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Äspö Hard Rock Laboratory

Laboratory tests on Friedland Clay

Friedland Clay as backfill material. Results of laboratory tests and swelling/compression calculations

Lars-Erik Johannesson

Lennart Börgesson

Clay Technology AB

April 2002

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel +46 8 459 84 00
Fax +46 8 661 57 19

Äspö Hard Rock
Laboratory

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Author
Johannesson, Börgesson
Date
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Date

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Christer Svemar
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Keywords: Clay, backfill, compressibility, swelling pressure, hydraulic conductivity

Abstract

In this report results from laboratory tests on Friedland clay, which is an alternative backfilling material for tunnels and shafts in the KBS-3 concept, are described. The following investigations and tests have been performed:

- Characterisation of the clay.
- Measurement of swelling pressure
- Measurement of hydraulic conductivity
- Measurement of compressibility

Calculations of the upwards swelling of the buffer and corresponding compression of the backfill in the KBS-3 concept with Friedland clay as backfill have also been made.

The tests showed that the swelling pressure varies between 50 kPa at the dry density 1233 kg/m^3 and ~550 kPa at the dry density 1573 kg/m^3. The hydraulic conductivity varies between $1.0 \cdot 10^{-11}$ m/s at the dry density 1452 kg/m^3 and $1.0 \cdot 10^{-12}$ m/s at the dry density 1765 kg/m^3. The compression properties of the clay is shown in Figure 1, with the void ratio as a function of the applied pressure, and can be described with the following equation:

$$e = A + B^{10}\log(\sigma)$$

where

A = 1,863

B = -0,371

e = void ratio

σ = effective stress (kPa)

The compression of the backfill (and thus also upwards swelling of the buffer) is depending on the assumption of the friction angle between the buffer and the wall of the deposition hole and on the initial density of the backfill. The compression was calculated to be between 0.2 m and 0.6 m for the densities achieved in the field tests in Äspö HRL. For the friction angle 10° (which is the short term friction angle of MX-80) the compression of the backfill was calculated to about 0.3 m.

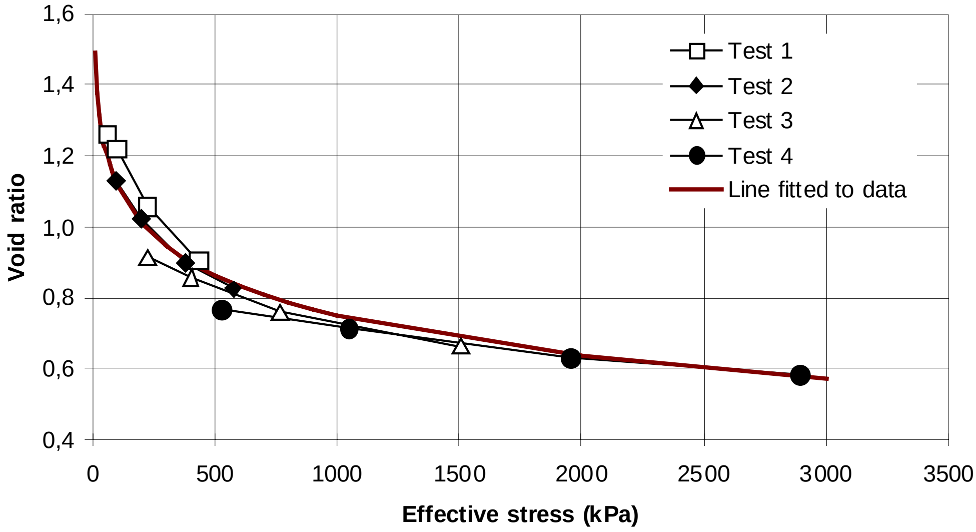


Figure 1 *Void ratio plotted as function of the vertical stress for the 4 tests performed on Friedland clay.*

Sammanfattning

I denna rapport redovisas resultat av laboratorietester på Friedland lera, som är ett alternativt fyllnadsmateral i tunnlar och schakt i KBS-3-konceptet. Resultat av följande undersökningar och tester redovisas:

- Karakterisering av leran
- Mätning av svälltryck
- Mätning av hydraulisk konduktivitet.
- Mätning av lerans kompressibilitet

Dessutom har beräkningar gjorts av buffertens uppsvällning och återfyllningens kompression i KBS-3-konceptet med tunnelfyllning av Friedland-lera.

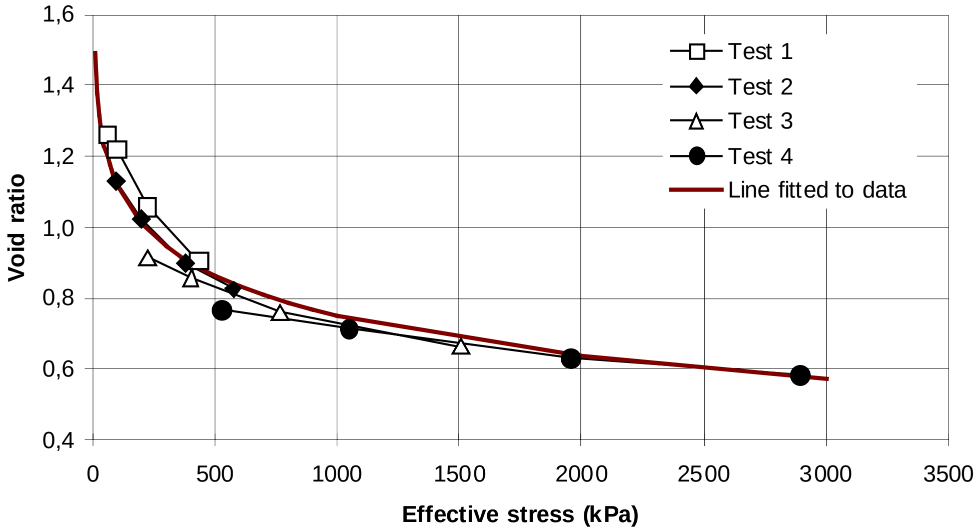
Försöken visade att svälltrycket varierar från 50 kPa vid en torrdensitet av 1233 kg/m^3 upp till ~550 kPa vid en torrdensitet av 1573 kg/m^3. Den hydrauliska kondukltiviteten varierar mellan $1.0 \cdot 10^{-11}$ m/s vid en torrdensitet av 1452 kg/m^3 och $1.0 \cdot 10^{-12}$ m/s vid en torrdensitet av 1765 kg/m^3. Komressionen hos leran visas i Figur 1, med portalet som funktion av pålagt tryck, och kan beskrivas med följande ekvation:

$$e = A + B \cdot {}^{10}\log(\sigma)$$

där

A	=	1.863
B	=	-0.371
e	=	portal
σ	=	effektivspänning (kPa)

Kompressionen av fyllningen (och uppsvällningen av bufferten) beror av antagen friktionsvinkel mellan bufferten och deponeringshålets vägg och av den initiella densiteten på fyllningen. Kompressionen av fyllningen beräknades till mellan 0.2 m och 0.6 m för de densiteter som uppnåddes i fältförsök i Äspö HRL. För antagen friktionsvinkel på 10° (vilket är friktionsvinkeln för MX-80) blev den beräknade kompressionen av fyllningen ca 0.3 m.



Figur 1 *Portalet uppritad som funktion av vertikala spänningen för 4 utförda försök på Friedland lera.*

Contents

1 Introduction

According to the KBS-3 concept the tunnels in the repository will be filled with backfill material. Several different mixtures of bentonite and crushed rock as backfill material have been tested both in the laboratory and in field tests. As alternative, a natural clay can be used. In this report Friedland clay is tested as an alternative backfilling material. Previous performed tests on Friedland clay have shown that the clay has low hydraulic conductivity and fairly high swelling pressure both at high salt content of the pore water and at low densities /1-1/. Field tests have however shown that it is difficult to reach high density of the clay at field compaction. An initial low density of the backfill might end up with a large compression of the backfill close to the deposition holes due to the swelling and subsequent decease in density of the bentonite buffer around the canister. It is therefore important to investigate the compressibility of the Frieldland clay in order to be able to calculate the expected deformation of the backfill around the deposition holes. This report deals with laboratory investigation on Friedland clay. The following tests have been performed on the clay:

- Characterisation of the clay.
- Measurement of swelling pressure
- Measurement of hydraulic conductivity
- Stepwise compression tests

2 Characterisation of the clay

Characterization of the clay was made partly according to a program described in a report with the title *Acceptance control of bentonite material* /2-1/. The characterization involved determination of following "parameters"; water ratio, normalized free swelling and liquid limit. In Table 2-1 the parameters are listed together with corresponding parameters determined on MX-80.

