was poured by hand into the form. The compaction rate was about 20 mm/s. The compacted blocks had a height of about 80 mm and a weight of about 10 kg.

After compaction, the bulk density and water ratio of the blocks were determined on one ore several small pieces which were sawed from the blocks with the same technique as for the laboratory-compacted samples. The density was also determined by weighing the blocks and measuring their volume.

3.5 MIXING TECHNIQUE

The technique used for mixing bentonite with water in the preparation of laboratory-compacted samples was very simple. The bentonite, with its natural water content (approximately 10%) was weighed and put in a mortar. The required amount of additional water to get the required water ratio of the bentonite was carefully poured into the bentonite during remolding with a spoon. Only distilled water was used in the tests. The mixing at high water ratios was somewhat more difficult than at low water ratios because of the tendency of the bentonite to form large aggregates during mixing. When such aggregates appeared, they were carefully disintegrated by a pestle.

The mixing of the bentonite for the block preparation was carried out in a larger mixer where up to 100 kg of bentonite were mixed simultaneously. For this mixing tap water was used.

4 LABORATORY COMPACTION

4.1 GENERAL

The samples were mixed, compacted and investigated as described in Chapter 3. Since the density of the particles (ρ_s) and the density of the water (ρ_w) were known, it was possible to calculate the degree of water saturation using to Eqn. 4-1 and the void ratio using to Eqn. 4-2.

$$S_r = \frac{w \cdot \rho \cdot \rho_s}{\left[\rho_s \cdot [w+1] - \rho\right] \cdot \rho_w} \tag{4-1}$$

$$e = \frac{\rho_s - \rho}{\rho - \rho_w \cdot S_r} \tag{4-2}$$

The pore volume of the compacted samples contains both water and gas if the degree of saturation is less than 100%. If the pores are completely filled with water the density is the maximum density at a certain void ratio. This density, which can be calculated by use of equation 4-3 by applying S_r = 1.00, is called *the density at saturation* (ρ_m). The so called *dry density* (ρ_d) can also be calculated from equation 4-3 by applying $S_r = 0$. The dry density is the minimum density for a sample at a certain void ratio.

$$\rho = \frac{\rho_s + \rho_w \cdot S_r \cdot e}{1+e} \tag{4-3}$$

In Fig. 4-1 the density at saturation and the dry density are plotted as a function of the void ratio (Eqn 4-3) for ρ_s = 2.78 g/cm^3 and ρ_w = 1.00 g/cm^3. A sample of bentonite with a certain void ratio thus has a density intermediate to these values. Sometimes it is useful to calculate the maximum density for a specific water ratio. This can be made by applying Eqn. 4-4.

$$\rho_m = \frac{1+w}{\frac{w}{\rho_w} + \frac{1}{\rho_s}} \tag{4-4}$$

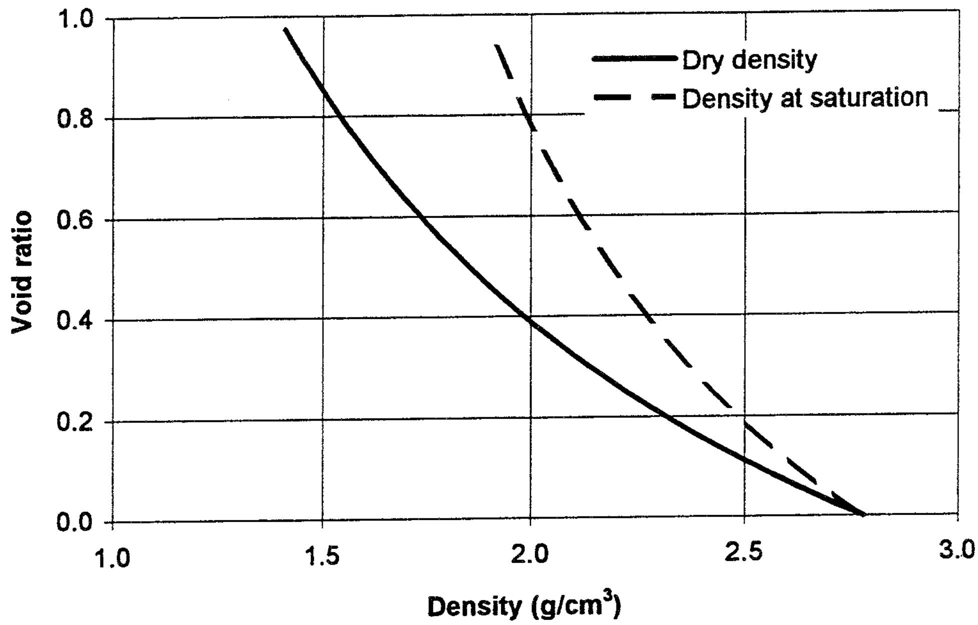


Figure 4-1. The density at saturation and dry density as a function of water ratio assuming ρ_s = 2.78 g/cm^3 and ρ_w = 1.00 g/cm^3.

4.2 INFLUENCE OF DIFFERENT FACTORS

4.2.1 General

The tests have yielded a good understanding of how different compaction factors affect the properties of the samples. The results will be accounted for and evaluated at the same time by considering the influence of the different factors. It has not been possible to combine all factors and the following "reference" conditions have been the basis for all tests:

Compaction pressure: 100 MPa
Bentonite type: MX-80
Compaction rate: 0.04 mm/s
Form geometry: height/diameter=2/5

4.2.2 Influence of water ratio

A large number of compaction tests were made on samples with a water ratio between 5% and 35% under "reference" conditions (see Section 4.2.1) except for the bentonite type, which was changed in some cases. The water ratio and density were determined after the compaction and the degree of saturation, void ratio, and dry density were then calculated by using Eqns. 4-1 to 4-3. In Fig 4-2 a the dry density is plotted as a function of the water ratio. The maximum dry density for a certain water ratio corresponding to complete water saturation is also plotted. The figure shows that the dry density decreases with increasing water ratio and approaches the curve for maximum dry density almost asymptotically.

The results are also plotted in Fig 4-2 b, with the void ratio as a function of the water ratio. The figure shows that the void ratio increases with increasing water ratio. An increase in water ratio from 10% to 20% results in an increase in void ratio by $\Delta e \approx 0.12$ while an increase in water ratio from 20% to 30% means a further increase in void ratio by $\Delta e \approx 0.20$.

In Fig 4-2 c the degree of saturation is plotted as a function of the water ratio. The figure shows that the degree of saturation increases rapidly with increasing water ratio for water ratios between 10% and 22%. Higher water ratios than 22% do not affect the degree of saturation, which cannot exceed about 96-98%.

In Fig 4-3 are the results from compaction tests of different types of IBECO-bentonites plotted in the same way described above (see Section 4.2.6).

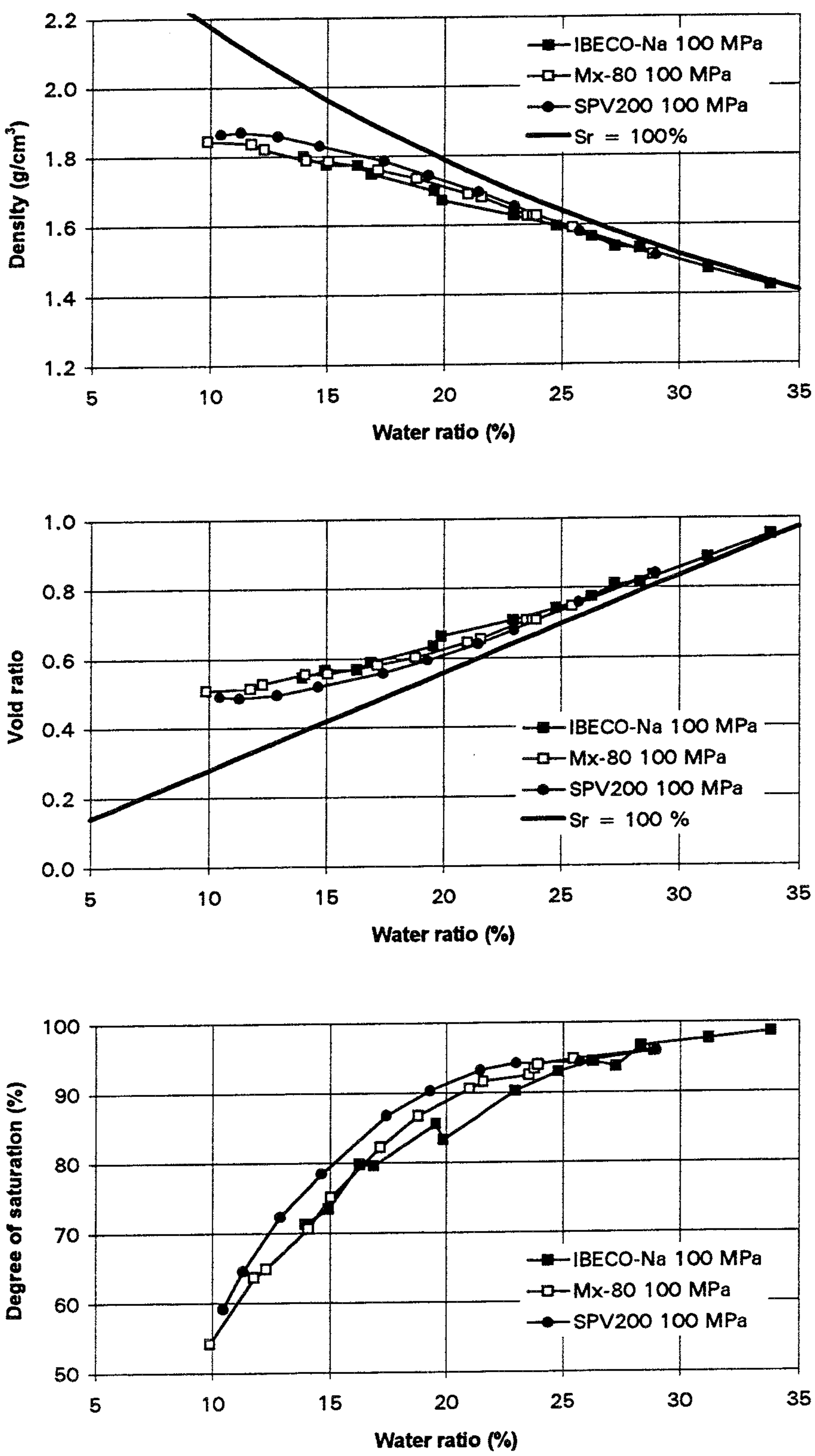


Figure 4-2. Dry density (a), void ratio (b), and degree of saturation (c) plotted as functions of water ratio for three bentonites. Compaction pressure = 100 MPa.

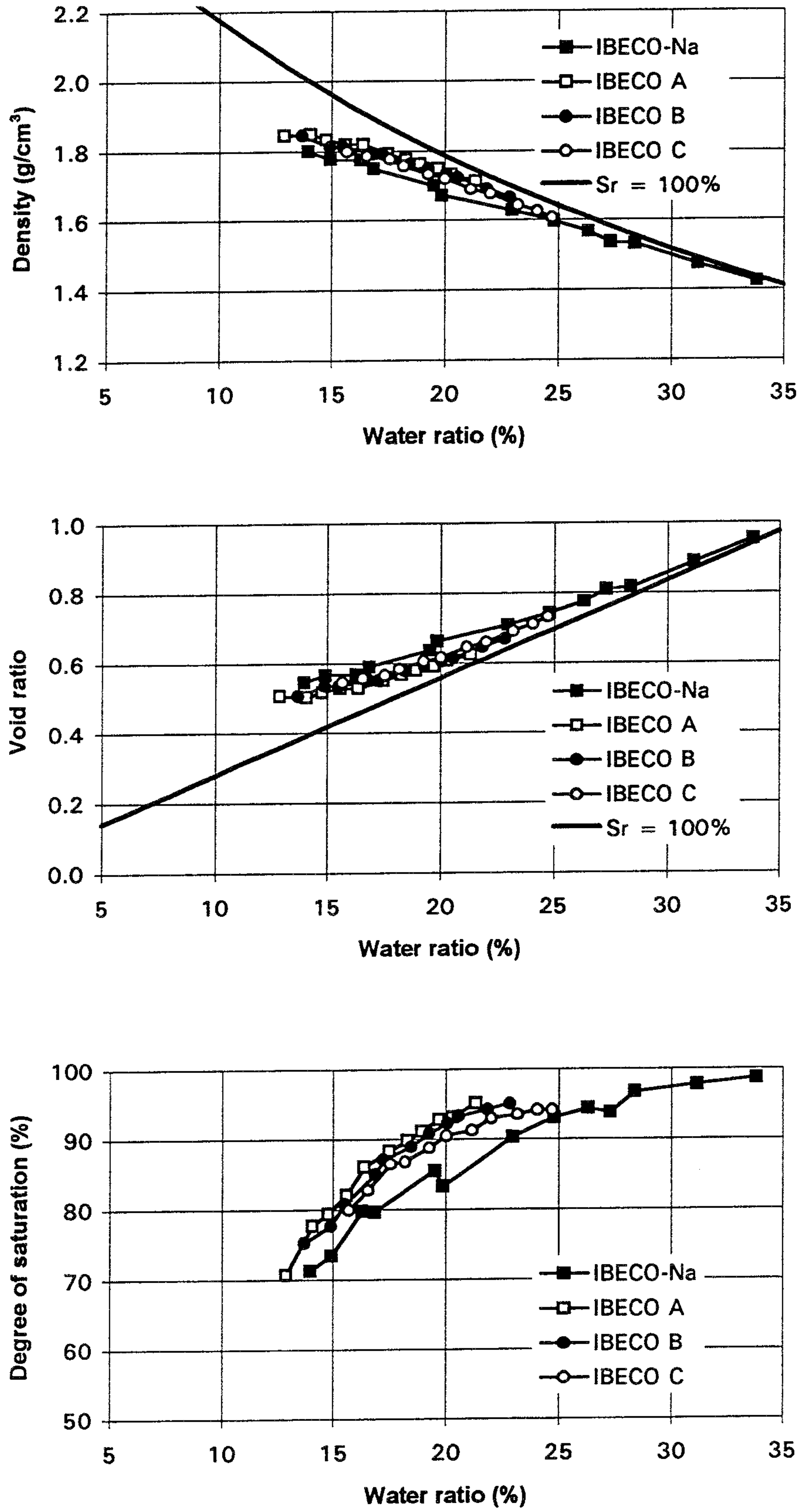


Figure 4-3. *Dry density (a) , void ratio (b), and degree of saturation (c) plotted as functions of water ratio for four types of IBECO bentonite. Compaction pressure = 100 MPa.*

4.2.3 Influence of form geometry

The ratio of the diameter and height of a form is expected to affect the homogeneity of a compacted sample due to the friction between the sample and the form. In order to investigate this effect samples of MX-80 were compacted in a large cylinder with a diameter of 49 mm and a height of 240 mm under reference conditions except for the height of the samples. Samples with 100 mm, 70 mm, 40 mm, 20 mm, 10 mm, and 5 mm height were compacted at four different water ratios; 10%, 15%, 18% and 22%. After compaction, the samples were cut to 10 mm thick slices on which density and water ratio were measured. The degree of saturation and void ratio were then calculated by Eqn 4-1 and Eqn 4-2.

