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Experiments on Crushed Salt Consolidation with True Triaxial Testing Device as a Contribution to an EC Benchmark Exercise

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Experimente zur Salzgruskompaktierung mit echt triaxialer Meßeinrichtung als Beitrag zu einem EG Benchmark-Test

Zusammenfassung

Es wird ein Benchmark-Laborversuch zur Salzgruskompaktierung beschrieben, der mit der im INE entwickelten echt triaxialen Meßeinrichtung zweifach durchgeführt wurde. Der Versuch war als isothermer hydrostatischer Laststufentest mit sechs Kriechphasen und einer Gesamtdauer von 45 Tagen ausgelegt.

Im Wiederholungstest wurde erstmals eine zusätzliche Technik zur weiteren Reduktion von Wandreibungseffekten in der Triaxialanlage angewandt. In beiden Versuchen wurden die Verformungen des Probenmaterials mit hoher Präzision gemessen, so daß daraus die Kompaktierungsraten während der Kriechphasen zuverlässig bestimmt werden konnten. Aus den Änderungen der Kompaktierungsraten während der Lastabsenkungen wurde der Spannungsexponent des Stoffgesetzes für Salzgrus ermittelt. Im ersten Versuch wurden mit Hilfe von schnellen Lastwechseln der elastische Kompressionsmodul für drei Kompaktierungsstufen ermittelt.

Die Versuchsergebnisse werden mit Modellrechnungen verglichen, die von INE im Rahmen des Benchmark-Projekts vor den Experimenten durchgeführt worden waren. Mit den Versuchsergebnissen der anderen Teilnehmer wird ein vorläufiger Vergleich vorgenommen. Der Vergleich der beiden Versuche ergab, daß die Wandreibung in den Messungen mit der echt triaxialen Meßeinrichtung nur einen relativ geringen Einfluß hat.

Abstract

The description of a Benchmark laboratory test on crushed salt consolidation is given that was performed twice with the true triaxial testing device developed by INE. The test was defined as an anisothermal hydrostatic multi-step test, with six creeping periods, and 45 days total duration.

In the repetition test, an additional technique was applied for the first time in order to further reduce wall friction effects in the triaxial device. In both tests the sample strains were measured with high precision, allowing a reliable determination of the consolidation rates during the creeping periods. Changes in consolidation rates during load reductions were used to calculate the stress exponent of the constitutive model. Elastic compression moduli were determined at three compaction stages in the first test with the use of fast stress changes.

The test results are compared with the model calculations performed by INE before the test under the Benchmark project. A preliminary comparison of the test results with those of the other participants is given. The comparison of the results of both tests shows that wall friction has only a moderate effect in the measurements with the true triaxial device.

Contents

INTRODUCTION

The consolidation behaviour of crushed salt plays an important role for the safety of radioactive waste repositories in rock salt formations. Under the present German repository concepts it is envisaged to use crushed salt for the backfilling of disposal and access drifts as well as for borehole plugs. To perform predictive calculations on the convergence effects and the resulting backfill consolidation, a constitutive law for the consolidation behaviour of the crushed salt is needed. Analytical expressions for such a material law can be derived from physical considerations of the consolidation process, but experiments are needed for each specified material to verify the functional forms and to determine the model parameters.

Measurements were performed by different authors /1/ /2/ on the consolidation behaviour of dry crushed salt which has been specified as reference backfill material for the investigations under the German nuclear waste disposal projects (the material was taken from the ASSE salt mine and has a broad grain size distribution with largest grains of about 31.5 mm diameter). The experimental results and the constitutive models fitted to them exhibit significant discrepancies. It is argued that this is due to the different experimental techniques used: Oedometer tests or triaxial tests, respectively.

The TSS large-scale in situ test (Thermal Simulation of Drift Disposal) that has been run in the ASSE salt mine since 1991 is going to furnish important data for the validation of crushed salt modeling /3/. Since 1996, the TSS test has been incorporated in the EC project BAMBUS /4/ (Backfill and Material Behaviour in Underground Salt Repositories), and within this project the Benchmark exercise CSCS (Comparative Study on Crushed Salt) is performed on the behaviour and modeling of crushed salt backfill, including laboratory tests with participation of 3 (German) partners: BGR[1], GRS[2] and INE/FZK. Through these activities it is hoped to settle the discrepancies in the existing results on the consolidation behaviour of the reference backfill material.

In this report the laboratory test of CSCS as performed with use of a true triaxial testing device shall be described. This device was especially developed by INE for the investigation of crushed salt consolidation at normal and elevated temperatures /5/,/6/. The test was defined as an isothermal hydrostatic multi-step test with 6 creeping periods.

The test was performed twice by INE. In the repetition test an additional technique was applied for the first time in order to further reduce wall friction effects in the triaxial device.

The results are compared with the model calculations performed by INE before the test under the Benchmark project. A preliminary comparison with the results of the other participants is given. The more detailed comparison will be published in the final report of the CSCS exercise.

1. THE TRIAXIAL TESTING DEVICE

The INE true triaxial testing device was designed for the investigation of the reference backfill material, i.e. crushed salt with a rather large maximum grain size. It has a cubic test cell of 250 mm side length and uses hydraulic pressure pads for triaxial stress loading. The pressure pads are made of thin stainless-steel sheets and are replaced in each new test.

[1] Bundesanstalt für Geowissenschaften und Rohstoffe [2] Gesellschaft für Reaktorsicherheit und Strahlenschutz

The evaluation of the amount of hydraulic oil supplied to the pressure pads is used to determine the deformation of the sample (OMB method). As an additional technique of deformation measurement, inductive displacement transducers are used to measure the displacement of the central zones of the test sample surfaces (IWA method).

For the repetition of the test (Test 2), sheets of Viton of 0.5 mm thickness were additionally placed on the front of the pressure pads and provided with a thin film of grease in order to allow easy gliding of the Viton. The aim of this procedure was to reduce wall friction effects which up to this time were estimated to be rather small in this device, but had not yet been investigated experimentally.

The testing device allows to apply stresses of up to 35 MPa and temperatures of up to 200°C. Low deformation rates (~10^{-9}/s) typical of nuclear waste repositories can be measured with good accuracy due to a stabilization of the room temperature to about ±1°C and of the test cell temperature to about ±0.1°C. The hydraulic oil pressure applied to the pressure pads is regulated with a precision of about ±0.02 MPa. Temperatures are measured at several positions of the testing device and used for corrections of the deformation measurements.