The initial water content defined as the weight of the water in the sample divided with the weight of the solid particles varied between 6-7%.

For determination of the normalized free swelling, 1.1 g clay was carefully poured in a measuring glass filled with 100 ml de-ionized water. After 24 hours the volume of the clay gel was determined and normalized with respect to the weight of solid particles. The expected value for MX-80 is about 15-20 ml. The free swelling volume of the Friedland clay was significantly lower (see Table 2-1).

The definition of the liquid limit (w_L) of a soil is the water content where the soil transforms from plastic to liquid state. This parameter is for a bentonite correlated to parameters as swelling pressure and hydraulic conductivity. The liquid limit was determined with the fall-cone method. The method is described by the Swedish Geotechnical Society (SGF) /2-2/. The expected liquid limit for MX-80 is 450-500 %. The liquid limit for the Friedland clay is significantly lower (Table 2-1).

Table 2-1. Parameters determined on the Friedland clay together with the corresponding parameters for MX-80.

	Water ratio (%)	Free swelling (%)	Liquid limit (%)	Notes
MX 80	8,9	17,4	457,1	Tests performed 01-10-01
Friedland	6,3	6,3	126,6	

3 Preparation of the samples and measurement of swelling pressure

Four samples were compacted with their natural water content to different densities (1770, 1860, 1960 and 2060 kg/m^3 after water saturation). The clay was compacted into oedometer rings to samples with the height 20 mm. A piston was placed on top of each sample. The samples were then allowed to have access to water in both ends for about 50 days. The water added to the samples had a salinity of 3.5 % (a mixture of 50/50 $NaCl/CaCl_2$). During saturation the swelling pressure was measured with a load cell placed on top of the piston. The results are shown in Figure 3-1. In Figure 3-2 the swelling pressure is plotted as function of the density of the sample (the density is back calculated from the measured density after finished test).

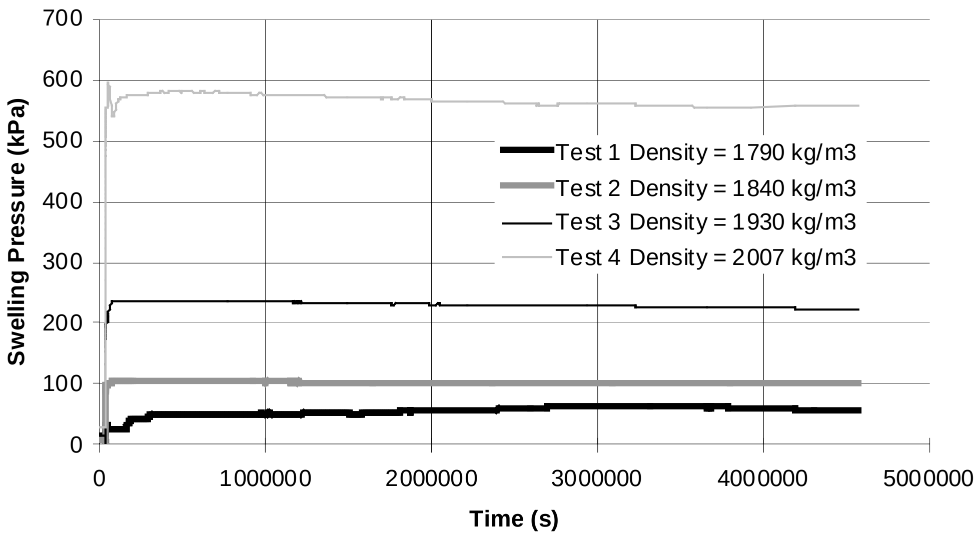


Figure 3-1 *Developed swelling pressure as function of time for the compacted samples with different densities at saturation.*

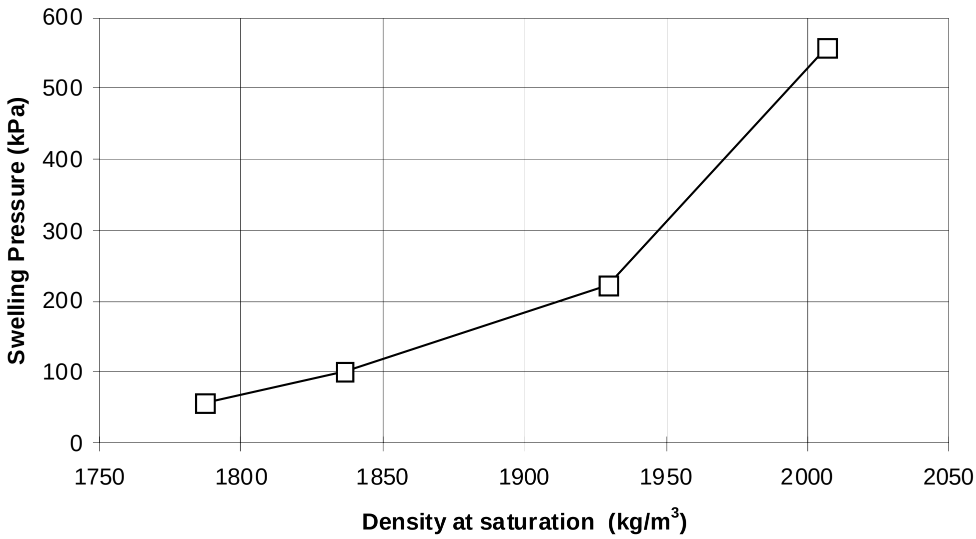


Figure 3-2 *Swelling pressure as function of the density at saturation.*

4 Oedometer tests

After completed saturation, the samples were placed in a load frame. Vertical loads were applied in steps. Vertical displacement and load were measured continuously. An example from the measurements is shown in Figure 4-1. Data from all the load steps are listed in APPENDIX I. The density and void ratio were back calculated for each load step. The calculated densities and void ratios are listed in Table 4-1. The void ratio at each load step as function of the vertical stress is plotted in Figure 4-2.

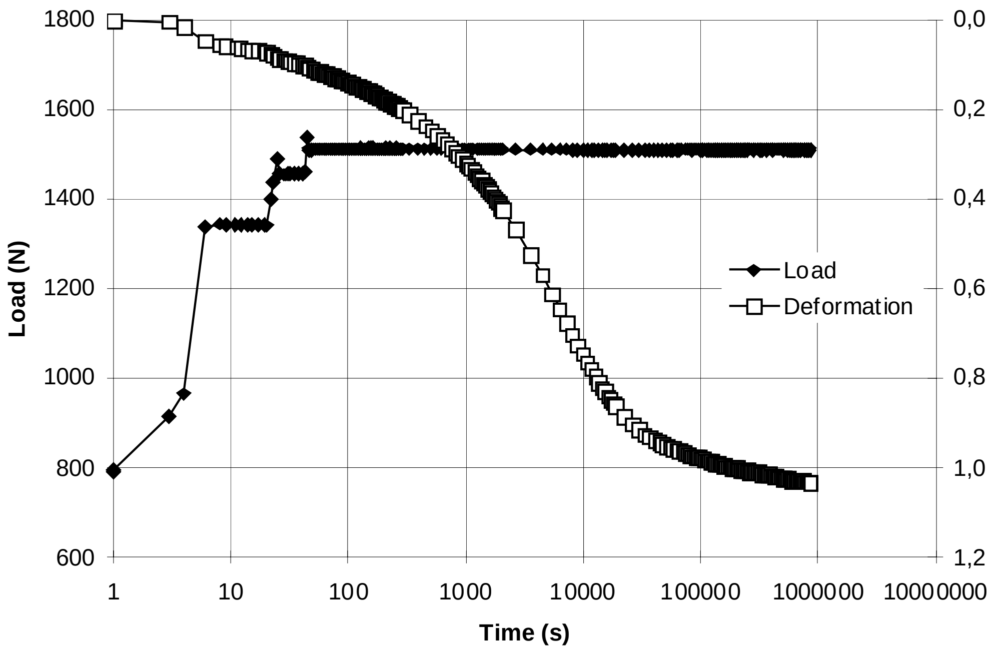


Figure 4-1 *Deformation and load as function of time for Test 3, load step 2.*

Table 4-1. Vertical pressure, density and void ratio for the 4 tests performed on Friedland clay at different load steps.