The results from the tests are shown in Figs 4-4 to 4-7, were the void ratio and the degree of saturation are plotted as a function of the distance from the upper surface of the sample. Each figure shows the results from all tests at a particular water ratio, hence giving 6 curves that represent different sample heights.

For the sample with a water ratio 10% and a height of 100 mm (see Fig 4-4) the void ratio increased along the sample from e=0.5 near the top of the sample close to the piston to e=0.7 near the bottom, which indicates a strong influence of friction between the sample and the walls of the form. The degree of water saturation decreased from S_r=57% near the top of the sample to S_r=38% near the bottom. The other samples with the same water ratio followed the same curves as the sample with a height of 100 mm (same change in void ratio per mm).

At the water ratio 22% (see Fig 4-7) there was no significant difference in void ratio and degree of saturation along the samples, which indicates that there was only little friction between the sample and the walls of the form.

The results from the tests on samples with water ratios 15% and 18% are shown in Fig. 4-5 and Fig. 4-6, respectively. The inhomogeneity especially of the high samples, which can bee seen in these figures, indicates a certain but rather moderate influence of friction, which decreasing with increasing degree of saturation.

As a whole these results show that the recorded inhomogeneity of the samples decreased with increasing water ratio and ceased when the samples were close to water saturation. The reason why the largest sample (100 mm) with a water ratio of 22% was homogenous is that it probably became completely saturated during the compaction (see Section 4.2.4) and that the clay-water mixture acted as a liquid with no internal or external friction at high pressure. After reloading, the sample swelled and the degree of saturation decreased.

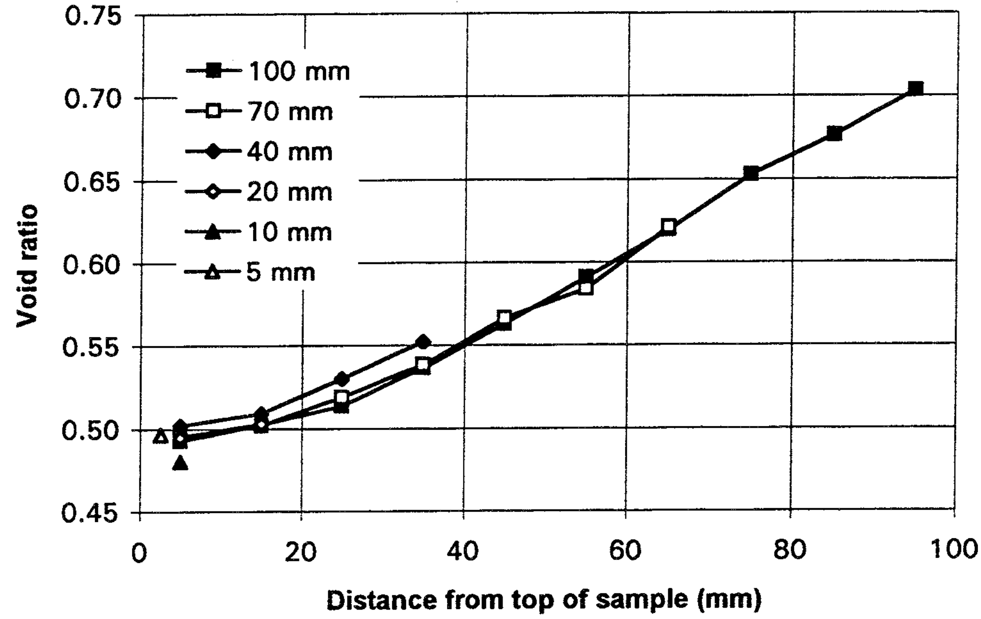


Figure 4-4. Void ratio (a) and degree of saturation (b), plotted as functions of the distance from the top surface of the sample for different sample heights. Water ratio = 10%.

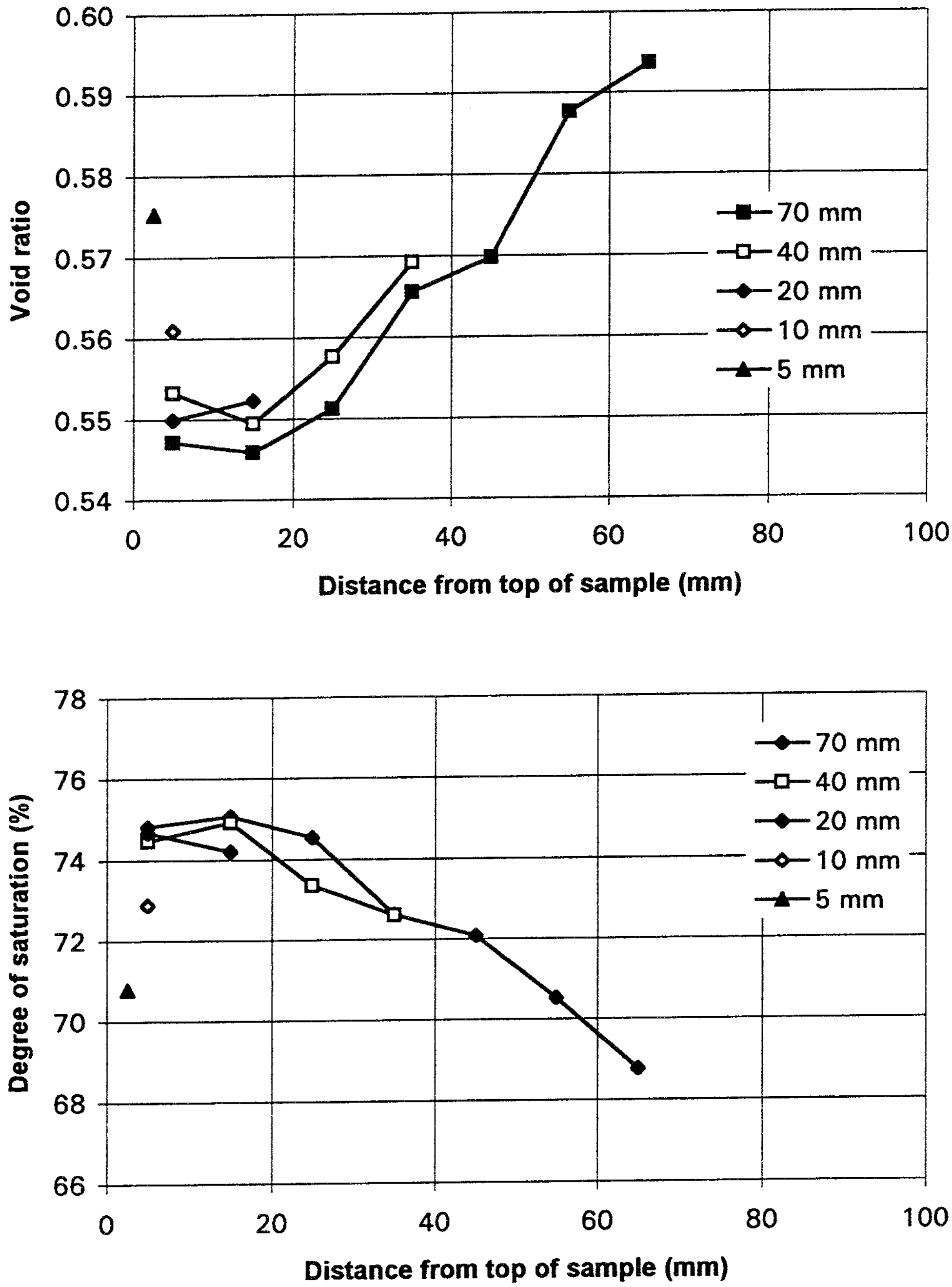
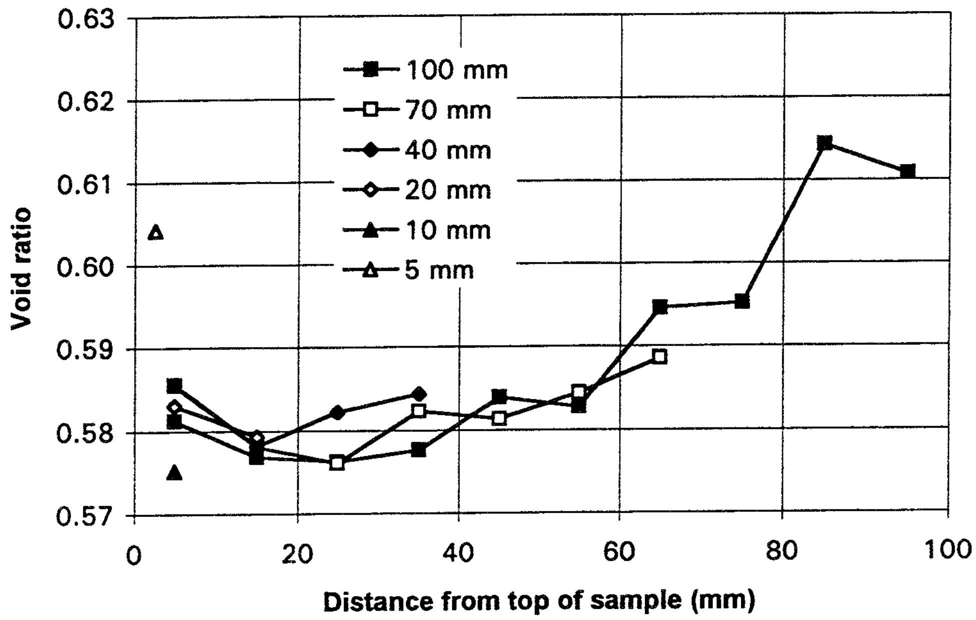


Figure 4-5. Void ratio (a) and degree of saturation (b), plotted as functions of the distance from the top surface of the sample for different sample heights. Water ratio = 15%.



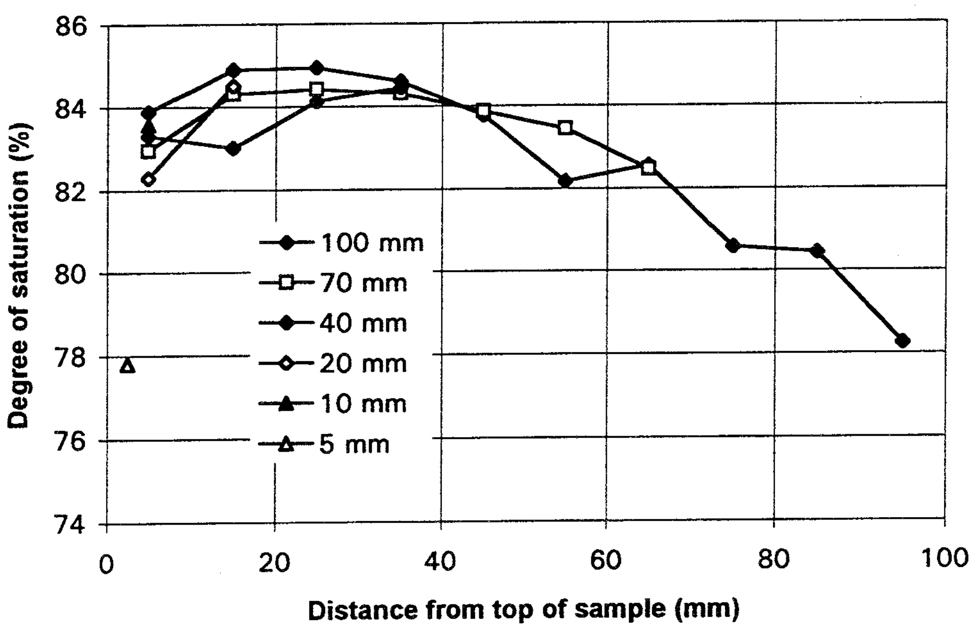


Figure 4-6. *Void ratio (a) and degree of saturation (b), plotted as functions of the distance from the top surface of the sample for different sample heights. Water ratio = 18%.*