In order to enable the linear stress rises within the prescribed loading history of the Benchmark experiment, the testing device was completed as follows: A clock driven potentiometer was installed to regulate the reference voltage which is used to define the prescribed stress levels (in combination with individual settings for the 3 spatial directions).

3. DESCRIPTION OF THE EXPERIMENTS

The experiments were performed using the testing material delivered by GRS. The different fractions were weighted and mixed to produce the desired grain size distribution as it was defined by the participants (Table 1). It corresponds to the reference backfill material apart from the fractions above 8 mm grain size, which were removed in order to meet the requirements of the smallest testing device (BGR) to be used in the Benchmark.

Mesh size / mm	Passage / %	Mesh size / mm	Passage / %
8	100	0.4	20.02
4	83.22	0.25	14.40
2	57.65	0.125	8.13
0.5	24.56	0.063	2.75

Table 1 Grain size distribution of the testing material (mesh passage)

The content of adsorbed water of the testing material was determined to be less then 0.1 wt.%.

In order to generate the prescribed initial porosity of 31%, 23.07 kg of the material were filled into the test cell which has an effective volume of 15394 cm^3 when the initial volume of the hydraulic pressure pads is taken into account (Test 1). In the repetition test (Test 2), the effective volume of the cell was somewhat smaller (15209 cm^3**)** due to the volume of the Viton sheets. Correspondingly the test cell was filled with 22.80 kg only.

The load history prescribed for the Benchmark experiment was composed of 3 cycles, each consisting of a first stress raising period of 2 days in order to reach hydrostatic stresses of 5, 10 and 15 MPa, a first creeping period of 6 days with one of these stresses, a period of about 1 day for stress lowering by relaxation, and a second creeping period of 6 days at a stress reduced by 15% as compared to the first one, i.e 4.25, 8.5 and 12.75 MPa. Additionally, some fast stress changes were proposed at the end of each cycle for the determination of the elastic compression moduli of the compacted material.

In Test 1 the proposed load history was achieved with some minor deviation during the last cycle. Because of a small defect (in the x-channel) the high stress creeping period was shortened from 6 to 5.5 days and the stress lowering was performed relatively fast instead of using stress relaxation as in the first two cycles. No additional fast stress changes were performed at the end of the third cycle, however, the fast stress drop towards the second creeping period could be evaluated to obtain information on the elastic modulus near the end of the test.

The load history of Test 1 is shown in Fig. 1. The loading was hydrostatic during all periods of the test. The fast stress changes at the end of the first two cycles of the first test are not resolved in the time scale of the graph. They are shown below in connection with the corresponding experimental results (see Fig.11 and 13).

In Test 2, the proposed load history was realized perfectly, except the fast stress changes at the end of the cycles which were not performed here. According to the proposal the temperature was adjusted to 25°C during both tests.

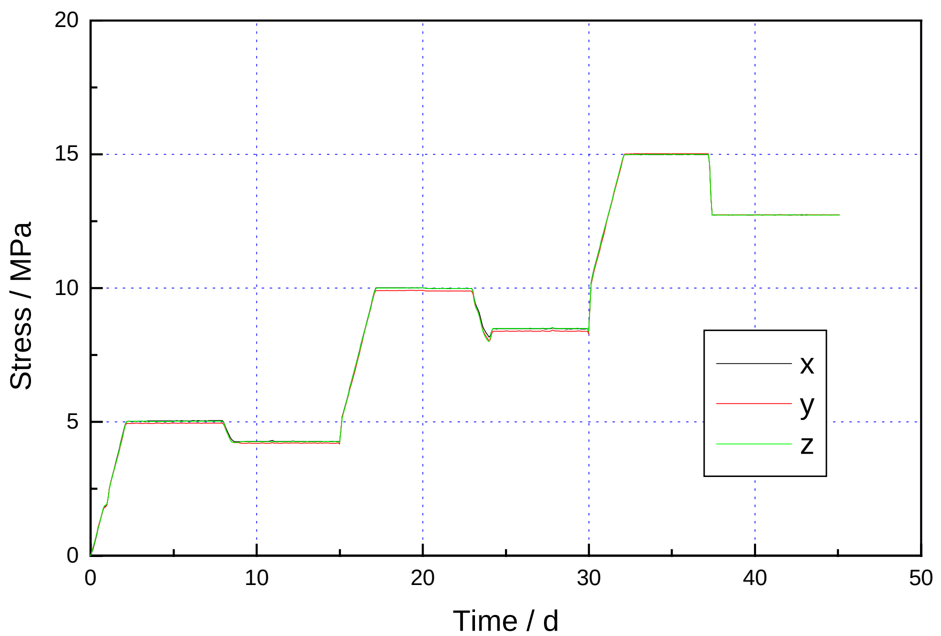

Fig. 1 Load history of the Benchmark experiment (Test 1)

In addition to the strain measurements with the triaxial testing device, the compaction reached at the end of the tests was determined separately. For both tests, a determination of the sample volume was performed for this purpose using an immersion method. In case of Test 1, a geometrical measurement of the sample was performed in addition.

4. EXPERIMENTAL RESULTS

The triaxial strains obtained in Test 1 from the two measuring methods are shown in Figures 2 and 3. Strains are defined as $-\Delta L/L_0$ under load within this paper, i.e. as total negative strains.