	Test 1			Test 2			Test 3			Test 4		
	Pressure (kPa)	Density (kg/m^3)	e	Pressure (kPa)	Density (kg/m^3)	e	Pressure (kPa)	Density (kg/m^3)	e	Pressure (kPa)	Density (kg/m^3)	e
Initial conditions	59	1787	1,26	100	1836	1,13	227	1930	0,91	528	2007	0,77
After load step I	100	1801	1,22	202	1879	1,02	403	1959	0,86	1046	2039	0,71
After load step 2	224	1865	1,06	386	1938	0,90	769	2012	0,76	1964	2090	0,63
After load step 3	425	1933	0,91	570	1975	0,83	1503	2070	0,66	2882	2124	0,58

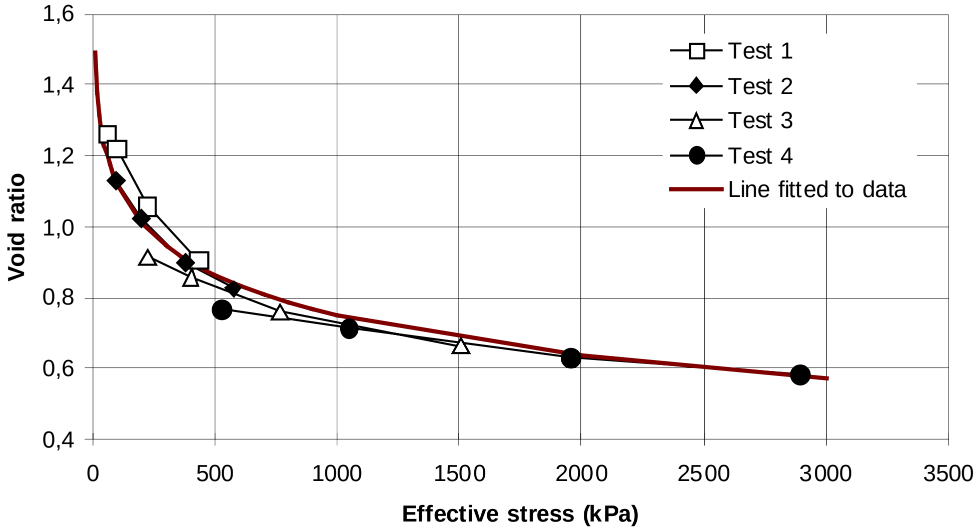


Figure 4-2 *Void ratio plotted as function of the vertical stress for the 4 tests performed on Friedland clay.*

5 Hydraulic conductivity

The hydraulic conductivity was also determined on the four samples after the consolidation of the last load step. The hydraulic conductivity for the samples was calculated in two ways:

- By applying a hydraulic gradient over the sample, measure both the inflow and the outflow from the sample and calculate the hydraulic conductivity with Equation 5-1.

$$k = \frac{q}{A \times i} \qquad (5\text{-}1)$$

where

k	=	hydraulic conductivity
q	=	water inflow/outflow per sec
i	=	hydraulic gradient
A	=	sample area

- The hydraulic conductivity can also be determined from the deformation/time relation at each load step with the following Equation 5-2 (oedometer technique):

$$k = \frac{T_v \times h^2 \times g \times \rho_w}{M \times t} \qquad (5\text{-}2)$$

where

k	=	hydraulic conductivity
T_v	=	time factor (in this case = 0,848)
h	=	half the height of the sample
M	=	Compression modulus
g	=	gravity acceleration (= 9,8 m/s^2)
ρ_w	=	density of pore water (normally = 1000kg/m^3)
t	=	time at 90% consolidation

In Figure 5-1 the hydraulic conductivity calculated with these two methods is plotted as function of the density of the samples.

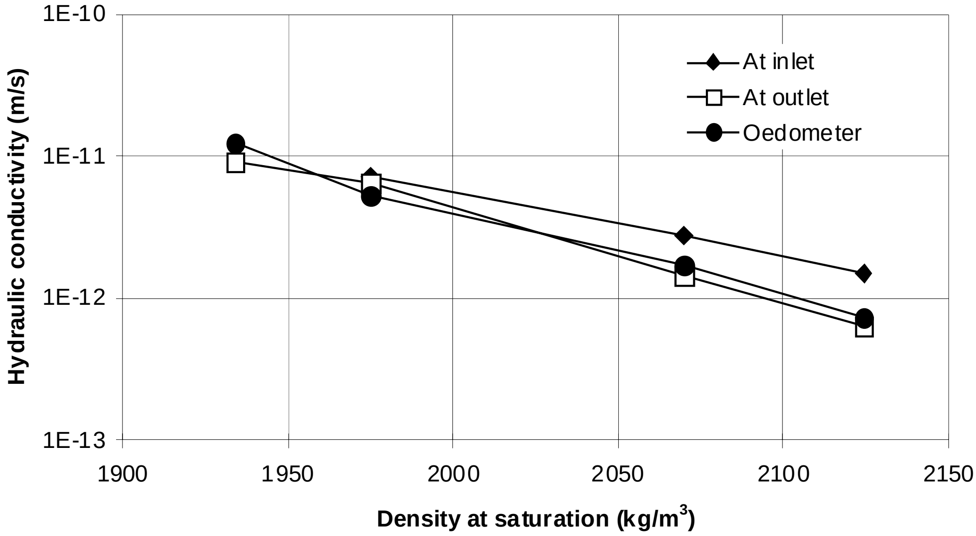


Figure 5-1. *Hydraulic conductivity of the Friedland clay plotted as function of the density at saturation.*

6 Calculation of compression of the backfill

In Figure 4-2 is a line fitted to the data observed from the oedometer tests. The line has the following equation:

$$e = A + B\log_{10}(\sigma) \qquad (6\text{-}1)$$

where

A = 1,863

B = -0,371

e = void ratio of the sample

σ = the effective stress on the sample (kPa)

A simplified calculation of the compression of the backfill above a deposition hole due to the swelling of the buffer in a KBS-3 tunnel can be made (see /6-1/ about the theory). The compression of the backfill material is depending on the following factors:

1. The initial density (or void ratio) of the backfill. In this case the initial void ratio of the backfill is assumed to be 0.9 (See chapter 7).
2. Deformation properties of the backfilling (Eqn. 6-1).
3. The friction between the buffer and the rock surface in the deposition hole
4. The void ratio and the resulting swelling pressure of the buffer.
5. The stress distribution in the backfill material due to the swelling pressure of the buffer.

The following assumptions are made:

- There is no friction between the backfill material and the rock in the deposition hole
- The void ratio of the buffer is a function of the swelling pressure according to Eqn. 6-2 (see /6-2/):

$$e = e_0 \times \left[\frac{p}{p_0}\right]^{\beta} \qquad (6\text{-}2)$$

where

e_0 = void ratio at the reference pressure p_0

e = void ratio at the pressure p

p_0 = reference pressure (= 1000 kPa)

β = pressure exponent (=-0,19)

- The reduced swelling pressure on the buffer/backfill interface due to the friction between the buffer and the rock (see Figure 6-2) can be calculated according to Eqn. 6-3 (see /6-1/):

$$P_{sa} = P_{sb} \times e^{-\left(\frac{2z\tan(\phi)}{r}\right)} \qquad (6\text{-}3)$$

where

P_{sa} = swelling pressure in the section between the buffer and the backfill.