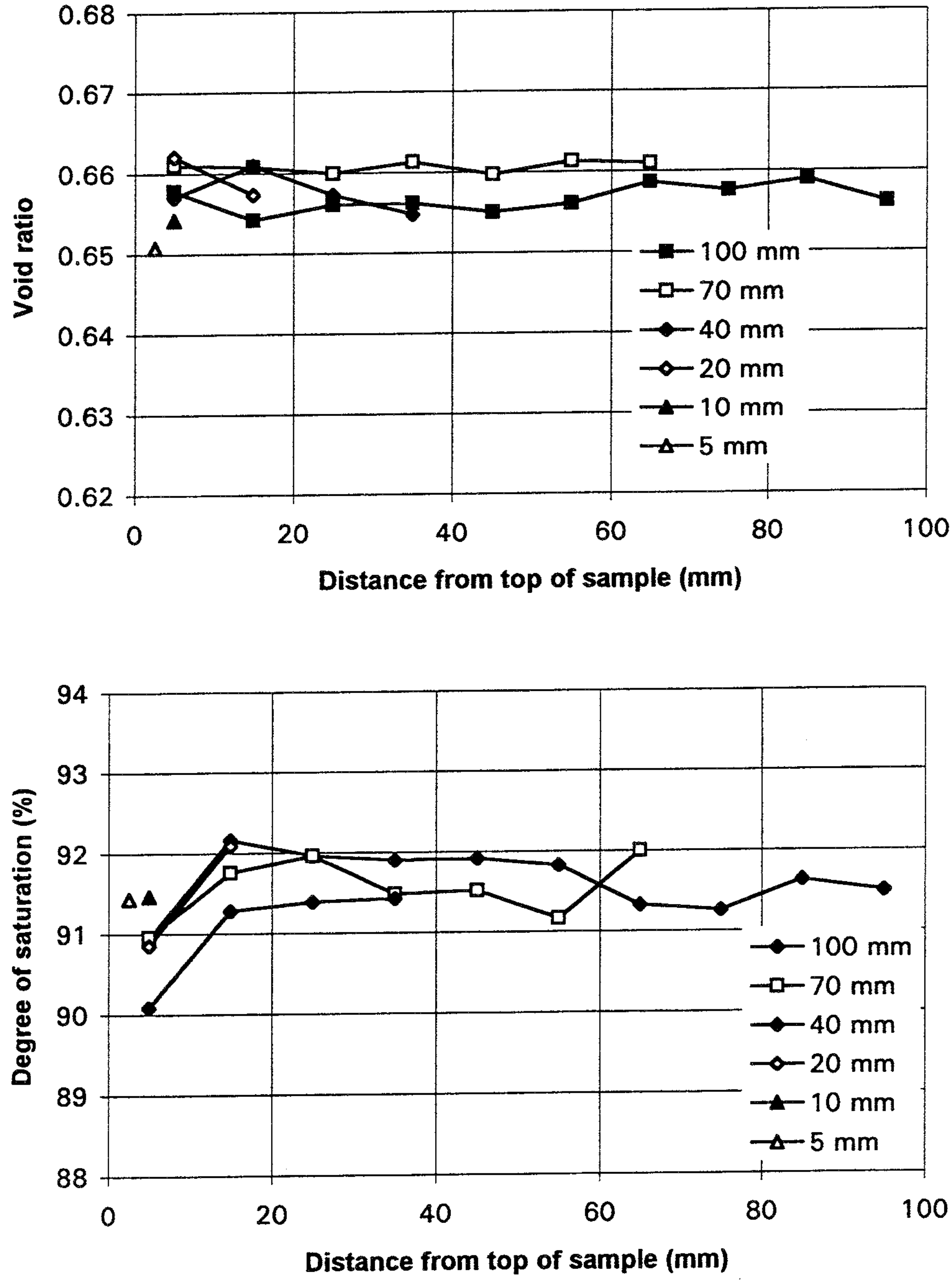
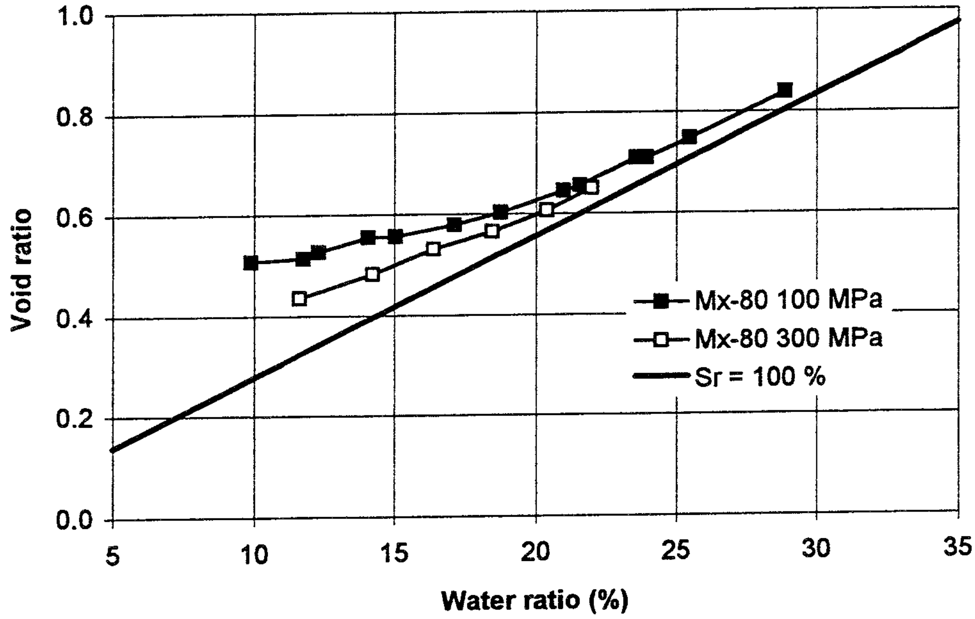


Figure 4-7. Void ratio (a) and degree of saturation (b), plotted as functions of the distance from the top surface of the sample for different sample heights. Water ratio = 22%.

4.2.4 Influence of compaction pressure

Two sub-projects were performed for investigating the influence of the compaction pressure. In one of them additional compaction series were made with a compaction pressure of 300 MPa on the two bentonites MX-80 and IBECO-Na under reference conditions (see Section 4.2.1). In Fig 4-8 the void ratio is plotted as a function of the water ratio for the two different compaction pressures 100 MPa and 300 MPa. The figures show that there was an obvious effect of increasing the compaction pressure from 100 MPa to 300 MPa at low water ratios while at a water ratio higher than 20-25% the effect was negligible.



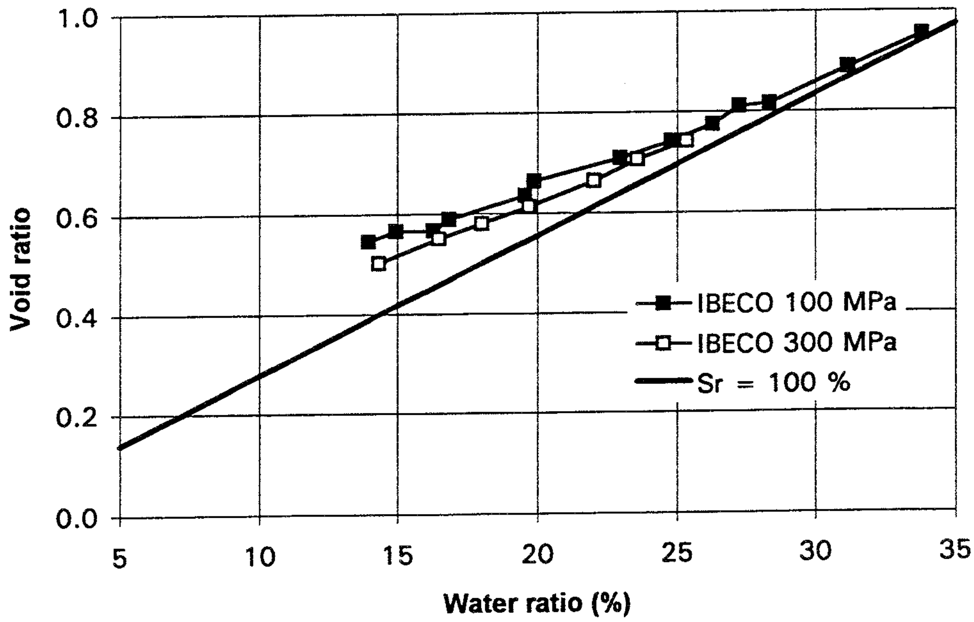


Figure 4-8. The void ratio as a function of water ratio for MX-80 (a) and IBECO-Na (b). Compaction pressure = 100 MPa and 300 MPa

In the other sub-project samples of MX-80 were compacted by applying five different compaction pressures (25 MPa - 150 MPa) at three different water ratios in the form with 50 mm diameter under reference conditions (see Section 4.2.1). At the highest load the volume of the samples in the form was measured. After reloading and removal of the samples from the form, the weight, water ratio, and density of the samples were determined. By this procedure, the degree of saturation and void ratio during the compaction and after removal of the samples from the form, could be calculated.

The results from these tests are shown in Fig 4-9 and Fig 4-10. Fig 4-9 shows that for a compaction pressure of 150 MPa the sample at compaction had 100% degree of saturation if the water ratio of the sample exceeded 17% (the curve for 150 MPa compaction pressure coincides with the curve for the minimum void ratio at S_r =100%). For the compaction pressures 50, 75 and 100 MPa the samples reached 100% degree of saturation if the water ratio of the samples exceeded 21%. It is concluded that if a sample during compaction reaches 100% degree of saturation is it not possible to compact it further.

The void ratio after unloading and removing the samples from the form, is shown in Fig 4-10. Due to the elastic swelling of the samples none of them reached 100% degree of saturation after unloading. Fig 4-10 also shows that at the water ratio 21% the void ratio was similar for all samples that were compacted under compaction pressures between 50-150 MPa. These results thus indicate that if the samples reach 100% degree of saturation at compaction the density after reloading is independent of the compaction pressure (see also Section 4.3).

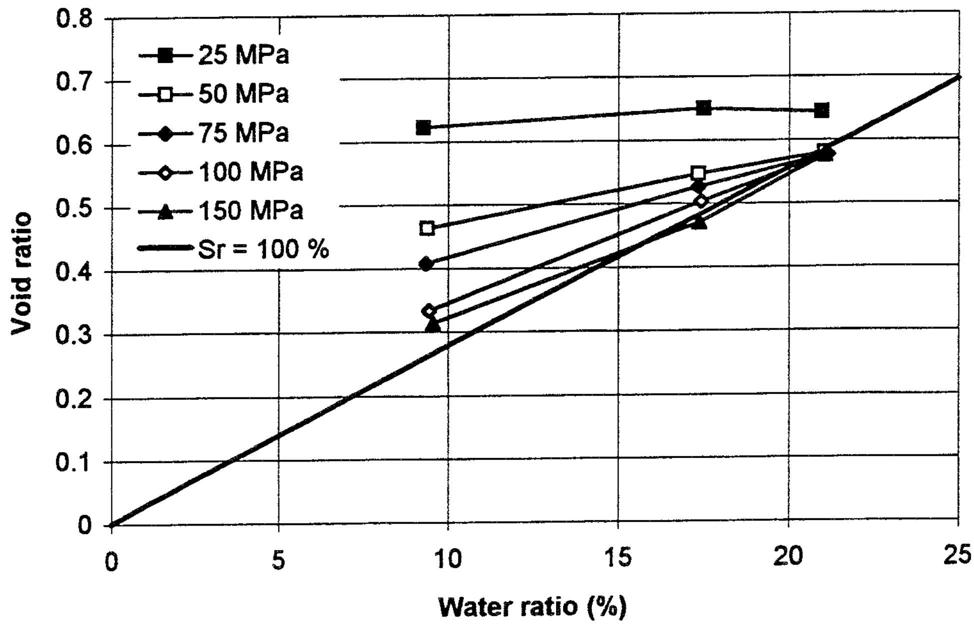


Figure 4-9. The void ratio as a function of water ratio for MX-80 during compaction. Compaction pressure 25 - 150 MPa.

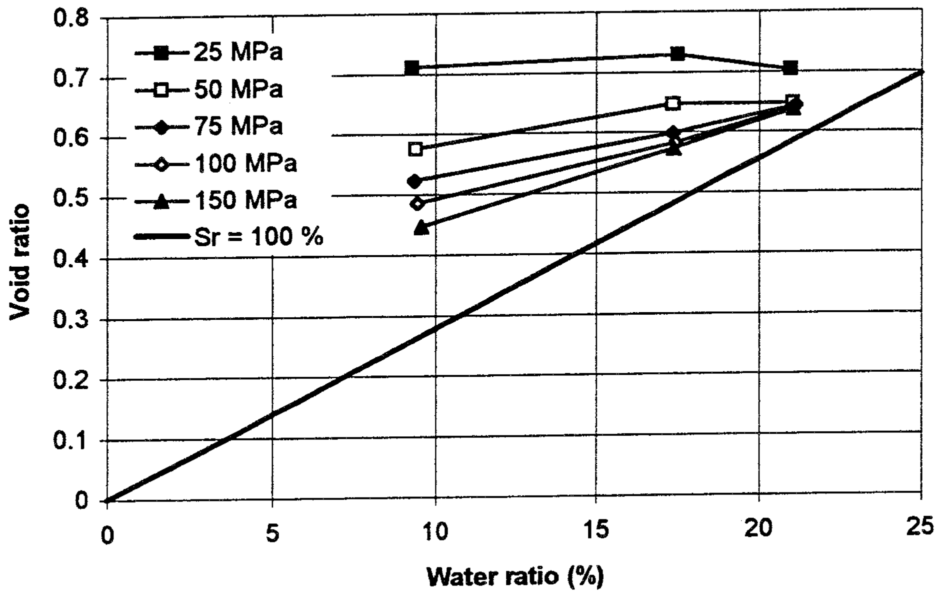


Figure 4-10. The void ratio as a function of water ratio for MX-80 after removal from the form. Compaction pressure 25 - 150 MPa.