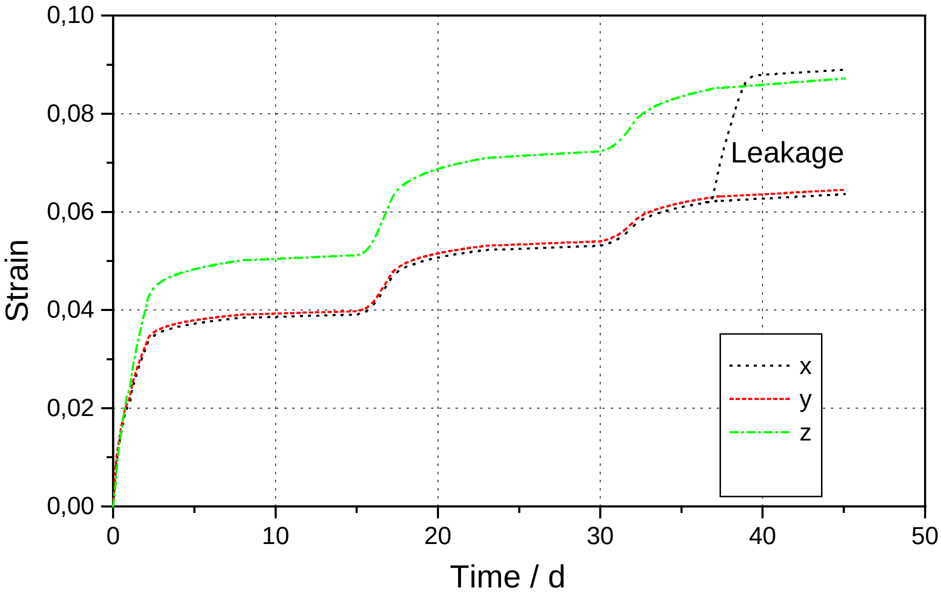

Fig. 2 Sample deformation as derived from OMB measurement (Test 1)

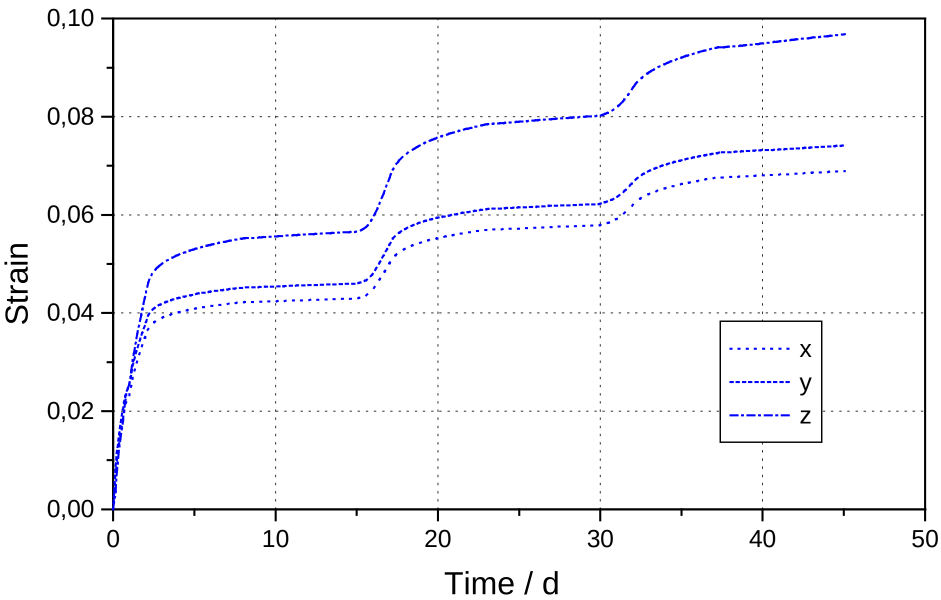

Fig. 3 Sample deformations as derived from IWA measurement (Test 1)

Some small corrections were applied in case of the OMB method concerning the hydraulic oil compressibility as well as the sligthly non linear dependency of the sample strain on the oil volume supplied to the pressure pads. The leakage in the x-channel after 37 days was stabilized after the stress reduction. For further evaluation of the results a corrected course as shown in Fig. 2 was used. The corresponding results of Test 2 are shown in Figures 4 and 5. For direct comparison the development of the mean strains with time as derived from the OMB and IWA data is shown in Fig. 6 for both tests.

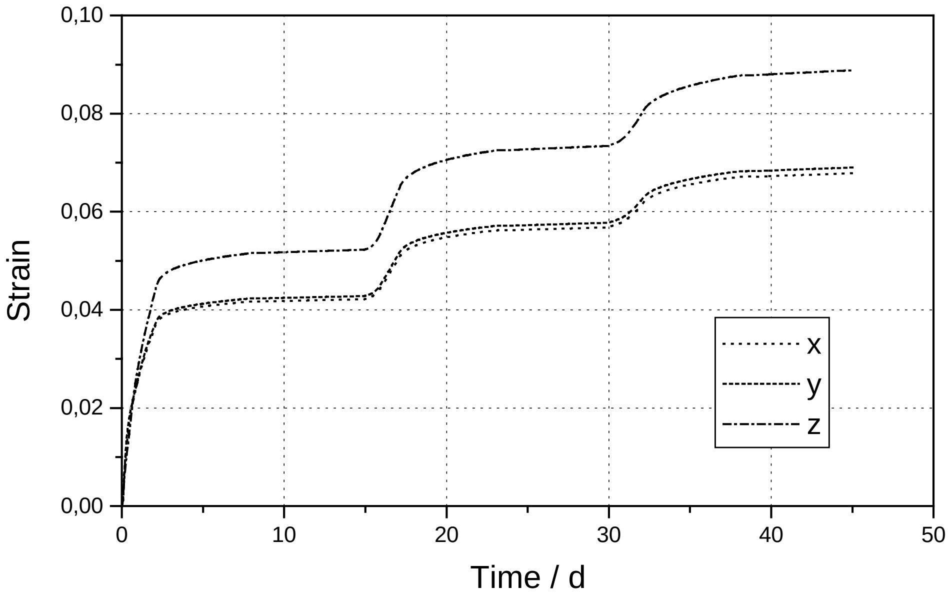

Fig. 4 Sample deformation as derived from OMB measurement (Test 2)