P_{sb} = initial swelling pressure of the buffer

r = radius of the deposition hole (= 0,875 m)

ϕ = friction angle between the buffer and the rocks surface of the deposition hole

z = vertical distance from the buffer/backfill interface

- The bentonite buffer above the canister is so thick that the buffer around the canister is not involved in the swelling (≥2 m)
- The vertical stresses on the backfill above the buffer (in the deposition hole) is constant.
- The vertical stresses in the backfill above the deposition hole (in the tunnel) is calculated according to the theory by Boussinesque:

$$\Delta\sigma = q \times \left[1 - \left(\frac{1}{1 + (r/z)^2}\right)^{3/2}\right] \qquad (6\text{-}4)$$

where

$\Delta\sigma$ = vertical stress in the backfill due to the swelling pressure of the buffer

q = swelling pressure of the buffer

r = radius of the deposition hole (= 1,75 m)

z = distance from tunnel floor to the position were the stress is calculated

With these equations the maximum deformation (compression) of the back fill can be calculated in the following steps :

A. The backfill above the buffer is divided in layers with defined thickness. The vertical stress at the centre of each layer from the swelling pressure of the buffer is calculated with Eqn. 6-4. Knowing this increase in stress the change in void ratio can be calculated with Eqn. 6-1 (for the centre of each layer). By assuming that the change in void ratio at the centre of the layers is valid for the layer the total compression can be calculated as the sum of the compression of all the layers. The calculation of the compression as function of the swelling pressure at the buffer/backfill interface is plotted in Figure 6-1 (black curve) assuming that the initial void ratio of the backfill is 0,9, which was measured in field compaction tests (see chapter 7)

B. Knowing the friction anglebetween the buffer and the wall of the deposition hole the pressure P_{sa} (see Figure 6-2) can be calculated with Eqn. 6-3. (P_{sb} is assumed to be 7000 kPa). The change in swelling pressure from Psb to Psa causes changing in void ratio of the buffer which can be calculated with Eqn. 6-2. With the known volume of the zone where the swelling occur and the average change in void ratio the swelling of the buffer can be calculated. The swelling as function of P_{sa} at different friction angles between the buffer and the wall of the deposition hole are plotted in Figure 6-1.

C. In Figure 6-1 the final compression of the backfill can be evaluated at inter section between the deformation curve of the backfill and the swelling curve of the buffer material. The results of the calculations are also summarized in Table 6-1.

Table 6-1. Results from calculations of compression at different assumptions of the friction between the buffer and the wall of the deposition hole.

Friction angle (°)	Swelling Pressure P_{sa} (kPa)	Displacement (m)	Depth of the zone involved in the swelling (m)
0	4600	0,581	7,000
10	2340	0,315	2,719
20	1875	0,225	1,583
30	1660	0,171	1,091

The friction angle of the buffer material is a function of the void ratio /6-2/. At the actual void ratio the friction angle is about 10°, which yields that displacement of the buffer/backfill interface will be about 0,3 m. This also means that the buffer above the canister needs to be 2,7 m thick instead of 1,5 m (present concept) if the swelling is not allowed to involve the buffer around the canister.

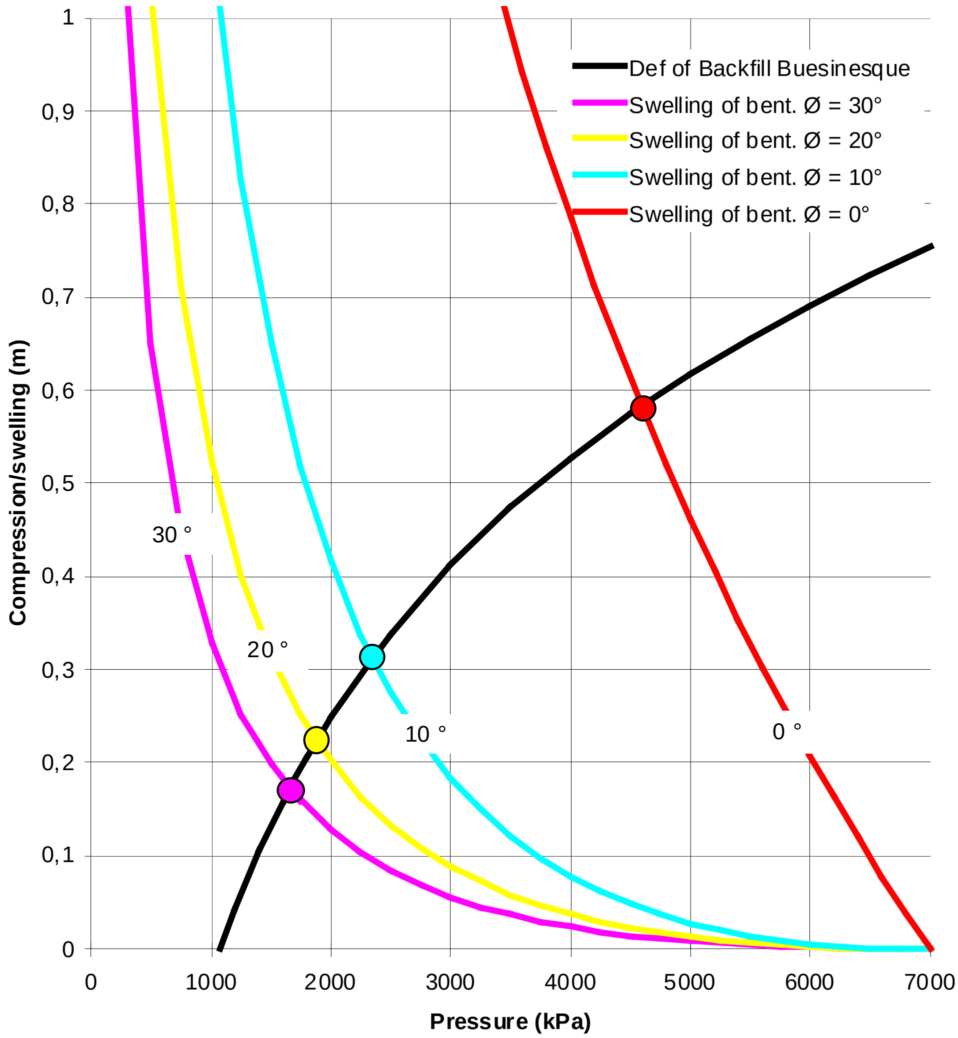


Figure 6-1. *The displacement of the interface between the compacted bentonite and the overlaying backfill. The calculations are made at different angles of friction between the buffer and the surface of the deposition hole.*

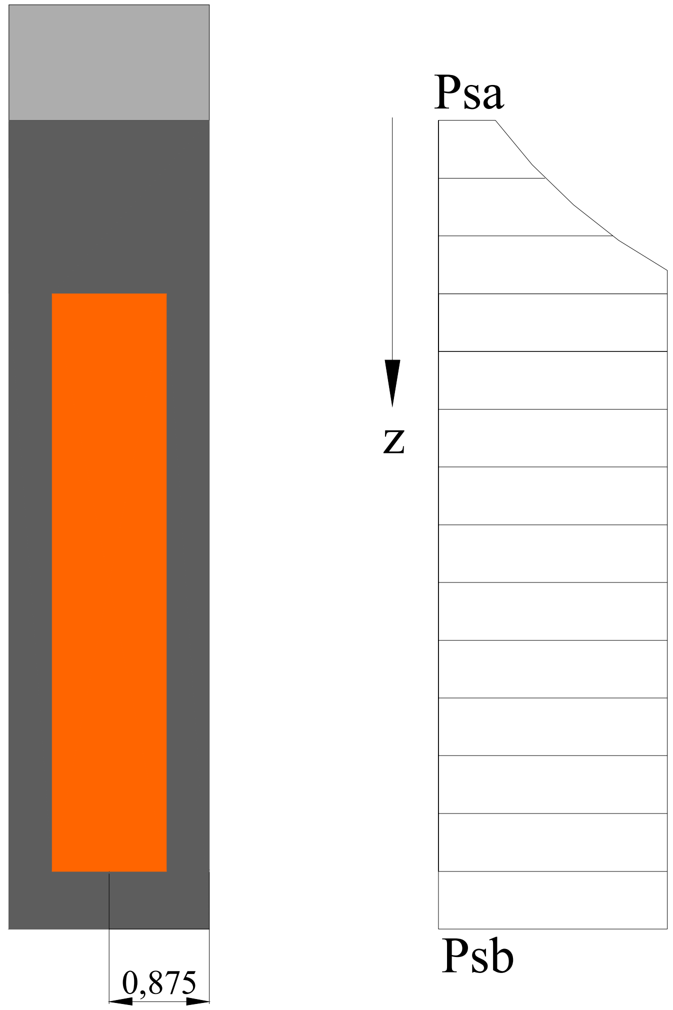


__Figure 6-2.__ A schematic drawing of the stresses in the buffer according to Eqn 6-3.

7 Comments and conclusions

In Figures 7-1 and 7-2 the results from previous preformed tests on Friedland clay are plotted. The tests are described in /1-1/.The preformed tests were made with different salinity of the water added to the samples. The measured swelling pressure in those tests are very similar to the new results presented previous in this report (c.f. Figure 3-2).The hydraulic conductivity measured in those old tests is however about one order of magnitude higher than the new measurements (valid for the range in density between 1930-2000 kg/m^3). Plausible explanations for the differences in hydraulic conductivity between the tests are the following:

- The free swelling capacity and the liquid limit for the Friedland clay delivered for the previous tests were 3.1 mm and 85 % respectively. These parameters are much lower than those determined on the clay used for the new tests (6.3 mm and 127% respectively), which indicates a difference in mineralogy between the clays. This may affect the hydraulic conductivity.