The results from these tests are also shown with the void ratio plotted as a function of the compaction pressure in Fig 4-11. This figure indicates that the void ratio after compaction was strongly dependent on the compaction pressure at low water ratio. At the water ratio 9.4% the void ratio decreased from 0.6 to 0.3 when the compaction pressure was increased from 25-150 MPa. At the water ratio 21% the void ratio was independent of the compaction pressure when the compaction pressure exceeded 50 MPa.

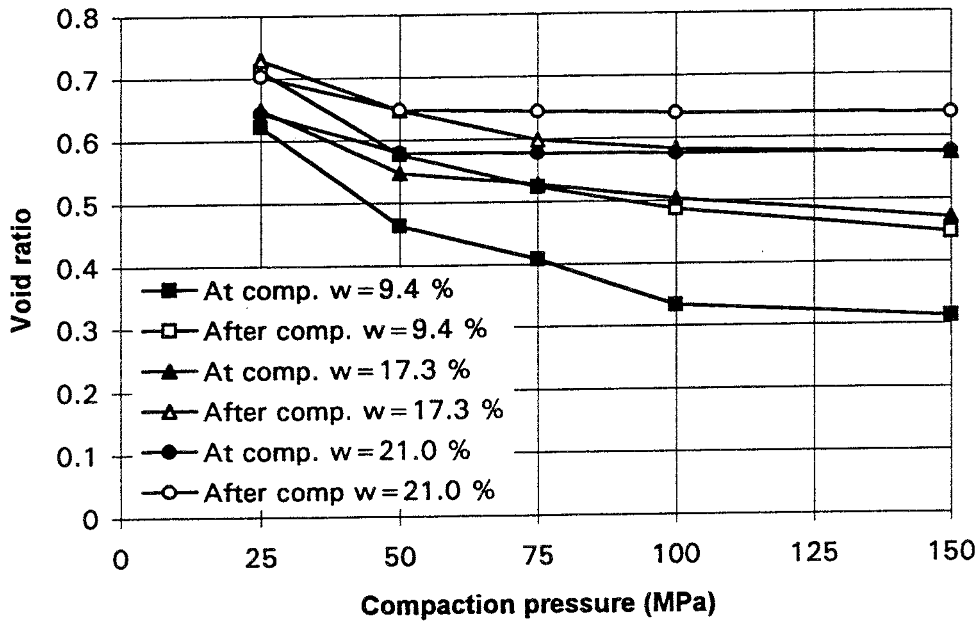


Figure 4-11. The void ratio as a function of the compaction pressure for samples with different water ratio.

4.2.5 Influence of compaction rate

All laboratory compactions have been made with a rather slow strain rate. Since the compaction of brick blocks on an industrial scale is expected to require a compaction procedure with quicker compression it is important to find out if the rate has a major influence on the properties of the block.

A series of tests on MX-80 was made at 100 MPa compaction pressure yielding samples with 50 mm diameter and 20 mm height. Three different press velocities, from 0.04 mm/s to 1.8 mm/s, were used at the water ratios 10% and 21%, respectively. The water ratio and density were measured and the void ratio and degree of water saturation calculated after removal from the form.

The results which are compiled in Table 4-1 show that the compression rate had very little influence on the compaction irrespective of the water ratio. No influence of an increase in rate by 50 times can be seen. The small differences in void ratio and degree of water saturation can be explained by measurement errors.

Table 4-1. Summary of press velocity tests

Press Velocity (mm/s)	w (%)	e	S_r (%)
0.04	10	0.49	61
0.3	10	0.48	60
1.8	10	0.48	59
0.04	21	0.63	92
0.3	21	0.63	91
1.8	21	0.63	91

4.2.6 Influence of bentonite type and granule size distribution

The bentonite type and granulometry may affect the result of the compactions. These effects can be studied by comparing the compaction curves of the different bentonites. The following types were used:

- Four types of sodium converted bentonites from IBECO (IBECO-Na, IBECO A-C)

- Two types of natural Na-bentonite from Wyoming (SPV200, MX-80)

The results from the compaction tests are shown in Figs 4-2 and 4-3.

Since the differences between the compaction curves from the six bentonites are very small no general conclusion of the influence of the bentonite type and granulometry on the compaction results can be drawn. In spite of this, Figs 4-2 and Fig 4-3 indicate the following:

- SPV200 was somewhat better (lower *e* and higher S_r) than MX-80
- The coarsely ground IBECO bentonites (IBECO A-C) were somewhat better (lower *e* and higher S_r) than the IBECO bentonite (IBECO-Na) in powder form.
- IBECO-Na and MX-80 had almost identical compaction curves
- The differences between the bentonites are very small

In Fig 4-12 all the compaction curves from the six bentonite types are shown.

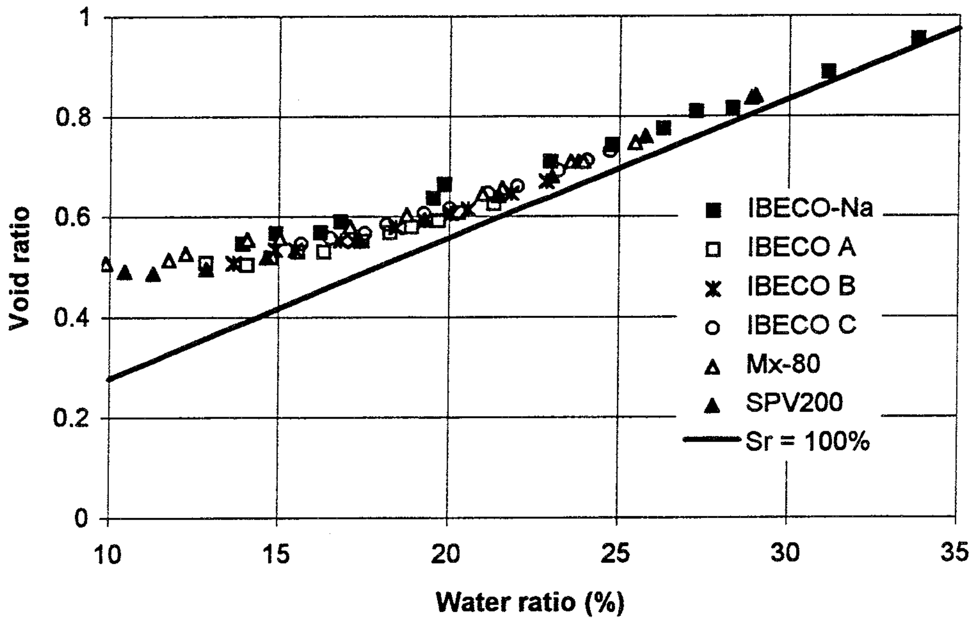


Figure 4-12. *The void ratio as a function of water ratio for different types of bentonites.*

4.3 ELASTIC EXPANSION AFTER COMPACTION

It was shown in Fig. 4-11 that all samples expanded after unloading and removal from the form. As Fig 4-11 indicates the expansion ratio $\delta_e=\Delta V/V$ is a function of the water ratio and the compaction pressure. In Fig 4-13 the expansion ratio is plotted as a function of the compaction pressure for three different water ratios. The figure shows that the expansion ratio was $\delta_e \approx 4\%$ and almost independent of the compaction pressure at a water ratio of 21%. At the water ratio 9.4% δ_e increased strongly with increasing compaction pressure up to as much as 10%.

The tests thus show the following:

- The expansion was about 4% when the samples had been compacted to complete water saturation.
- The expansion increased with increasing compaction pressure when the samples were unsaturated.
- The expansion increased with decreasing degree of saturation

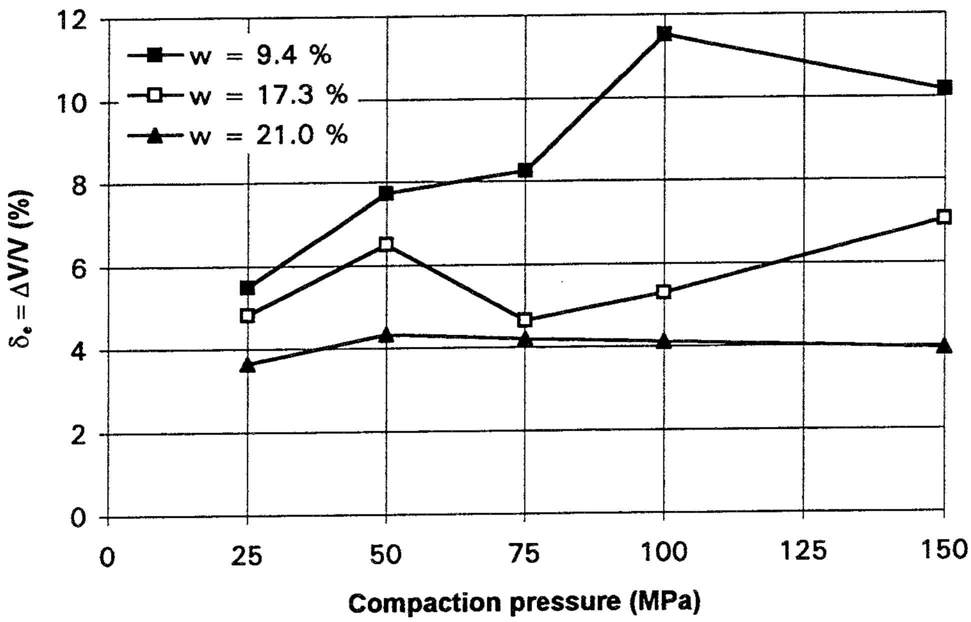


Figure 4-13. The expansion ratio as a function of the compaction pressure for MX-80 samples compacted at different water ratios..

4.4 EFFECT OF USING LUBRICATED AND HEATED FORMS

In order to investigate different techniques for reducing the friction between the form and the bentonite two compaction series have been performed. Samples were compacted in a large cylinder with a diameter of 49 mm and a height of 240 mm. They had a height of approximately 110 mm after compaction. The compaction pressure was 50 MPa. In one of the series samples were compacted at the two water ratios 9 % and 18 %. Tests with and without lubricated form were performed. The lubrication oil was applied on the form with a paintbrush. Also tests with a heated form were performed. During these tests heat wires were applied around the form. The temperature on the form was measured and the power in the heat wires controlled in order to yield a constant temperature.

After compaction, the samples were cut into 20 mm thick slices and the density and water ratio were measured. The degree of saturation and void ratio could then be calculated by Eqn 4-1 and Eqn 4-2. The results are shown in Fig 4-14 and Fig 4-15. In the sample with 9% water ratio (see Fig 4-14) and no lubricating oil or heating at the compaction, the void ratio varied over the sample from 0.57 to 0.87. When the form was heated the void ratio was found to vary between 0.53 and 0.87. No desiccation of the sample due to the heating could be observed in this test. The heated form gave a somewhat more efficient compaction near the upper part of the sample since the void ratio in the upper 20 mm was about 10% lower than without heating. However, no reduction in friction between the bentonite and the form was achieved since the inhomogeneity was actually larger at the heated compaction. At the test where lubricating oil was used the void ratio varied from 0.57 to 0.80. The results indicate that the latter sample was somewhat more homogeneous than the sample without lubricating oil.

In Fig 4-15 the results from the corresponding tests with 18% water ratio are plotted. The figure shows that these samples were much more homogenous than those with the lower water ratio, due to the lower friction between the bentonite and the form during compaction. (see also Section 4.2.3). Fig 4-14 also shows that the test with lubricated form gave an almost homogenous sample. The tests with heated form (80°C and 160°C, respectively) resulted in a more effective compaction near the top of the samples than the sample with no heated form. Furthermore, the void ratios of the heated sample was higher at the bottom than of the unheated samples. It should be noted, however, that some desiccation was observed in the tests with heating at 160 °C, which can explain the low void ratio near the top of the sample. This phenomenon did not appear when the form was heated to 80°C.