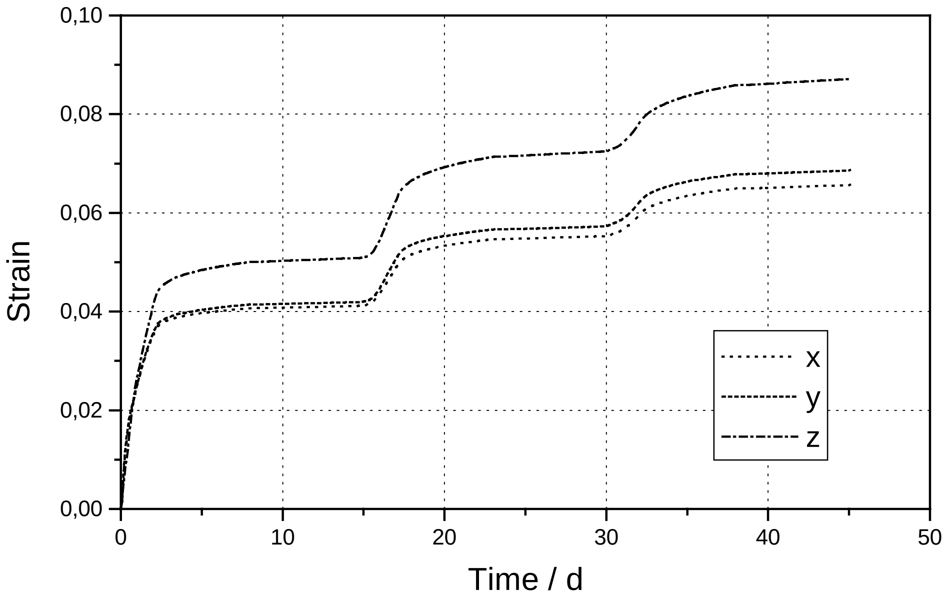

Fig. 5 Sample deformations as derived from IWA measurement (Test 2)

An effect can be noticed in these results which was also found in most of the earlier experiments: At hydrostatic loading, the strains in both horizontal directions (x, y) are nearly equal, but substantially lower than in the vertical direction. As the test cell itself is fully symmetric in the three directions, the reason for this effect is supposed to be an anisotropy of the test sample. An explanation might be that the granular particles of the testing material have mostly an oblong or flattened shape and during controlled filling of the test cell they remain predominantly orientated horizontally. This orientation could have the effect of a special reinforcement against horizontal compaction. To clarify this situation it is planned to perform a special test on granular salt with a more or less cubic shape of the grains.

It can also be seen from Figures 2, 3 and 6 that the IWA measurements in Test 1 are higher by about 10% as compared to the OMB results. This indicates a non-ideal deformation which was confirmed by the inspection of the sample removed from the test cell after the test. This must be attributed to wall friction effects during the compaction of the sample: The thin walled pressure pads have a finite rigidity against shrinking and are stressed tangentially by the internal fluid pressure. The first effect is more important at low pressure, the latter becomes larger the more the pressure pads are blown up, i.e. the stronger the sample becomes compacted.

In Test 2 there are no significant differences between the OMB and IWA results, as can be seen from Figures 4, 5 and 6. Inspection of the sample after the test also showed a fairly plane shape of the sample surfaces. This means, that the wall friction effects were very small due to the greased Viton sheets additionally applied in this test. It can therefore be assumed, that in this test the stresses within the sample were really hydrostatic and isotropic as demanded.

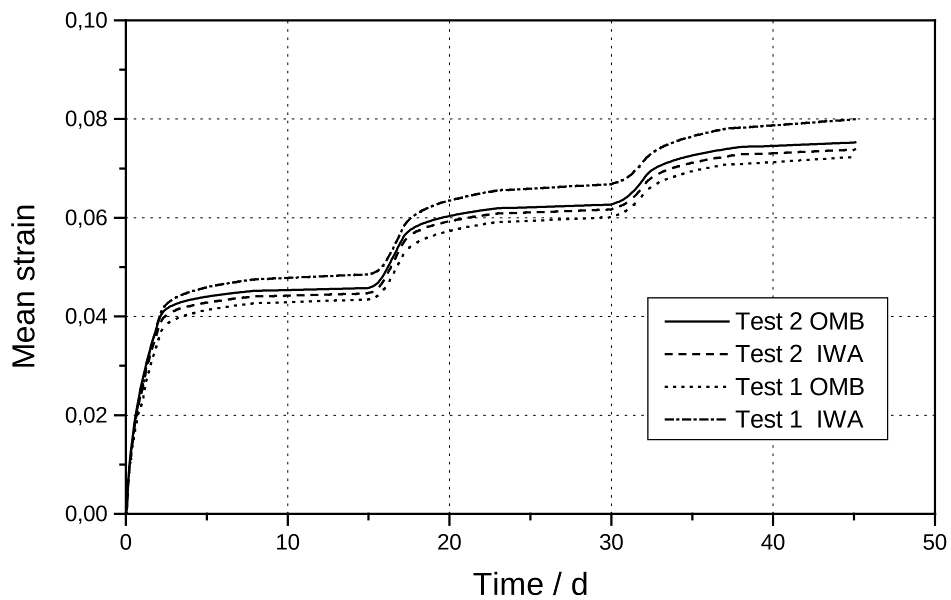

Fig. 6 Mean strains resulting from OMB and IWA measurements (Tests 1 and 2)

For Test 1, a final compaction after 45 d of (20.30±0.3)% is obtained from the OMB method, corresponding to a final porosity of (13.4±0.33)% for the initial porosity given of 31%. From the sample volume determinations after the test, final compactions of (20.24±0.5)% (immersion method) and (19.25±1)% (geometrical measurement) were achieved, respectively.

For Test 2, a final compaction of (21.06±0.3)% was found from the OMB measurement, corresponding to (12.6±0.33)% porosity. The immersion method resulted in a final compaction of (21.22±0.5)%.

The slightly higher compaction observed in Test 2 seems to be due to the reduced wall friction, as there are no other significant differences between the two tests. The amount of these discrepancies is in good agreement with theoretical estimations regarding the effect of wall friction expected in the Benchmark test.

For both tests the agreement between the in-line determination of the compaction (OMB method) on the one hand and the volume determination performed after triaxial testing on the other is very satisfactory. This still holds, when an estimated elastic compaction of about 0.2% is subtracted from the in-line results, which were derived from the sample strains under load (i.e. 12.5 MPa).

Evaluation of strain rates

In Figures 7 – 10, the strain rates in the three directions during the creeping periods are shown for both tests. They were derived by fitting polynomials of third order to the OMB and IWA data and subsequent differentiation. The unrealistic curvatures in some cases, in particular in the IWA results, are due to small accidental variations of the room temperature and applied stresses. Smoother curves are obtained when the mean strain rates are calculated from the three components.