- The new tests were performed on samples which were loaded in steps after saturation up to the density where the hydraulic conductivity was determined. The previous performed tests were made on samples which were compacted to a certain density, then saturated and tested in respect of hydraulic conductivity. (Different stress history between the samples).

- The grain size distribution is different between the two clays. The clay used for the new tests had a much finer grain size distribution.

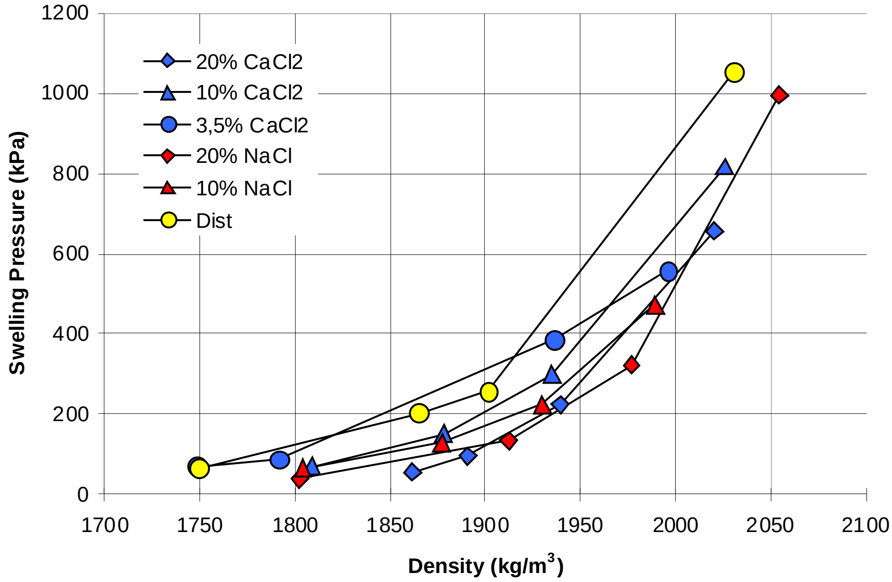


Figure 7-1. *The swelling pressure for the Friedland clay plotted as function of the density at saturation and the salinity of the pore water (previous preformed tests /7-1/).*

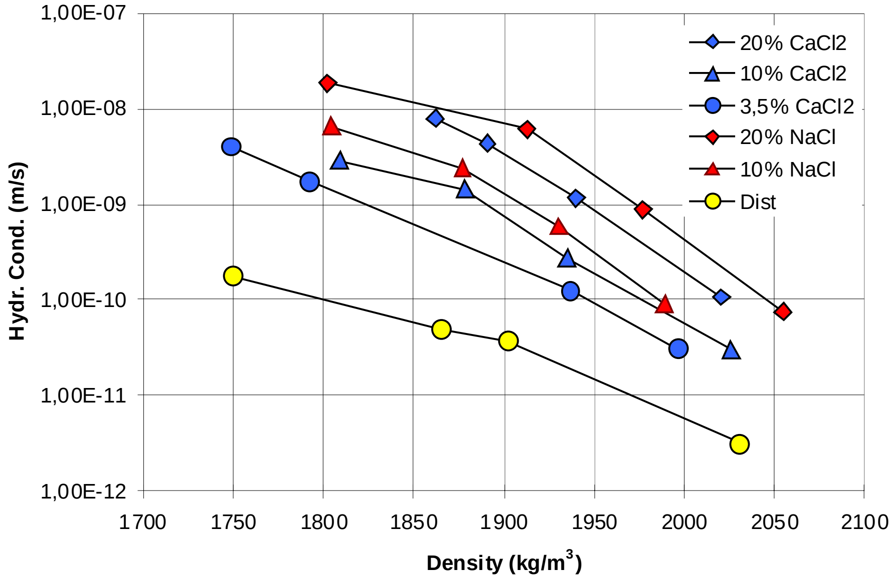


Figure 7-2. *The hydraulic conductivity for the Friedland clay plotted as function of the density at saturation and the salinity of the pore water (previous preformed tests /7-1/).*

Field compaction tests have also been made on the Friedland clay. The tests are described in detail in /7-1/. The compaction was made at Äspö in inclined layers (35°) with thickness of about 20 cm (after compaction). The compaction equipment used for the tests are described in /7-2/. The tests were made with the clay at two different water ratios, 5.1-7.6, and 12.5-13.2 respectively. The average densities for the two water ratios are shown in the table below.

Table 7-1. The average dry density of the filling compacted in field.

Depth (cm)	Average dry density (kg/m^3)	Water ratio (%)
5	1380-1420	5.1-7.6
10	1350-1390	5.1-7.6
20	1440-1460	5.1-7.6
10	1230-1250	12.6-13.2
15-20	1320-1390	12.5-13.2

The table indicates that it might be possible to reach a density at compaction in field of about 1400 kg/m^3 (dry density corresponding to a void ratio of about 0.9).This value was used in the calculations of the settlement shown in Section 6 of this report.

References

/1-1/ **Pusch R, 2001.** Experimental study of the effect of high porewater salinity on the physical properties of a natural smectitic clay. SKB Technical Report TR-01-07.

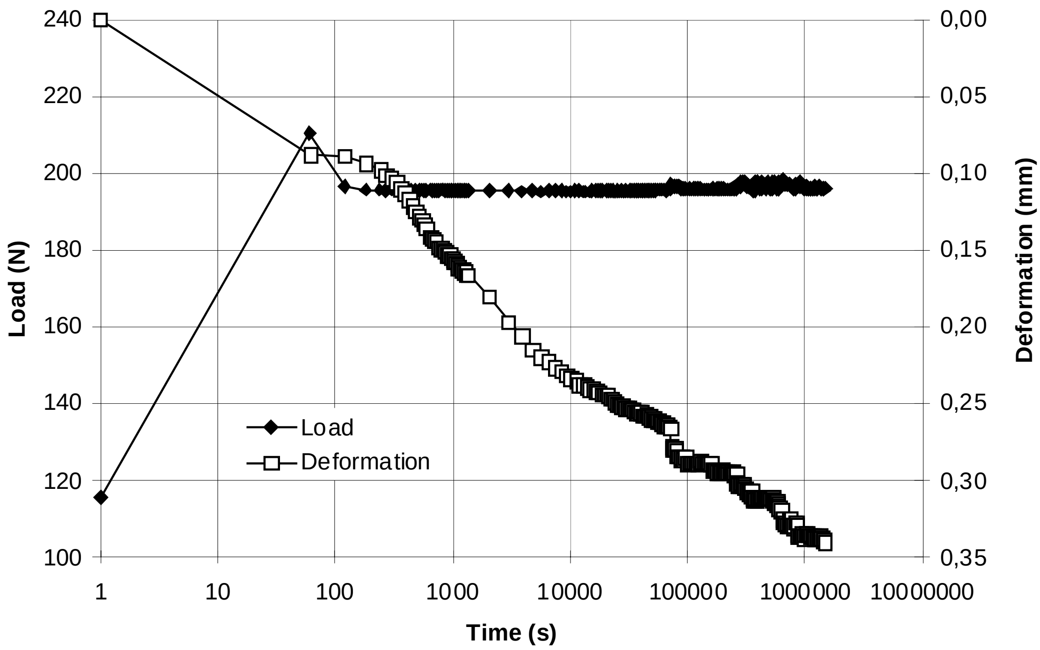
/2-1/ **Karnland O, 1999**. Acceptance control of bentonite material.
SKB QP TD S63-99-0064

/6-1/ **Börgesson L, 1982.** Prediction of the behaviour of the bentonite-based buffer materials. SKBF/KBS Stripa Project 82-08.