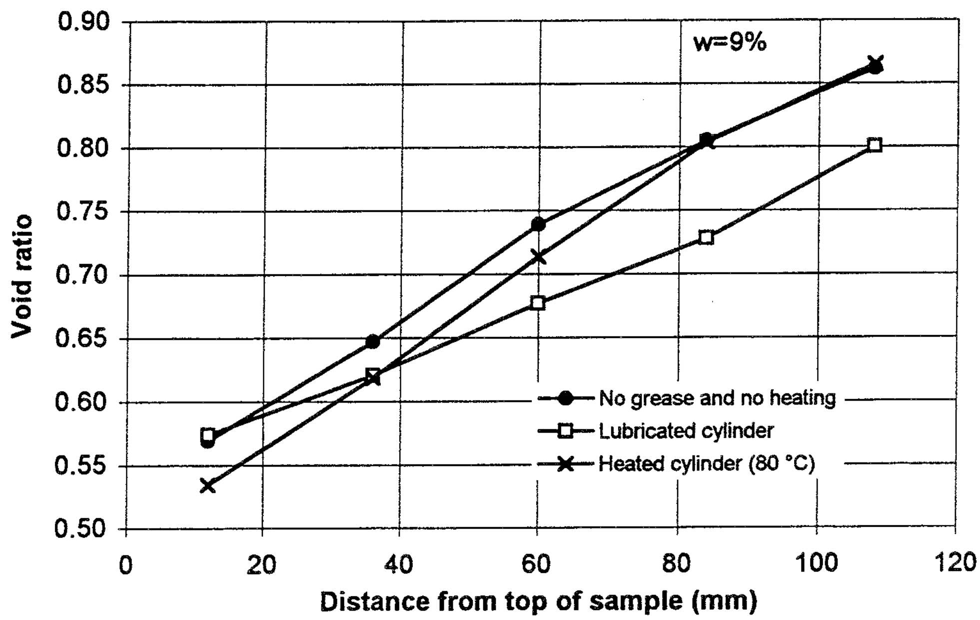


Figure 4-14. *The void ratio as a function of the distance from the top surface of the samples. Water ratio = 9%.*

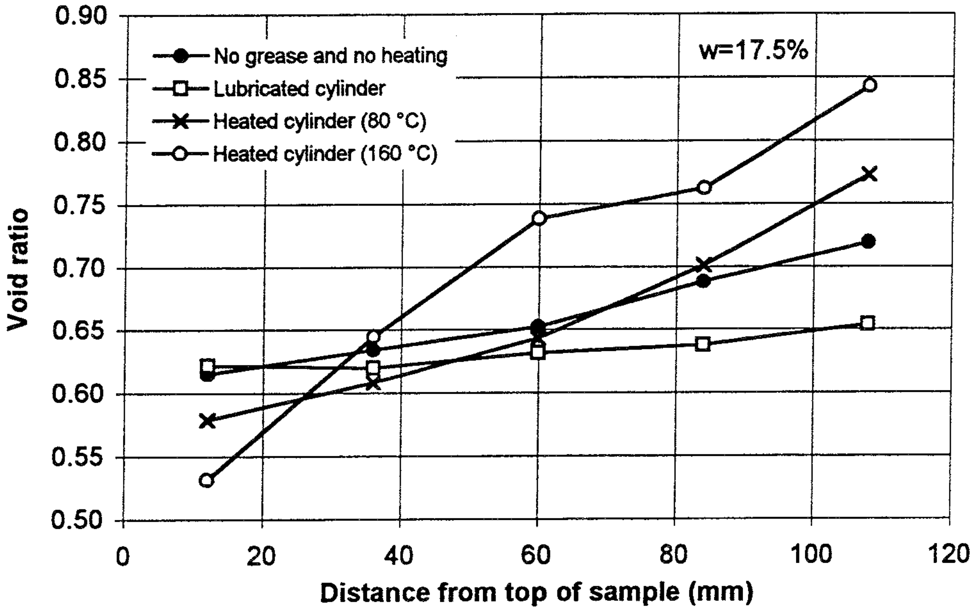


Figure 4-15. The void ratio as function of the distance from the top surface of the samples. Water ratio = 18%.

In the other test series samples with 49 mm diameter and 100 mm height were compacted with and without lubricated form. In these tests the quality of the samples with respect to cracking was studied. A total number of 63 samples were compacted. All samples with high water ratio had cracks assumed to be caused by air that was trapped in the sample during the compaction. Lubricating the form in these tests did not affect the evolution of cracks. In Table 4-2 results from tests with rather low water ratio, similar compaction pressure and compaction rate are shown. It indicates that lubrication of the form before compaction prevents cracking.

Table 4-2. Results from the tests with lubricated form on samples with height 100 mm and diameter 49 mm.

No	w (%)	Com.pr. (MPa)	Def rate (mm/s)	Lubr. form	Cracks
B3	9	50	20	No	Yes
C4	8.5	50	20	No	Yes
C6	8.5	50	20	No	Yes
E1	12	50	20	No	No
E2	12	50	20	No	Yes
H5	8.5	50	20	Yes	No
H6	8.5	50	20	Yes	No
H7	8.5	50	20	Yes	No

4.5 DEAIRING BY VACUUM

One of the main problems at compaction of larger blocks of bentonite is that they crack due to air that is entrapped in the block (see also Section 5.2). In order to avoid this problem the compaction can be made during deairing under vacuum. Beside preventing cracks, the vacuum may also affect the void ratio and the homogeneity of the samples. In order to investigate these effects compaction tests were carried out in the laboratory. At first compaction tests with and without vacuum were made on samples of MX-80 with 50 mm diameter under reference conditions (see Section 4.2.1). Results from the tests are shown in Fig 4-16 and Fig 4-17. The results show that the compaction was somewhat more effective when vacuum is used at relatively high water ratio (w > 17%). No effect of vacuum was observed in samples with lower water ratio.

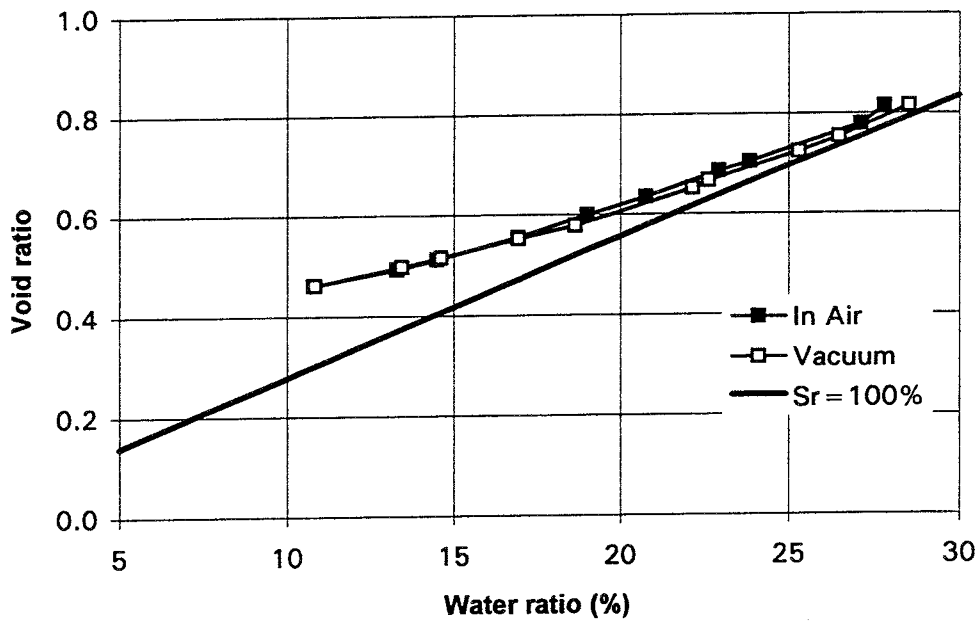


Figure 4-16. Void ratio as a function of water ratio for samples compacted in air and during vacuum.

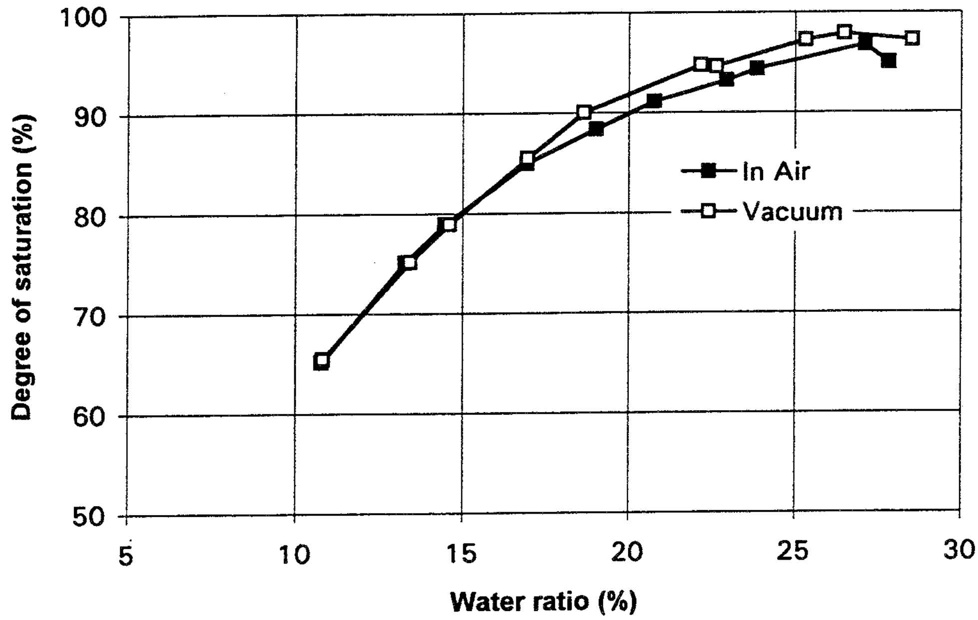


Figure 4-17. Degree of saturation as a function of water ratio for samples compacted in air and during vacuum.

Compaction tests with vacuum were also performed in a compaction cylinder with 49 mm diameter and 240 mm height, in order to study the effect of the geometry on the homogeneity of the samples which, after compaction, had a height varying between 20 and 100 mm. After compaction the samples were cut in 10 mm thick slices and the void ratio and density determined. From these parameters the void ratio was calculated. Tests were performed on bentonites with a water ratio of 9% and 21%. The results from the tests are shown in Figs 4-18 and 4-19. Fig 4-18 shows that for the sample with a water ratio of 9% and a height of 100 mm, the influence of vacuum was not very large as manifested by the small difference in homogeneity. Corresponding tests on samples with 21% water ratio (see Fig 4-19) have shown that the void ratio varied between 0.62 to 0.64 along the sample when vacuum was used. When no vacuum was used the void ratio was somewhat higher, probably because air was entrapped during the compaction. The scatter of the void ratio for the samples compacted with and without vacuum were within the same range.

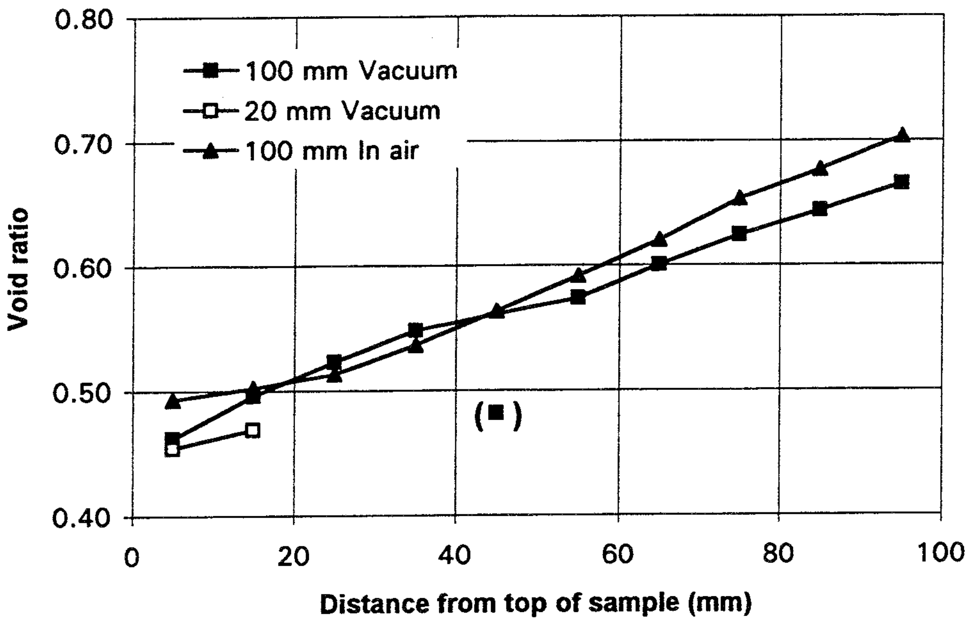


Figure 4-18. The void ratio plotted as a function of the distance from the top of the sample. Water ratio ≈ 9%.

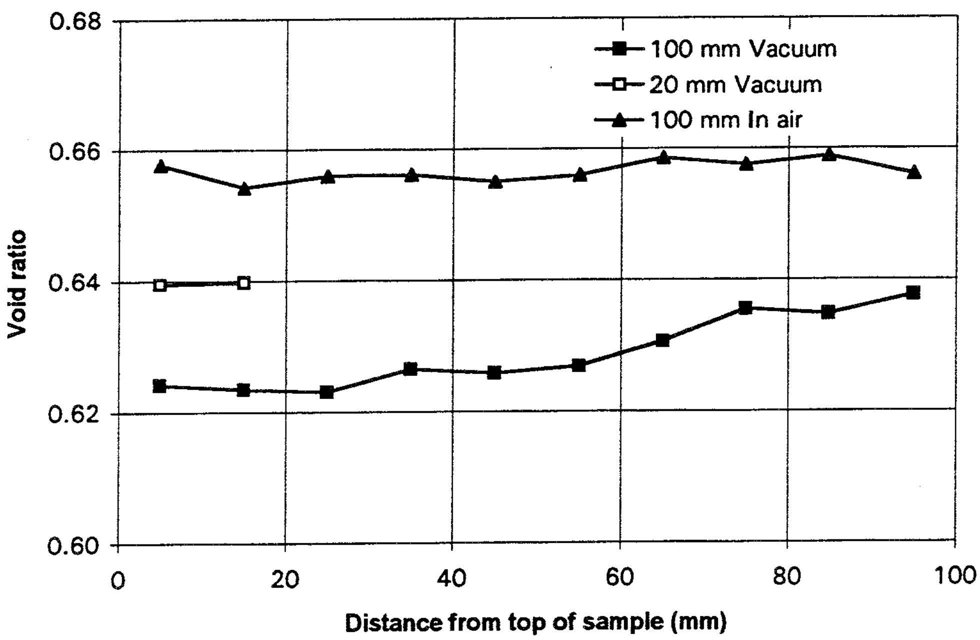


Figure 4-19. The void ratio plotted as a function of the distance from the top of the sample. Water ratio ≈ 21%.

Generally, these tests indicate that vacuum increases density a little at high water ratio but that it has an insignificant effect on both density and homogeneity at low water ratios.