From these results the mean strain rates immediately before and after the stress reductions are taken to calculate the apparent stress exponent n using the relation

$$n = \log(VR)/\log(VS)$$

where VR an VS are the ratios between the mean strain rates and the stress levels before and after the stress drops. The results are given in the Tables 1 – 4 for the two tests. The data are corrected for the small differences in creep compaction before and after the stress reduction with the use of the existing constitutive model for the reference backfill material /2/.

As can be seen from these data, Test 1 indicates a stress exponent in the region 5 – 6.5, whereas from Test 2 somewhat higher values of about 7.5 are found. Both results are still lying within the scatter of the previous INE results, from which it was concluded to use a value of 5 for the stress exponent of the constitutive law for the time being. On the other hand, these new results are consistent with other more recent results that indicate a somewhat higher stress exponent when the stress drops are rather small (and achieved slowly by relaxation), which are applied in order to investigate the stress dependency.

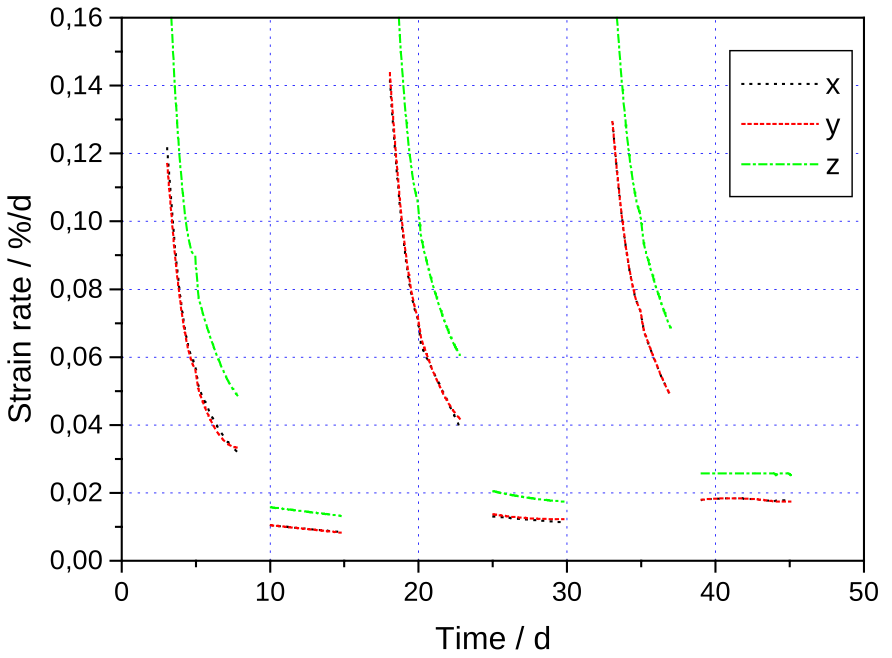

Fig. 7 Strain rates in creeping periods as derived from OMB measurements (Test 1)

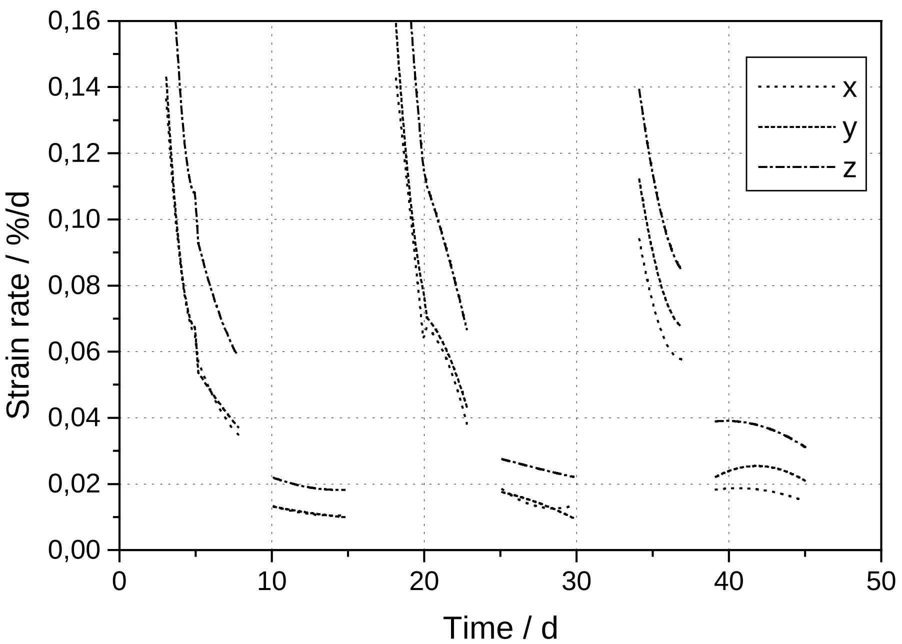

Fig. 8 Strain rates in creeping periods as derived from IWA measurements (Test 1)

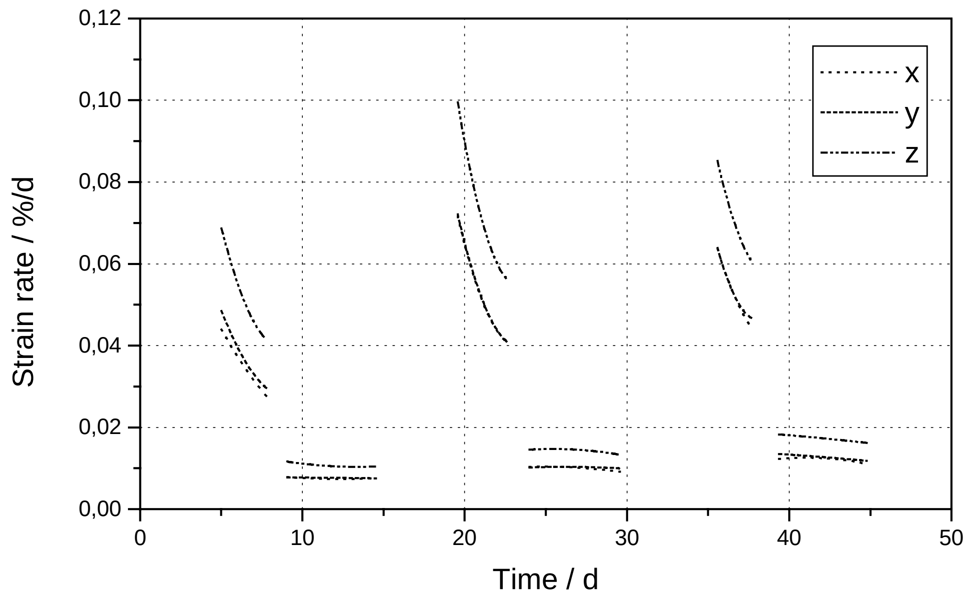

Fig. 9 Strain rates in creeping periods as derived from OMB measurements (Test 2)