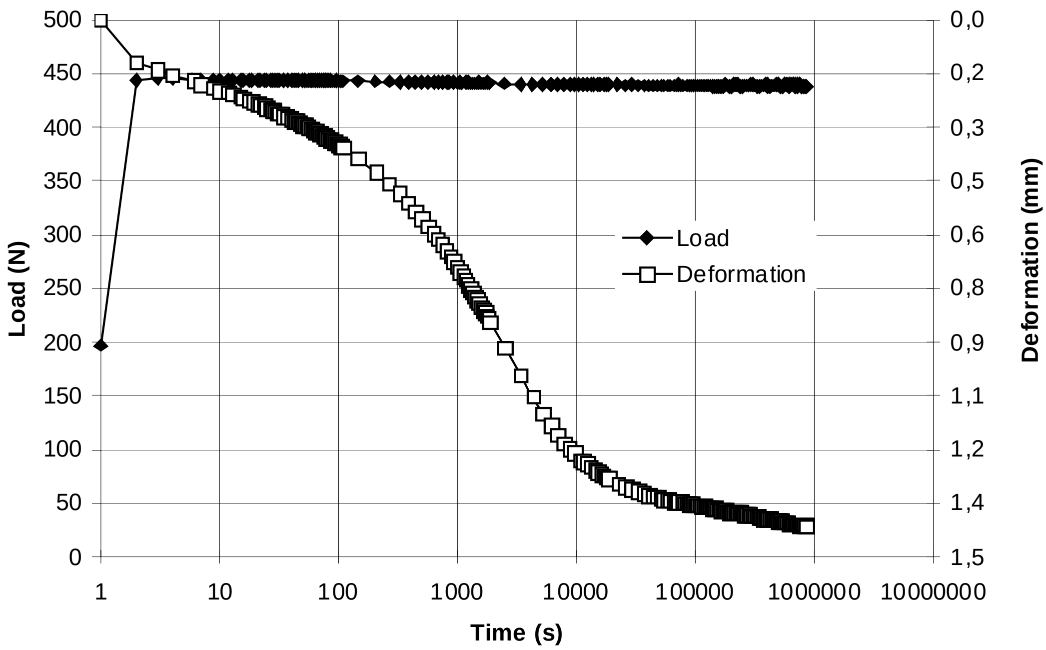
/6-2/ **Börgesson L, Johannesson L-E, Sandén T, Hernelind J, 1995.** Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element application. SKB Technical Report 95-20.

/7-1/ **Puch R, Gunnarsson D, 2001.** Field compaction test of Friedland clay at Äspö HRL. SKB International Progress Report IPR-01-36.

/7-2/ **Gunnarsson D, Börgesson L, Hökmark H, Johannesson L-E, Sandén T, 2001.** Report on the installation of the Backfill an Plug Test. Äspö Hrad Rock Laboratory. SKB International Progress Report IPR-01-17.



Test 1. Load step 1



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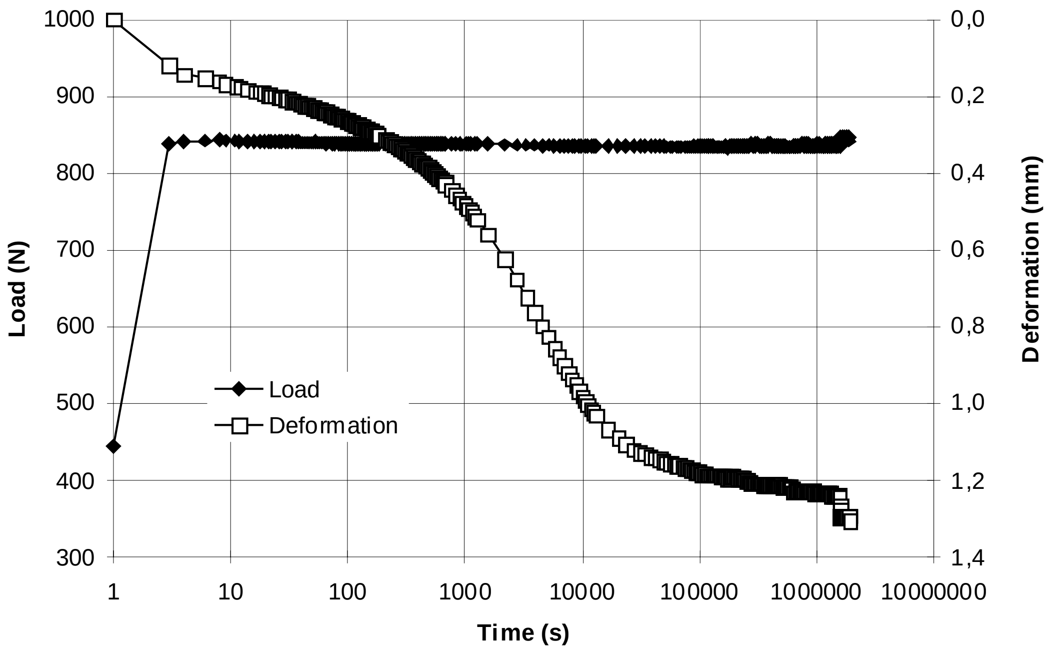

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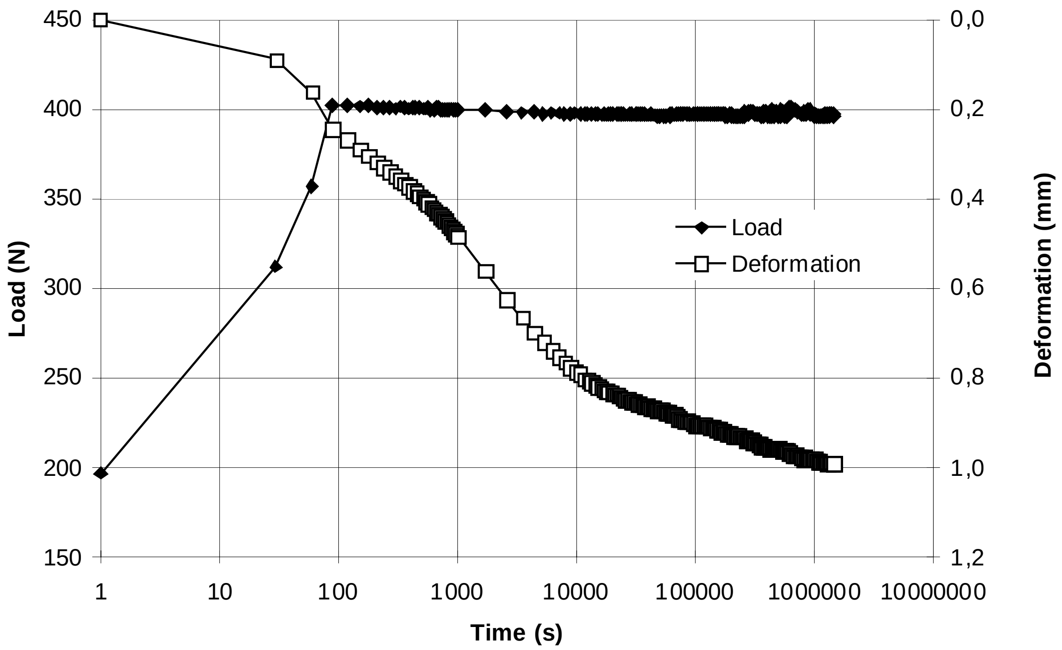

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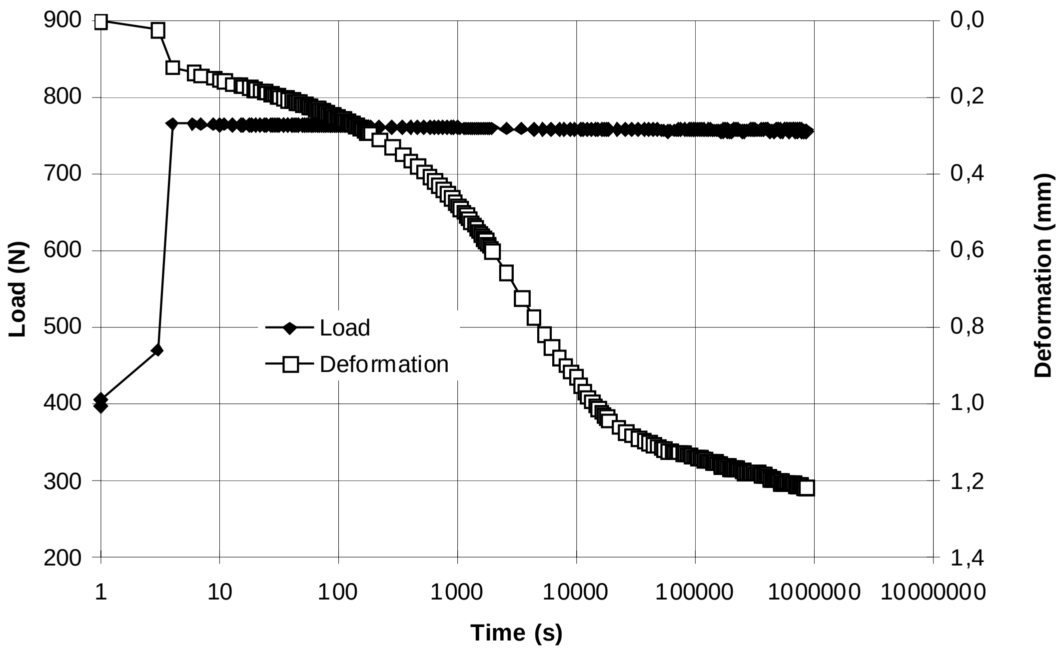