5 COMPACTION ON AN INDUSTRIAL SCALE

5.1 GENERAL

The weight of manually handable blocks should not exceed 10 - 15 kg. Large quantities of such blocks must be prepared on an industrial scale for time and economic reasons. The production line must include the following:

- Storage units for large volumes of bentonite
- Machines for mixing large volumes of bentonite with water
- Transportation units for mixed bentonite
- Press for fast compacting
- Machines for packing the blocks
- Storage place for the blocks

The tests were performed at Höganäs Bjuf AB in Bjuv where refractory bricks and other refractory products are made. This company has all the facilities listed above except automatic packing.

A large number of block compaction tests have been performed in Bjuv. All these tests will not be described in detail. Instead an overview will be given of the problems that were discovered and how they were overcome during the process of developing the most appropriate technique.

5.2 PROBLEMS ASSOCIATED WITH INDUSTRIAL COMPACTION

5.2.1 General

Some problems associated with industrial compaction of blocks were early observed in laboratory tests but others were not observed until larger blocks were compacted. Examples of problems are different types of damage of the blocks at the compaction. They may have been caused by the equipment or by the material composition. Other problems are associated with handling and storing of the blocks after compaction. They have to be packed to prevent desiccation and damage during handling and transportation of the blocks. A further problem is that mould can grow on the blocks. On some blocks mould was found only after some time.

5.2.2 Cracking

During the compaction tests at Höganäs Bjuf AB cracks were observed 1n many blocks. Some cracks were more frequent on blocks with low water ratio while other types of cracks occurred at high water ratio. The following main types of cracks were observed:

1. Cracks due to the friction between form and bentonite
2. Cracks due to air being entrapped in the blocks at the compaction
3. Cracks due to elastic swelling during reloading and removal of the block from the form
4. Cracks due to brittle edges of the blocks
5. Cracks caused by a too wide gap between the pistons and the form

The first type of cracks was most common in blocks with low water ratio, the reason being higher friction between the bentonite and the form sides at low water ratio (see Section 4.2.3 and Section 4.4). In the tests at Höganäs Bjuf AB such cracking was largely reduced by applying lubricating oil on the form. The oil can be automatically sprayed on the form at the compaction.

The second type of cracks was most common in blocks with high water ratio, the reason being difficulties for the air in the bentonite to dissipate out during compaction. Examples of means to avoid this type of cracks are:

- Stepwise loading
- Compaction under vacuum
- Low compaction rate
- Use of coarsely ground bentonites

On nearly all the tests performed at Höganäs Bjuf AB the blocks were compacted in steps. They were completely reloaded between the pressurizings and the upper piston was moved out from the form so that air could leave the blocks from their upper surfaces.

No vacuum could be applied to the compaction devise since there were gaps between the form sides and the pistons (see also Section 5.2.3). These gaps were of great importance for deairing the blocks during compaction. Tests were also performed with smaller gaps, which, for some bentonite types, yielded more cracks due to entrapped air.

The blocks could have been compacted at a lower compaction rate with the available equipment but this would have reduced the production rate too much.

Despite stepwise compaction was used it was not possible to get crack-free blocks without using coarse-grained bentonites. The best blocks were achieved with IBECO C bentonite which had the coarsest granule size.

The third type of cracks mainly occurred in blocks with a low water ratio. Tests performed in the laboratory (see Section 4.3 Fig 4-13) indicate that the elastic volume expansion of the samples after compaction can be as large as 11% when bentonite with a low water ratio is compacted. Fig 5-1 shows a schematic drawing of the technique for pushing a block out of a form in the device used at Höganäs Bjuf AB. In *Stage I* the block is compacted by the two pistons. The block affects the form with a horizontal pressure. The block is then pushed out of the form by the lower piston. In *Stage II* nearly the hole block has been pushed out of the form. The part of the block that is outside the form has expanded while the part of the block that is still inside the form is prevented from expanding. This will cause large strain in the lower part of the block which can result in cracks. This type of cracks can be prevented by using bentonite with a high water ratio. The damage can also be prevented by making the form somewhat conical but such a form can hardly be used when the blocks are compacted by two pistons.

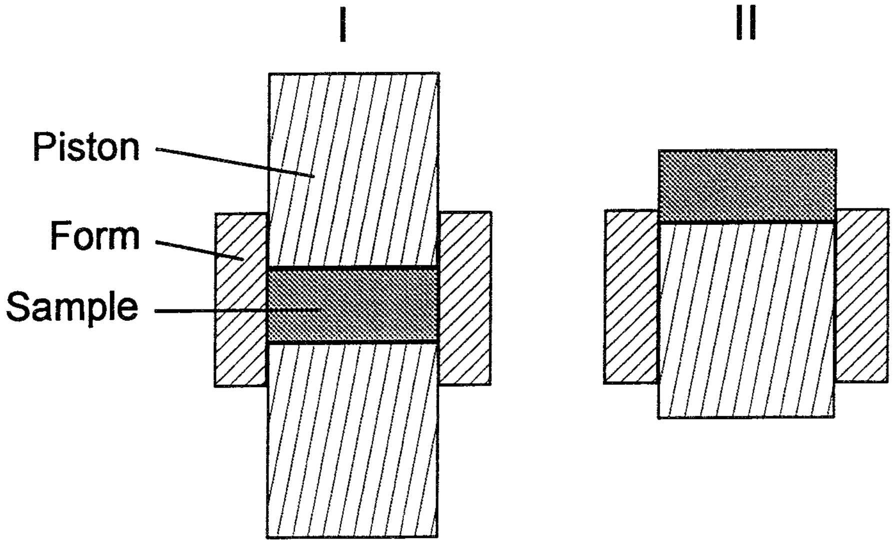


Figure 5-1. *Schematic drawing of the technique used for pushing a block out of a form.*

<u>The fourth type</u> of cracks were common in blocks compacted by use of coarsely ground bentonite (IBECO C). Six blocks with different water ratios were compacted. The water ratio varied between 16 and 21.5%. Immediately after compaction all of the blocks were in perfect condition. Two days after compaction, damage was observed in the blocks with low water ratios. Material had began to fall from the edges of the blocks. After approximately one month, damage was observed in all the blocks but the blocks were still coherent. The damage is assumed to be caused by incomplete crushing of the granules during the compaction. Thus the granules still behave as individual granules within the blocks and the adhesion between them is too weak. In order to prevent this type of damage, a less coarsely ground bentonite can be used and/or the coarsely ground bentonite can be mixed with finely ground bentonite in order to increase the adhesion between the granules. However, this latter method can cause cracks due to entrapped air. An optimal mix of granules should prevent both types of damages.

The fifth type of cracks is common in blocks with high water ratio. Material is squeezed out of the form trough the gaps between the form and the pistons (se also Section 5.2.3) and this causes damage of the edges of the blocks. To prevent this type of damage, the following measures can be taken:

- Use bentonite with low water ratio
- Decrease the gaps between form and pistons

5.2.3 Liquefaction

It is beneficial if the bentonite becomes almost saturated during compaction since it yields a high homogeneity of the blocks (see Section 4.2.3). As found in laboratory tests bentonite may be liquefied during compaction if a sample is completely water saturated. The phenomenon appears if the water ratio of the bentonite and the compaction pressure are critically high (see Section 4.2.5).

Tests performed at Höganäs Bjuf AB show, however, that liquefied bentonite will eject from the form through the gaps between the form sides and the pistons. This problem can be avoided by sealing the gaps. However, this type of reconstruction was not possible in the used equipment. The problem was avoided by reducing the gaps, use of coarsely ground bentonite and a reduced compaction load.

5.2.4 Sticking

During compaction bentonite often sticks to the form and the pistons. After reloading and removal of the block from the form, material can adhere to the pistons and material thus lost from the blocks so that large cavities can be formed on the surface of the blocks. This phenomenon is more common at high water ratios. Three different techniques were used to avoid this problem in the laboratory, namely:

1. Use a geotextile between the bentonite and the pistons during compaction
2. Spray the form and upper surface of the bentonite with dry bentonite before compaction
3. Lubricate the form and the pistons before compaction

At industrial compaction of blocks a geotextile causes practical problems and cannot be used. Powder of bentonite also gives difficulties at industrial compaction. In the equipment used at Höganäs Bjuf AB lubricating oil can automatically be sprayed on the form at each compaction since this is a standard technique in brick fabrication. In the tests with lubricated form the oil was not automatically sprayed on the form but applied with a paintbrush by hand. The performed tests showed that the adhesion of bentonite to the form could be prevented by using this method.

5.2.5 Storage

The blocks must be wrapped in plastic during storage. Example of problems associated with the storage are:

- Desiccation of the blocks through the plastic
- Sticking of the blocks to each other if many blocks are stored together on a pallet
- Appearance of mould on the blocks

At compaction of large quantities of blocks they will probably not be packed individually. Instead many blocks will be packed in the same package and if this is the case, there is a risk that the blocks will adhere after some time of storage.

On several occasions mould was observed on the blocks some time after compaction. The blocks smelled and white spots were observed on the surfaces of the blocks.

In order to investigate the listed problems, a series of tests was made. Small samples with 35 mm diameter were compacted at a compaction pressure of 100 MPa. The initial water ratio varied between 10% and 25%. After compaction, samples with the same water ratio were stored pair-wise in a plastic package. One sample was put on the top of the other in the package and the samples were loaded under pressure of ~50 kPa, which corresponds to the weight of approximately 2.5 m bentonite. Separate sets of samples were packed both with and without vacuum. After about 2 months the packages were opened and the water ratio of the samples measured. The samples were also examined visually in order to see if any mould had grown on the samples and if the samples adhered.

The results from the measurements of the water ratios are shown in Table 5-1. It is concluded that all the samples had desiccated. The samples stored in vacuum decreased in water ratio by 0.5 - 2% units while the other had decreased in water ratio by between 1 and 5%. In none of the packages the samples adhered and only in one package mould was observed (see Table 5-1).

Table 5-1. Water ratio before and after 2 months storage. Samples were stored both with and without vacuum.

No	w (%) before package	w (%) vacuum	w (%) no vacuum
1	10.0	9.5	9.1
2	14.2	13.2	12.7
3	15.6	14.5	13.9
4	18.1	16.8	15.5*)
5	18.5	17.1	16.5
6	19.9	18.5	17.4
7	22.0	20.2	19.1
8	23.2	21.3	19.6
9	24.1	22.2	20.8
10	25.4	23.2**)	20.4

*) After 3 months storage
**) mould

The following conclusions concerning packing and storage of blocks can be drawn:

- The blocks will not adhere when stored
- If the water ratio is less than 20% there will be no mould on the blocks
- The plastic used for package was not sufficiently tight although it is intended for vacuum packing This problem has to be further investigated.

6 BLOCK PROPERTIES

6.1 GENERAL

After emplacement of the blocks and the canister in a deposition hole, water will be taken up and 100 % degree of saturation will be reached in the buffer material after a period of time that depend on the density, initial degree of saturation of the blocks, and access to water. It is of great importance to know the properties of the bentonite after as well as before the wetting process. Examples of the properties that are of great importance before wetting are:

- The density and homogeneity of the blocks
- The tensile strength of the blocks for estimating how they can be managed without damages
- The compaction strength of the blocks for determining the stability of stacks of blocks

Examples of important block properties after wetting are:

- Swelling pressure
- Hydraulic conductivity
- Drained compression and swelling properties
- Shear strength

In this chapter mainly tests and results from experiments that are relevant to handling and emplacement of blocks before heating and wetting will be described. The properties that are relevant for the barrier function after emplacement are described in several other reports. However, some geotechnical tests have been made on the coarsely ground bentonites in order to compare the properties with those of MX-80.

6.2 BLOCK PROPERTIES BEFORE WETTING

6.2.1 Compaction properties

After compaction of blocks at Höganäs Bjuf AB the density and water ratio were determined and the void ratio and degree of saturation calculated. The results from the tests are shown in Fig 6-1. They are divided in two groups, namely blocks of finely ground (IBECO Na and MX-80) and blocks of coarsely ground bentonites (IBECO A-C and Gk/Qi). In Fig 6-1 results from compaction tests on MX-80 in laboratory scale are also plotted. The figure shows that the difference is very small between the two groups of blocks as well as between the blocks and the samples.

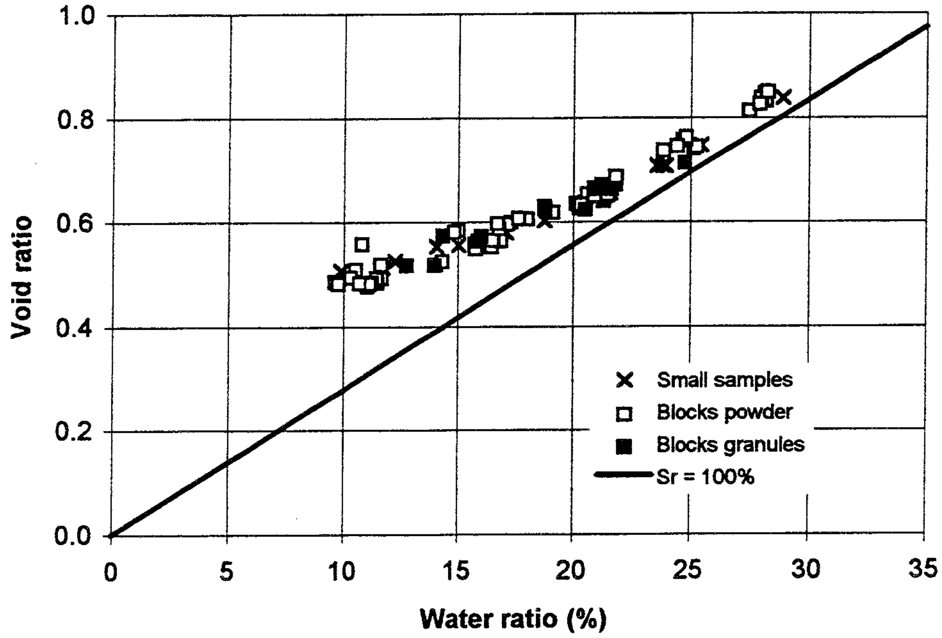


Figure 6-1. Compilation of compaction results. Void ratio as a function of water ratio for blocks and small samples (Φ = 35 mm).