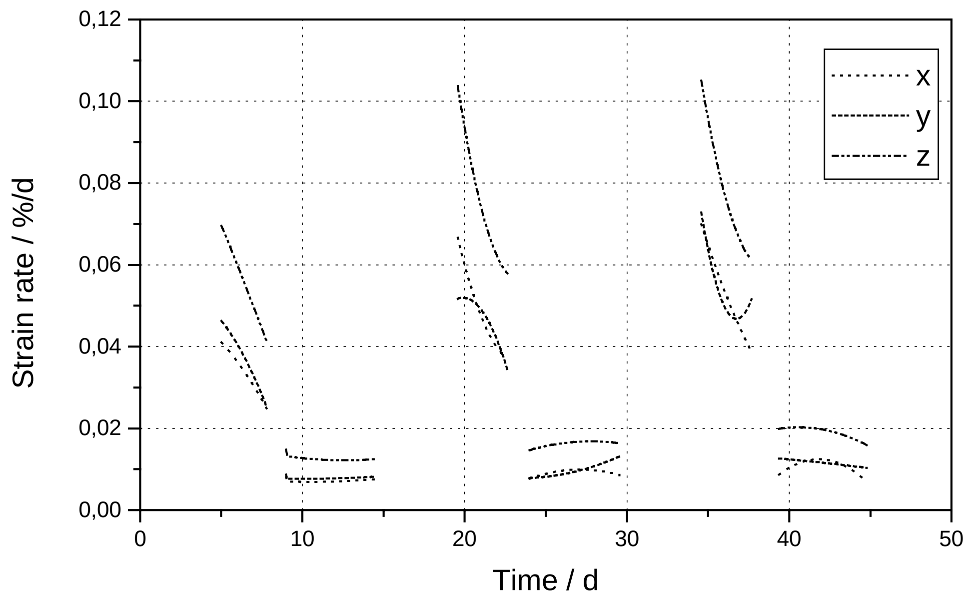

Fig. 10 Strain rates in creeping periods as derived from IWA measurements (Test 2)

Stress (MPa)	Time (d)	Volume Strain	Porosity	Strain Rate (%/d)	Ratio R2/R1	Stress Exponent
5.0	7.8	.1227	.2135	.0381		
4.25	10.0	.1235	.2128	.0122	.341	6.62
10.0	22.8	.1676	.1711	.0472		
8.5	25.0	.1687	.1700	.0157	..360	6.29
15.0	37.0	.1988	.1388	.0553		
12.75	39.	.2000	.1375	.0205	.400	5.64

Table 1: Mean strain rates (R1, R2) at load changes (OMB method, Test 1)

Stress (MPa)	Time (d)	Volume Strain	Porosity	Strain Rate (%/d)	Ratio R2/R1	Stress Exponent
5.0	7.8	.1227	.2135	.0434		
4.25	10.0	.1235	.2128	.0162	.397	5.68
10.0	22.8	.1676	.1711	.0494		
8.5	25.0	.1687	.1700	.0213	.465	4.71
15.0	37.0	.1988	.1388	.0611		
12.75	39.	.2000	.1375	.0245	.432	5.17

Table 2: Mean strain rates at load changes (IWA method, Test 1)

Stress (MPa)	Time (d)	Volume Strain	Porosity	Strain Rate (%/d)	Ratio R2/R1	Stress Exponent
5.0	7.95	.1298	.2075	.0312		
4.25	8.90	.1300	.2073	.0091	.292	7.58
10.0	23.0	.1751	.1639	.0433		
8.5	24.0	.1754	.1637	.012	.277	7.9
15.0	37.9	.2080	.1292	.0490		
12.75	39.2	.2084	.1288	.0151	.308	7.25

Table 3: Mean strain rates at load changes (OMB method, Test 2)

Stress (MPa)	Time (d)	Volume Strain	Porosity	Strain Rate (%/d)	Ratio R2/R1	Stress Exponent
5.0	7.95	.1298	.2075	.029		
4.25	8.90	.1300	.2073	.0093	.32	7.01
10.0	23.0	.1751	.1639	.041		
8.5	24.0	.1754	.1637	.0115	.280	7.83
15.0	37.9	.2080	.1292	.049		
12.75	39.2	.2084	.1288	.015	.306	7.29

Table 4: Mean strain rates at load changes (IWA method, Test 2)

If the tendency towards stronger compactions and higher stress exponents caused by wall friction reduction will be confirmed in future experiments, a revision of the existing constitutive law fitting (see below) will have to be considered. It must be emphasized, however, that no indication for very high stress exponents could be found as they were derived from the Oedometer experiments /1/, ranging from 20 to 12 for temperatures of 50 to 200°C.

Determination of elastic parameters

Fast stress changes for the determination of elastic parameters were performed in Test 1 in the first 2 cycles, whereas in the third cycle only the fast stress drop between the first and the second creeping period was evaluated for this purpose. The stress changes and the resulting volume strain changes are shown in Figures 11 - 16 with an expanded time scale. As can be seen from Figures 11 and 13, the response to loading and unloading of the sample is approximately equal. This means that creep consolidation or effects of induced temperature changes did not distort these short-term measurements.

Average elastic compression moduli of 3590, 5180 and 5360 MPa were derived from these results for porosities of 21.2, 16.9 and 14.0%, respectively. The increase of the compression modulus with compaction agrees with expectation and with the observation of other authors on comparable material /7/. However, the absolute values of the moduli are significantly higher (about a factor of 2.5) than those determined by /7/. An explanation for this might be that in /7/ the sample was compacted in a short-term test with 9 unloading/reloading cycles, during which the pressure was reduced to near zero. This loading history might have produced a less stiff material than the more careful procedure of the tests reported here. Besides, in /7/ the compression moduli were calculated as the average over the total unloading and reloading cycles, which results in smaller values compared to the only gradual stress reduction of about 20% used here.