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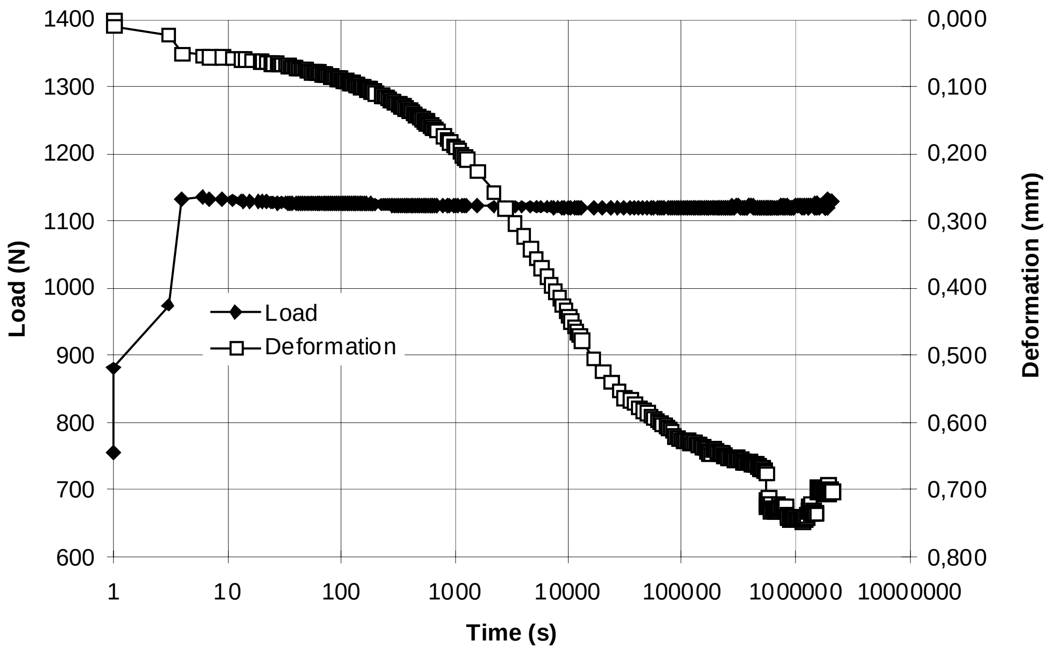

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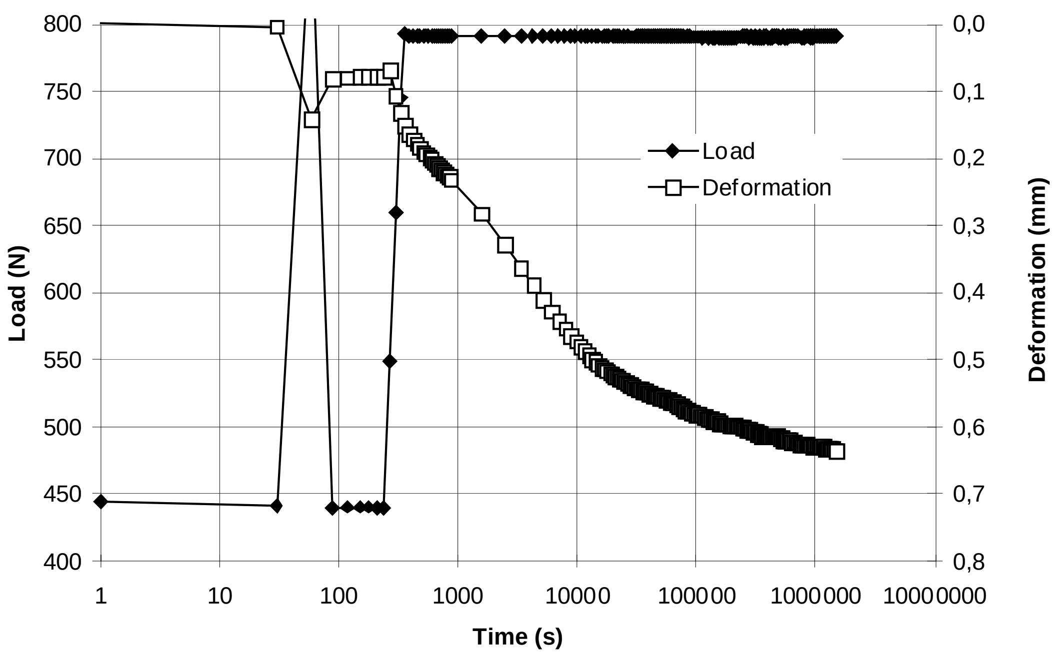

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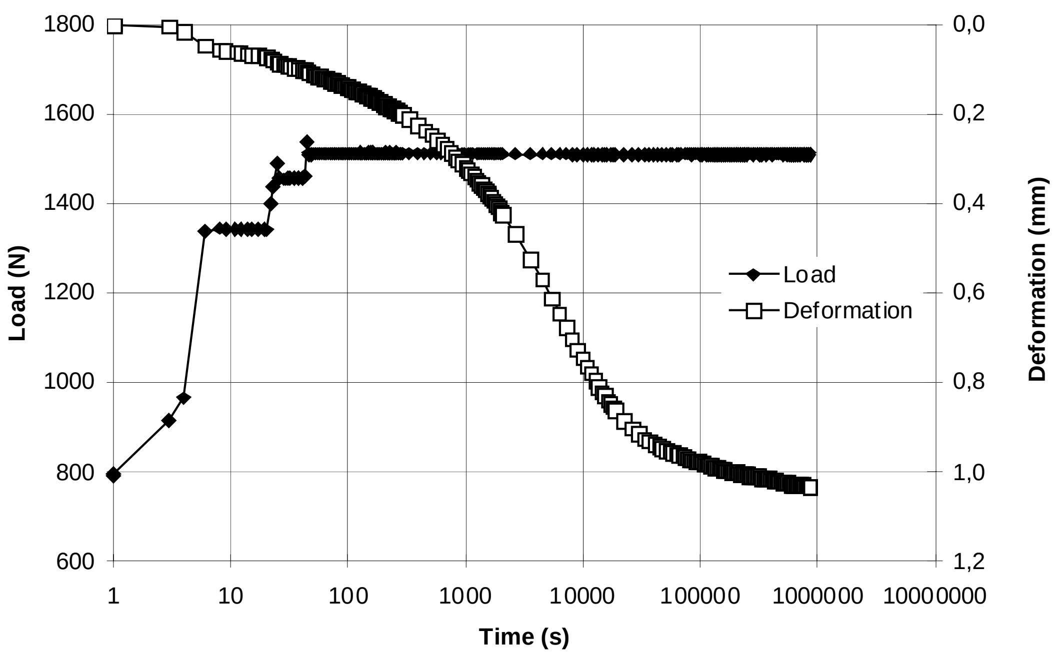