In order to see if there was any inhomogeneity within the blocks, the density and water ratio were measured on several specimens extracted from some blocks (see Fig 6-2). Some of the results from these measurements are shown in Table 6-1. The table indicates that the scatter in density and void ratio was very small within the blocks. It was largest in the block with the lowest water ratio (Sample I) while the two other blocks were rather homogenous. These results show the same tendency as the tests performed in the laboratory scale. The samples with low water ratio became somewhat more inhomogeneous after compaction due to the friction between form sides and the bentonite than the blocks with high water ratio.

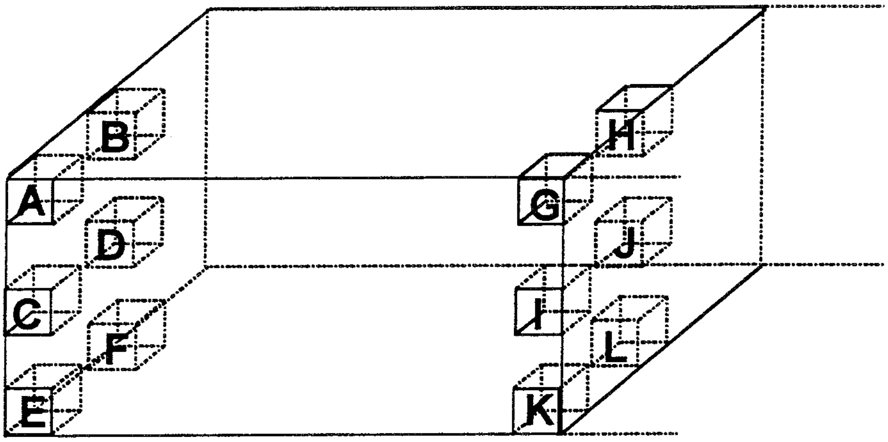


Figure 6-2. The locations within a block where the density and water ratio were measured. Only half of the block is shown.

Table 6-1. Results from laboratory tests on three blocks of MX-80.

No	Sample I				Sample II				Sample III			
	w %	ρ g/cm³	S_r %	e	w %	ρ g/cm³	S_r %	e	w %	ρ g/cm³	S_r %	e
A	11.5	2.01	59.3	0.54	15.7	2.03	75.0	0.58	20.4	2.07	91.4	0.62
B	11.7	2.03	60.9	0.53	15.8	2.05	77.5	0.57	20.5	2.05	89.7	0.63
C	11.6	2.04	62.1	0.52	15.9	2.07	79.8	0.55	20.4	2.05	90.0	0.63
D	11.7	2.04	62.8	0.52	15.8	2.06	78.1	0.56	20.1	2.06	90.4	0.62
E	11.6	2.09	66.7	0.48	15.8	2.08	79.9	0.55	20.5	2.05	90.2	0.63
F	11.7	2.06	63.8	0.51	15.7	2.07	78.6	0.55	20.0	2.06	90.2	0.62
G	11.7	2.04	61.8	0.53	15.8	2.06	77.7	0.56	20.2	2.06	89.8	0.63
H	11.7	2.06	64.6	0.50	15.9	2.07	79.7	0.55	20.4	2.05	90.0	0.63
I	11.8	2.07	65.4	0.50	15.8	2.07	78.7	0.56	20.1	2.06	89.8	0.62
J	11.8	2.06	64.2	0.51	15.8	2.07	79.6	0.55	20.4	2.05	89.8	0.63
K	11.7	2.08	66.0	0.49	15.7	2.08	79.8	0.55	20.2	2.05	89.5	0.63
L	11.7	2.05	63.1	0.52	15.6	2.06	77.1	0.56	20.0	2.06	89.7	0.62
Mean	11.7	2.05	63.4	0.51	15.8	2.06	78.5	0.56	20.3	2.06	90.0	0.63

6.2.2 Tensile strength

The tensile strength of the blocks and the strain at failure are two important parameters for evaluating how the blocks can be managed without breakage. Simple bending tests have been performed in order to make a rough determination of these properties.

Samples with 50 mm diameter and 20 mm height were compacted under 100 MPa pressure. The samples were cut by sawing to small beams with the dimensions 35 x 10 x 20 mm. The beam-shaped samples were supported at the ends, and loaded with a gradually increasing force applied in the center of the sample. (See Fig 6-3).

The deformation and force were continuously measured at the center of the sample during the experiment. Using the recorded force, the maximum moment and deformation of the beam were calculated by Eqn 6-1 and Eqn 6-2

$$M = \frac{Qc}{4} \tag{6-1}$$

$$\omega = \frac{Qc^3}{24EWa} \tag{6-2}$$

where

M = moment
Q = vertical force
a= sample height
b= sample with
c= sample length
ω = maximum displacement
E = Young's modulus
W = moment of resistance

The maximum tensile stress is given by Eqn 6-3

$$\sigma_t = \frac{M}{W} \tag{6-3}$$

where

$$W = \frac{ba^2}{6} \tag{6-4}$$

Eqns 6-1, 6-3 and 6-4 yield

$$\sigma_t = \frac{6Qc}{4ba^2} = \varepsilon E \tag{6-5}$$

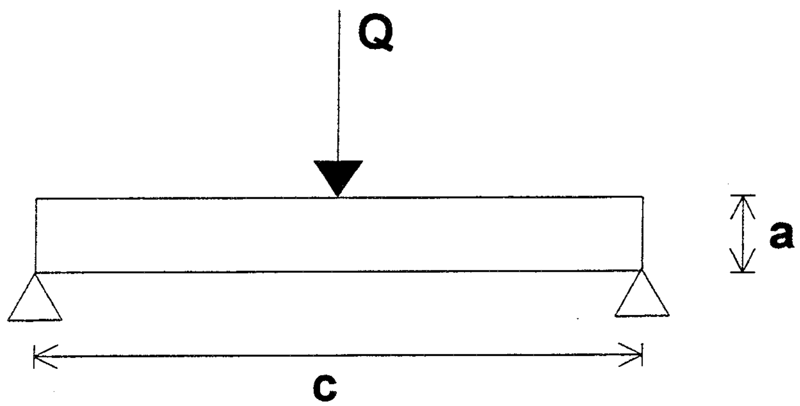
The maxim tensile strain can be calculated by combining Eqn. 6-4 and Eqn. 6-5

$$\varepsilon_f = \frac{a\omega 6}{c^2} \tag{6-6}$$

The tensile stress at failure, i.e. the tensile strength σ_{tf} is an indication of the sensitivity of the blocks to mechanical breakage during transport and handling. The results can also be used as an approximate value of the shear strength according to Eqn 6-7 but should be supplemented with uniaxial compression tests.

$$\tau_f = \frac{\sigma_{tf}}{2} \qquad (6\text{-}7)$$

Tests on samples of MX-80 and IBECO with different granulometry and with different water ratios were made. The results of the tests are summarized in Table 6-2. The stress/strain curves from some of the tests are shown in Fig 6-4.



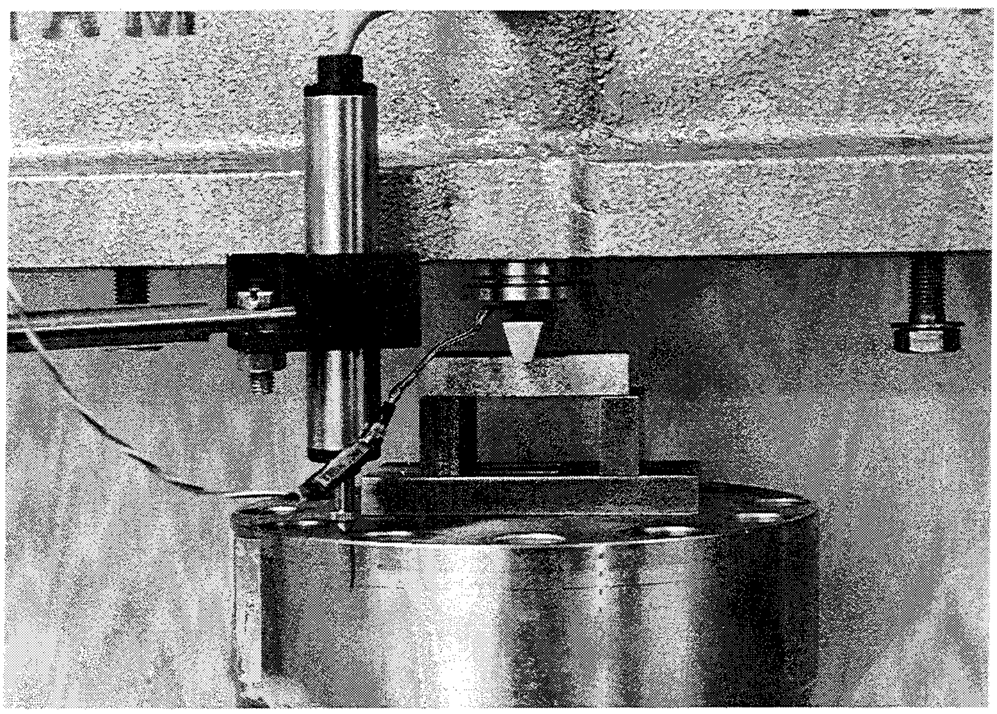


Figure 6-3. Test arrangement for determination of the tensile strength.

Table 6-2. Tensile strength of MX-80 and IBECO bentonite blocks, compacted at 100 MPa.

Bentonite type	w (%) Initial	Final	e	S_r %	σ_{tf} MPa	ε_f
MX-80	10	10	0.51	55	2.8	2.4
MX-80	18	17	0.60	79	1.9	0.7
MX-80	26	24	0.76	88	1.3	1.0
IBECO-Na	10	12	0.50	64	1.6	0.7
IBECO-Na	17	16	0.54	81	1.2	0.8
IBECO-Na	24	21	0.65	91	1.0	0.9
IBECO A	10	13	0.50	70	1.9	0.7
IBECO A	17	16	0.54	85	2.4	1.0
IBECO A	24	22	0.65	95	1.4	1.0
IBECO B	10	14	0.51	73	2.0	0.8
IBECO B	17	17	0.55	84	1.7	1.0
IBECO B	24	22	0.66	94	1.4	1.3
IBECO C	10	16	0.55	79	1.5	0.7
IBECO C	17	17	0.57	83	1.2	0.7
IBECO C	24	23	0.68	93	1.5	1.3

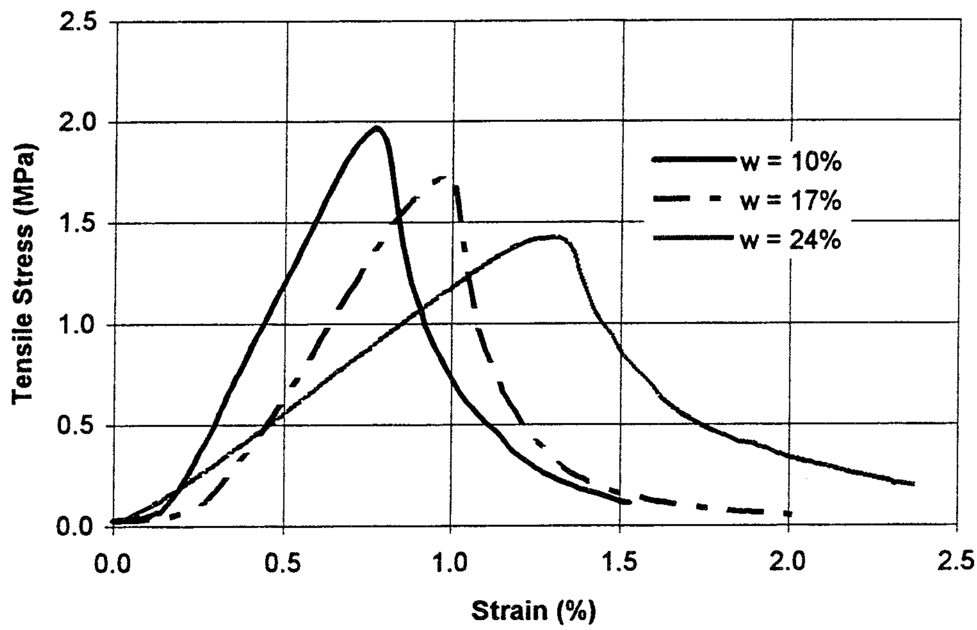


Figure 6-4. Example of stress/strain relations measured during the tensile strength tests on IBECO B.

σ_{tf} is a function of both the void ratio and the degree of saturation (see Fig 6-5 and Fig 6-6). The high strength of the sample with the low water ratio is probably a combined effect of the low void ratio and the low degree of saturation. The tests also indicate that the granulometry of the bentonites only gave small variation in tensile strength.

The strain at failure was generally very small. With one exception it was smaller than 1,5%. It was found that the strain at failure decreased with decreasing water ratio indicating to an increasing brittleness.