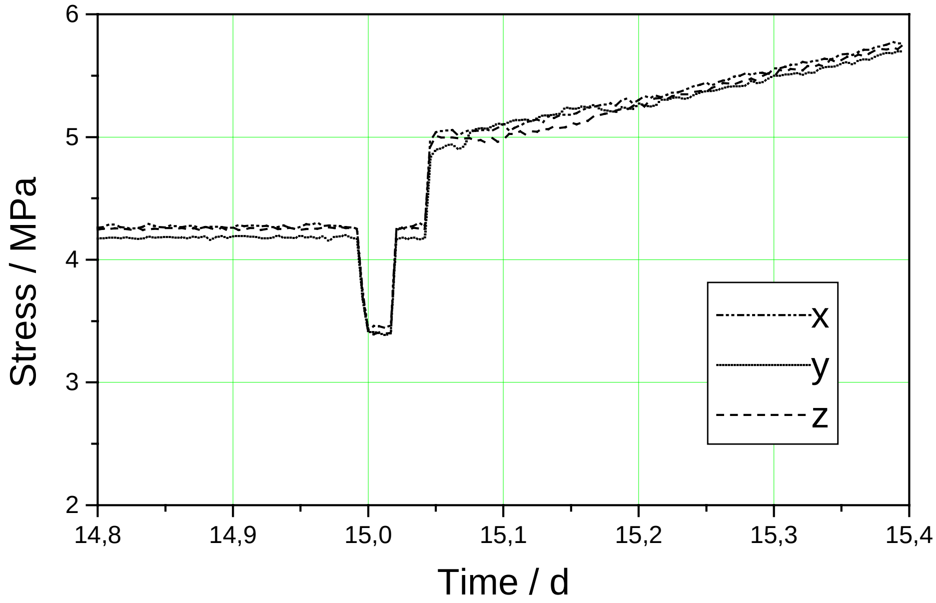

Fig. 11 Stress variation during fast stress steps of cycle 1 (Test 1)

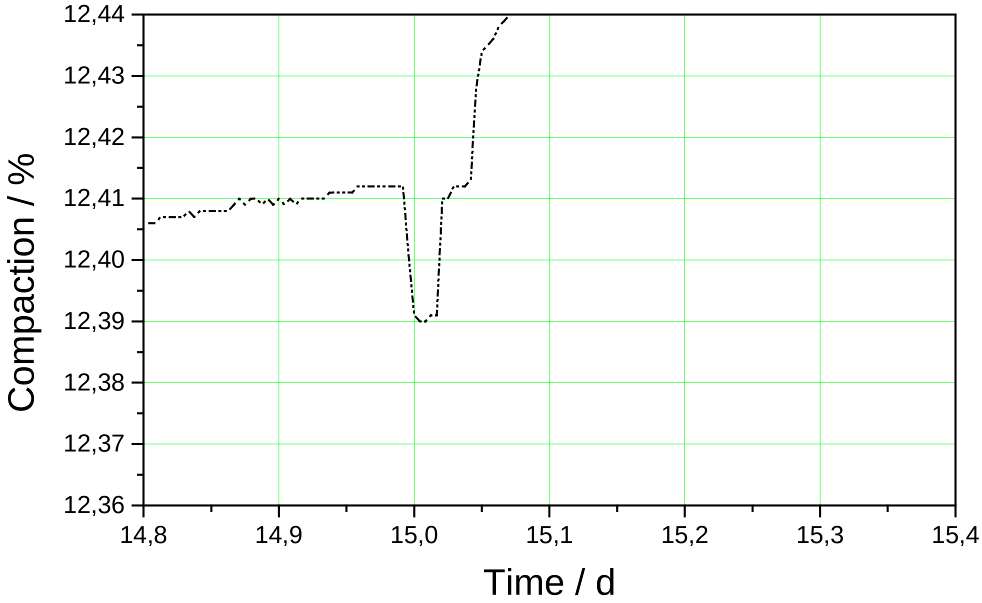

Fig. 12 Quasi elastic reaction to fast stress steps of cycle 1 (Test 1)

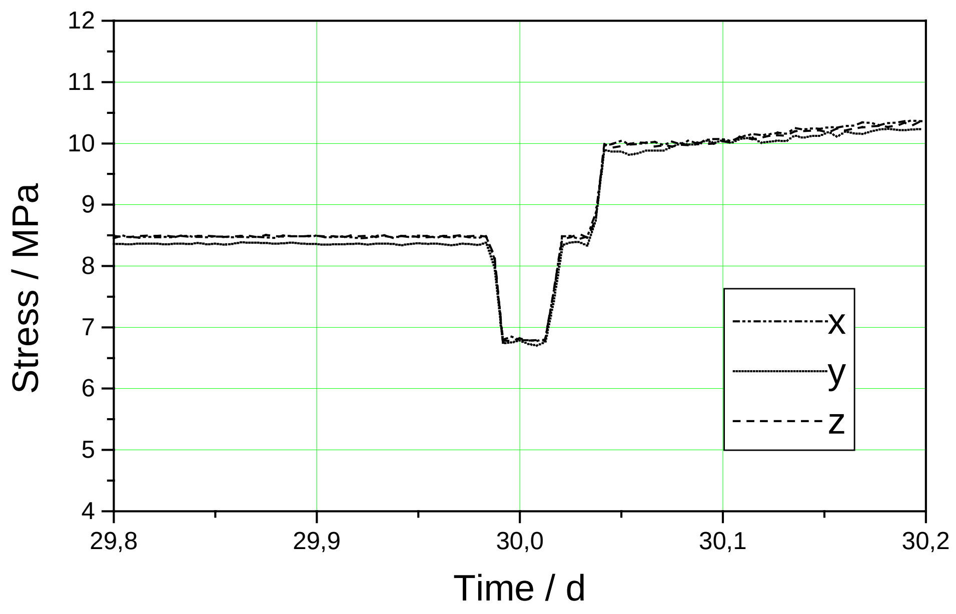

Fig. 13 Stress variation during fast stress steps of cycle 2 (Test 1)