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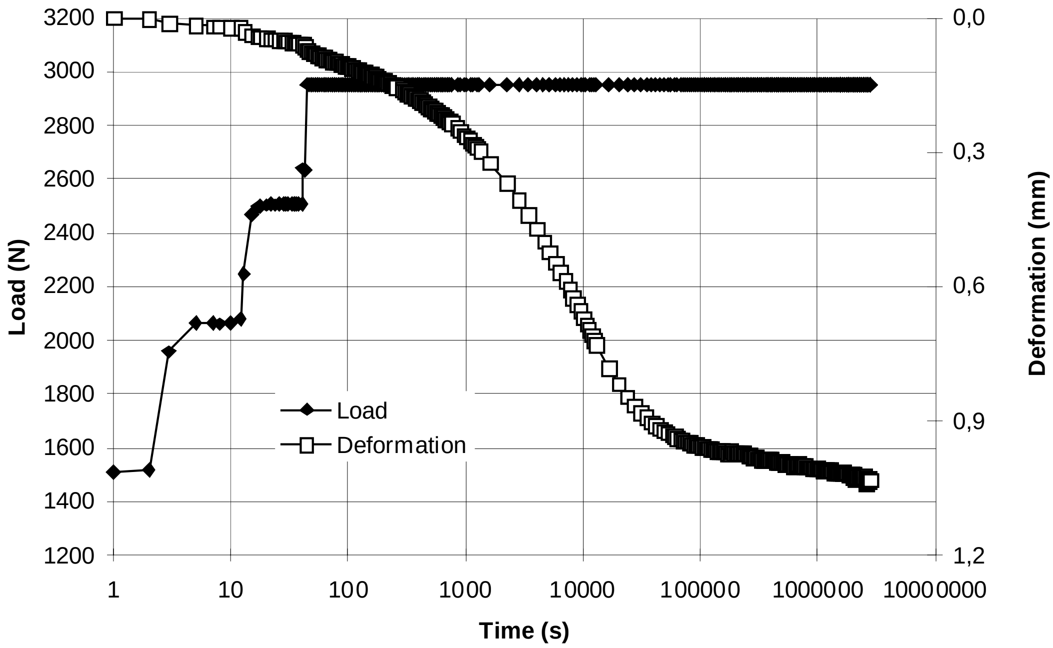

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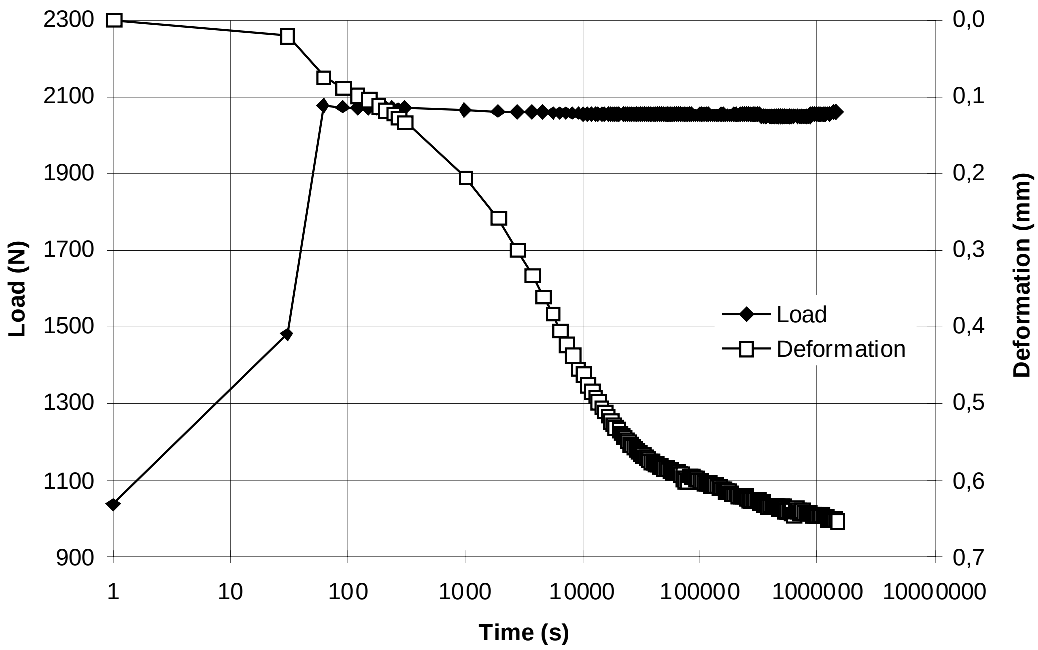

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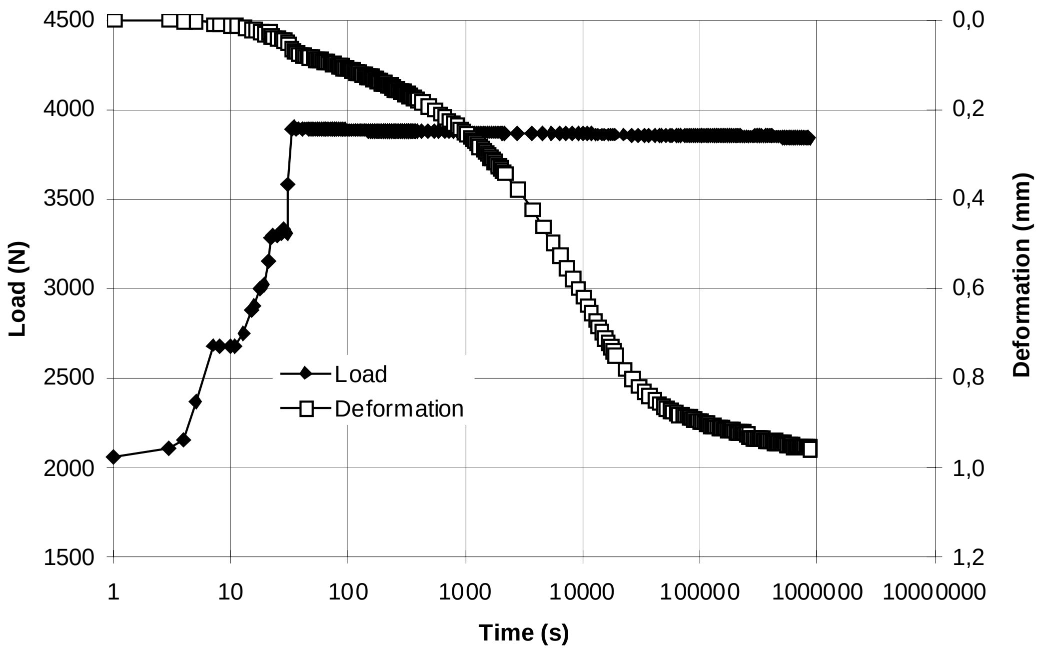

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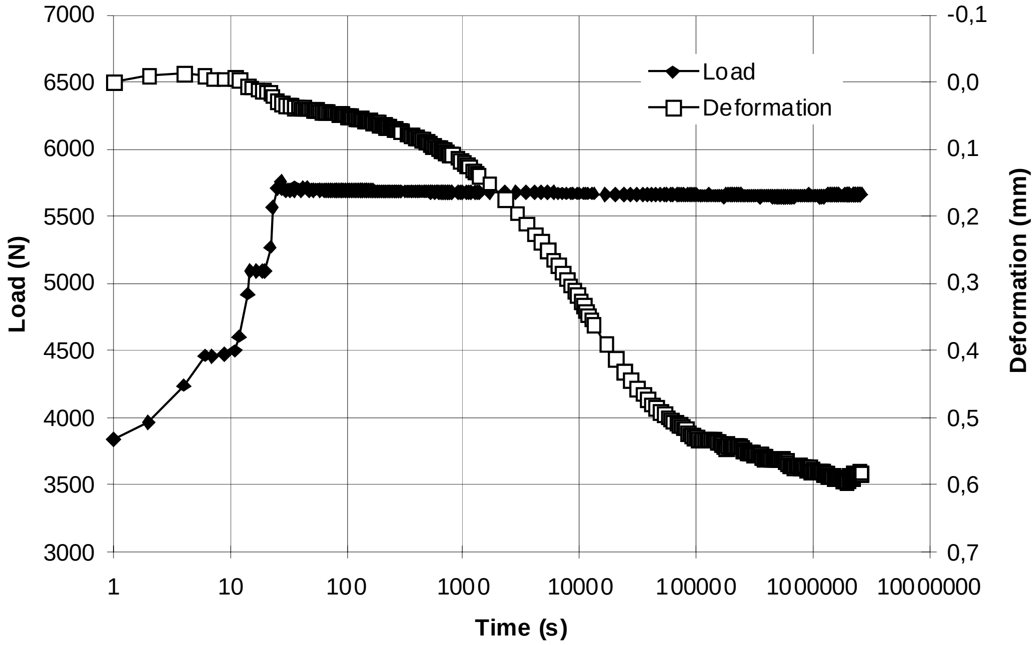

Test 4. Load step 3