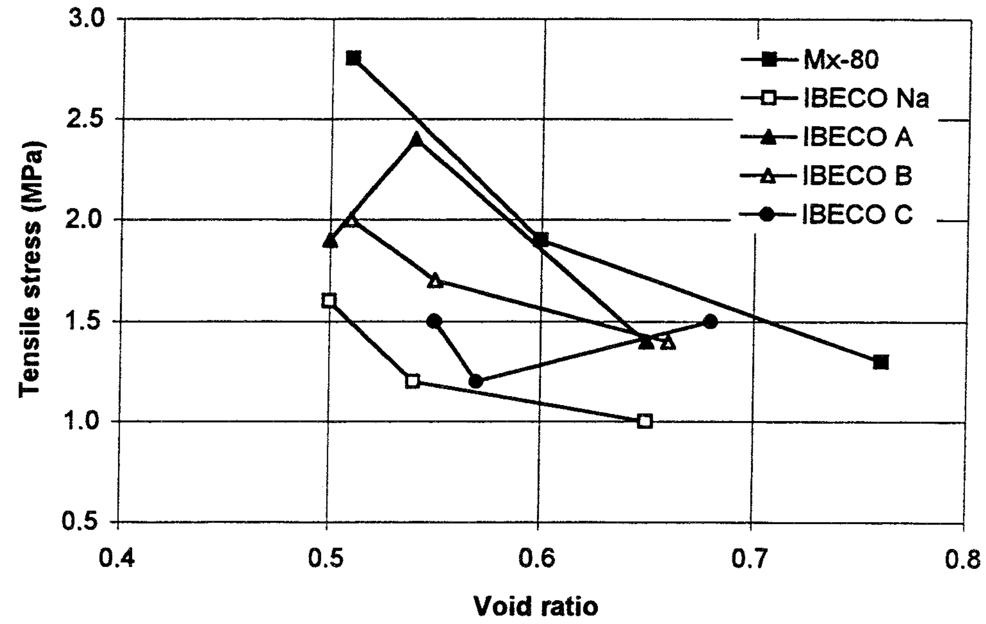


Figure 6-5. *Tensile stress at failure as a function of void ratio for different bentonites.*

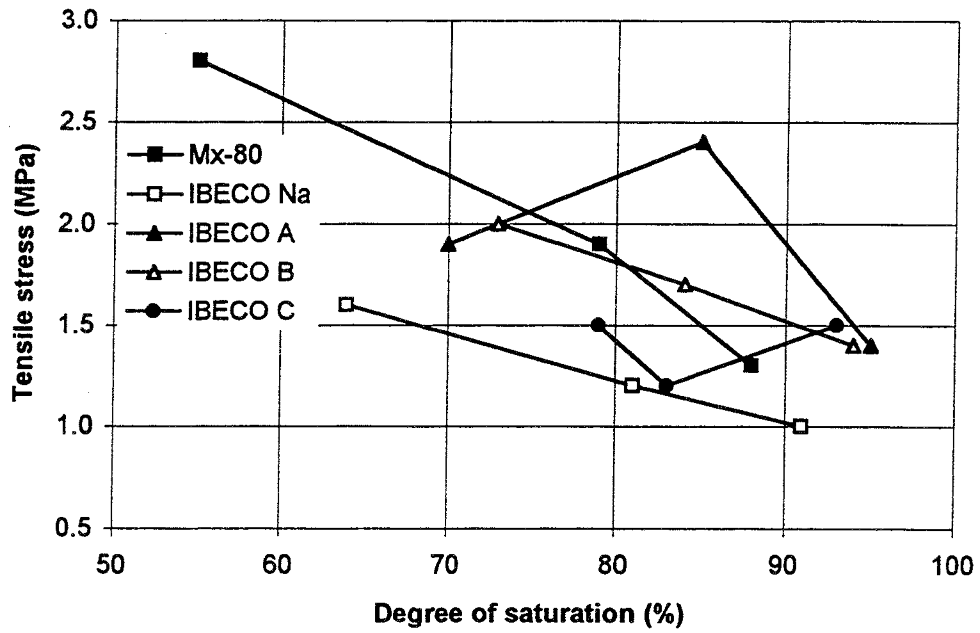


Figure 6-6. *Tensile stress at failure as a function of degree of saturation for different bentonites.*

6.3 BLOCK PROPERTIES AFTER WATER SATURATION

The present report deals with tests aimed at investigating the influence of the granule size distribution, while general tests for determination of the properties of water saturated bentonite are reported separately.

The swelling pressure and the hydraulic conductivity of the investigated bentonites are given in Table 6-3. In Fig 6-7 and Fig 6-8 the hydraulic conductivity and swelling pressure are plotted as a function of the density at saturation. The results show that the hydraulic conductivity and swelling pressure are in the same range for all the bentonites.

Table 6-3. Hydraulic conductivity and swelling pressure of some bentonites.

Type	Density (g/cm^3)	Hydr. cond. (m/s)	Swelling Press. (kPa)
IBECO-Na	1.96	3.6E-13	7300
IBECO A	1.98	1.2E-13	7700
IBECO-B	1.97	1.3E-13	6900
IBECO C	1.92	4.0E-13	4400
MX-80	1.97	2.0E-13	3500

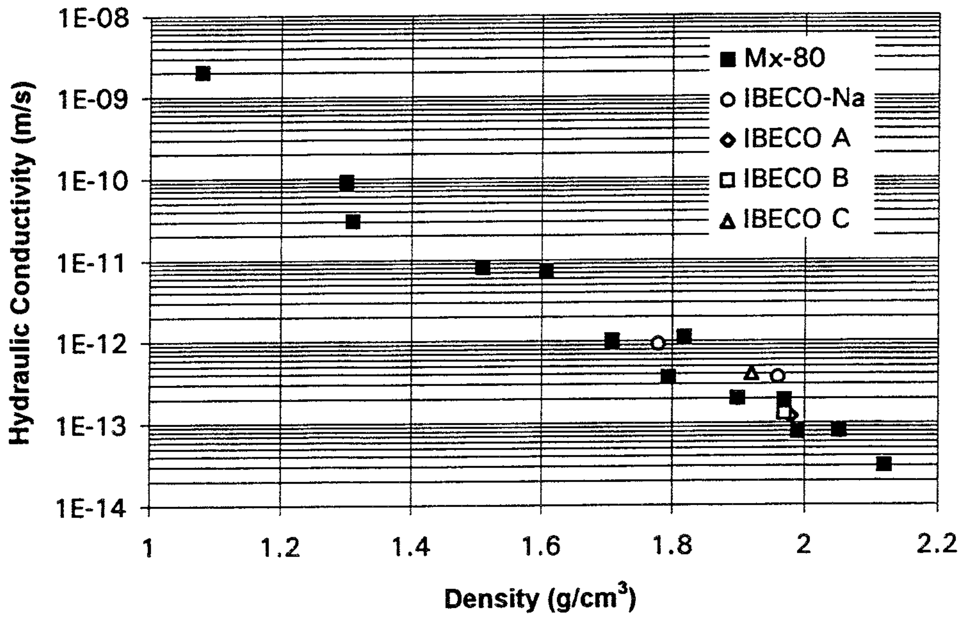


Figure 6-7. Hydraulic conductivity of the bentonites as a function of the density at saturation.

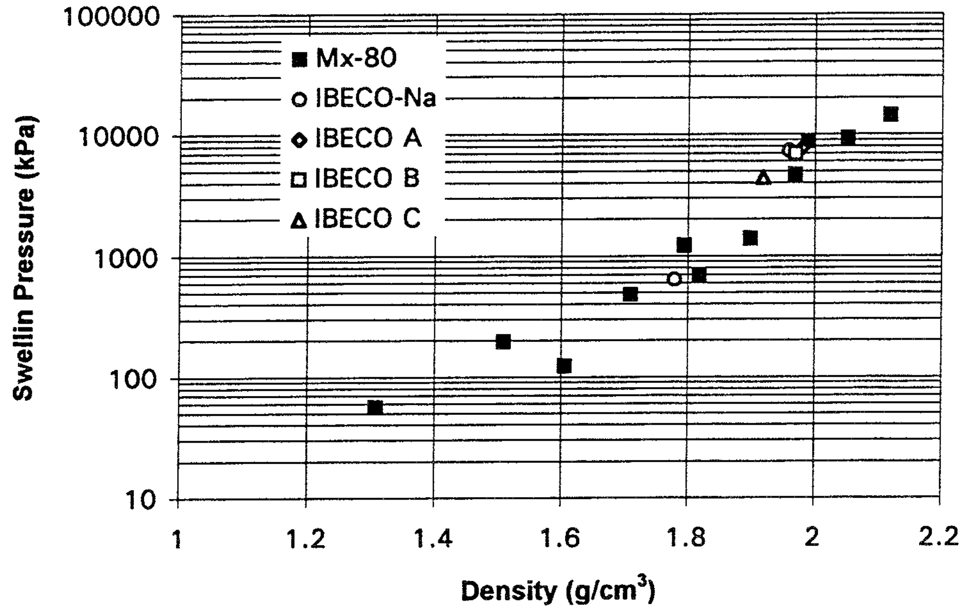


Figure 6-8. *Swelling pressure of the bentonites as a function of the density at saturation.*

7 CONCLUSIONS AND DISCUSSION

7.1 GENERAL

Experiments with compaction of brick blocks were carried out at Höganäs Bjuf AB. Although these tests were preceded by tests in the laboratory several additional problems with the quality of the blocks were noticed. They were mainly of two types, viz. damage appearing at the compaction and damage occurring during the storage of the compacted blocks. The first type of damage had the form of cracks in the blocks of the following four types:

1. Cracks due to the friction between the form and bentonite
2. Cracks because air being entrapped in the blocks at the compaction
3. Cracks due to elastic swelling during unloading and removal of the block from the form
4. Cracks due to brittle edges of the blocks

Other types of damage and problems were the following:

1. Damage due to sticking of the bentonite to the form and pistons.
2. Desiccation of the blocks during storage.
3. Appearance of mould on the blocks during storage.

The problems were discovered and solved during the process of developing and testing the most appropriate technique for industrial block production. This chapter will very briefly describe the optimum technique that yields blocks of good quality at the desired density and degree of saturation.

7.2 PROPOSED OPTIMUM TECHNIQUE

- In order to minimize the air entrapped in the blocks during compaction the following steps are proposed

    1. Use coarsely ground bentonite of the type IBECO C or similar
    2. Stepwise compaction
    3. Use fairly large gaps between the pistons and the form
    4. Make blocks with the height/diameter ratio no larger than 0.4

- In order to prevent damage of the blocks due to friction between the bentonite and the form, it should be lubricated with oil before the bentonite is poured into the form. The lubricating oil also prevents damages on the blocks due to sticking of bentonite to the form and pistons.

- In order to prevent damage of the block due to the expansion during removal of the block from the form, it should be compacted to a high degree of saturation. In the case when a compaction pressure of 100 MPa is used the water ratio of the bentonite should not be below 18%. The damage can also be prevented by making the form slightly conical.

- To prevent desiccation the blocks they must be wrapped in plastic sheeting after compaction. The plastic tested so far did not prevent the bentonite from desiccation. More tests are required for selecting a suitable type.

- To prevent moulding, the water ratio of the bentonite should not exceed 20%.

7.3 EXAMPLE OF A PRODUCTION PLANT AND A BLOCK COMPACTED WITH THE PROPOSED TECHNIQUE

The full scale tests of compacting brick blocks were carried out by Höganäs Bjuvf AB in Bjuv. The company produces refractory bricks and other refractory products. Within the factory there are facilities for storing and mixing large quantities of clay. The tests in this project were carried out in a machine for uniaxial compaction.

A block of IBECO C bentonite, compacted at Höganäs Bjuf AB with a compaction pressure 50 - 100 MPa, is shown in Fig 7-1. After compaction, the water ratio and density were determined on a number of specimens extracted from the blocks (see Fig 6-2). The results from the determination of the density and water ratio are shown in Table 7-1. The table also shows the calculated degree of saturation and void ratio. The block was totally free from defects immediately after compaction.

Table 7-1. Results from laboratory tests on a block of IBECO C.

No	w (%)	ρ (g/cm3)	S_r (%)	e
A	18.4	1.98	77.0	0.66
B	18.1	2.00	78.5	0.64
C	18.4	1.99	78.1	0.65
D	18.0	2.01	78.9	0.64
E	18.2	2.00	78.4	0.64
F	18.4	2.00	79.5	0.64
G	18.5	2.01	80.2	0.64
H	18.4	2.02	80.7	0.63
I	18.5	2.01	79.9	0.64
J	18.0	2.02	80.5	0.62
K	18.2	2.01	80.0	0.63
L	18.3	2.02	81.2	0.63
Mean	18.3	2.01	79.4	0.64

Figure 7-1. *Example of a block compacted at Höganäs Bjuf AB*

7.4 IMPROVEMENTS

After compaction of the blocks they must be transported and stored for some time before they are emplaced in the repository. To prevent desiccation during this time the blocks must be wrapped in water tight plastic sheeting. The tested plastic sheeting was not sufficiently tight to prevent desiccation of the bentonite and more tests have to be made for developing an appropriate package.

The blocks compacted with the coarsely ground bentonite IBECO C had a very high quality. After some time, however the edges of the blocks fell off while the rest of the blocks were still of high quality. This effect may be due to incompletely crushed granules during compaction. Hence the granules still operate as individual granules within the blocks and the adhesion between them is weak. In order to prevent this type of damage, a less coarsely ground bentonite can be used or the coarsely ground bentonite can be mixed with finely ground bentonite in order to increase the adhesion between the granules. To find the optimum mix for preventing damage of the blocks more tests have to be performed.

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[1] Department of Geology, Earth Sciences Centre, Göteborg University, Göteborg, Sweden
[2] Geological Survey of Sweden, Earth Sciences Centre, Göteborg, Sweden
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