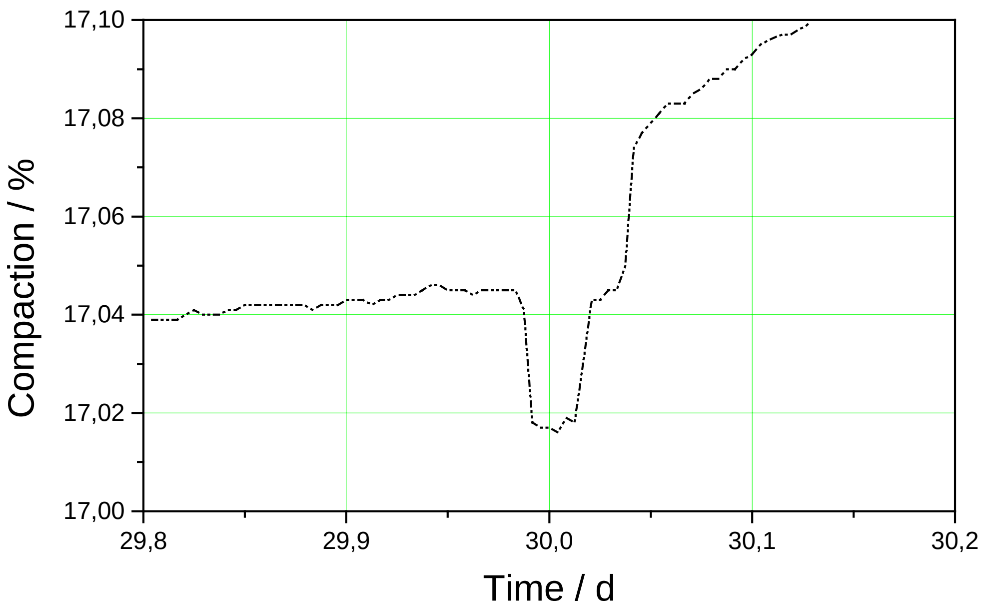

Fig. 14 Quasi-elastic reaction to fast stress steps of cycle 2 (Test 1)

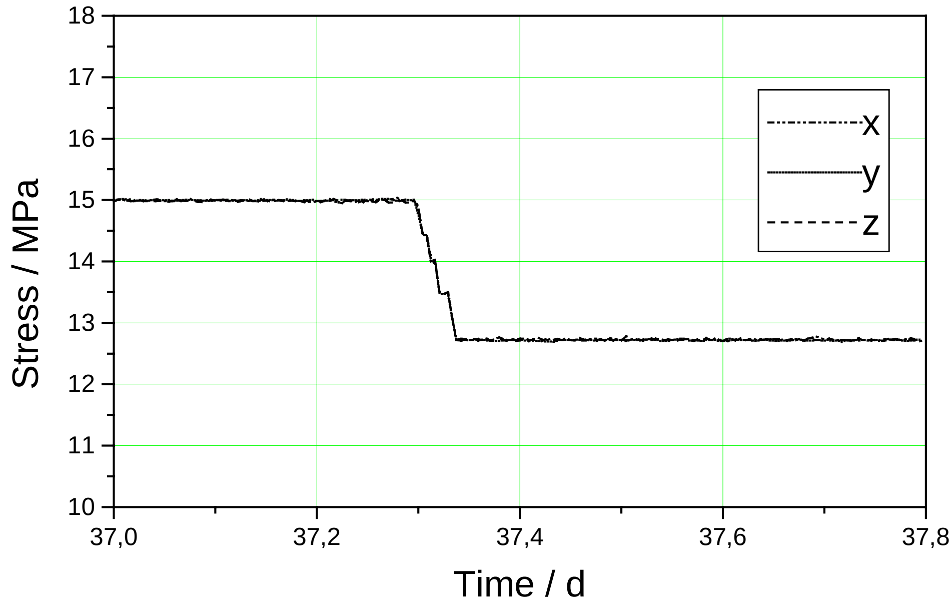

Fig. 15 Fast stress drop after the first creeping phase of cycle 3 (Test 1)

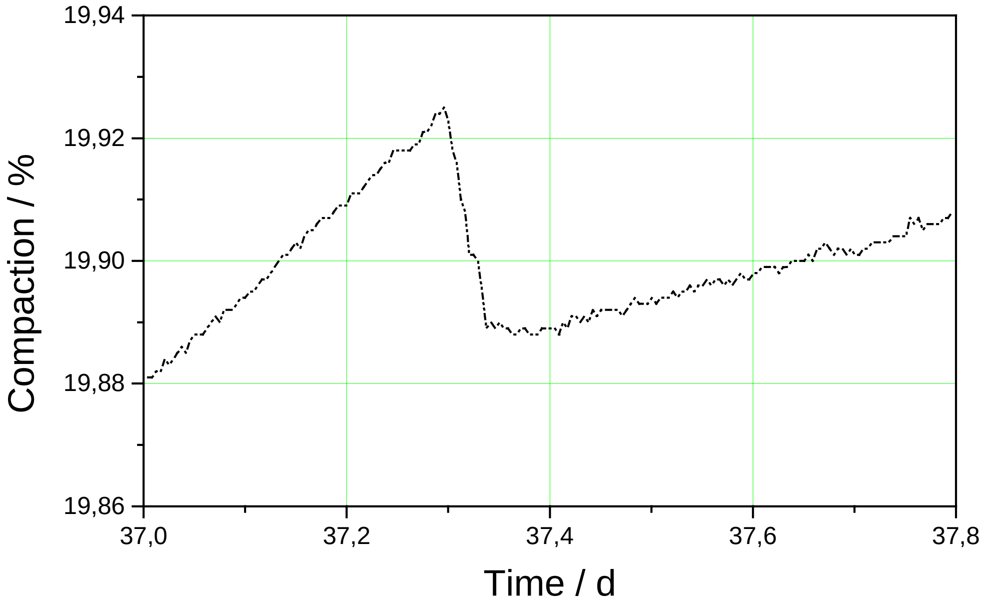

Fig. 16 Quasi-elastic reaction to fast stress drop in cycle 3 (Test 1)

5. COMPARISON OF EXPERIMENT AND MODEL CALCULATION

Predictive calculations were performed for the Benchmark test using the Finite Element code MAUS /8/. The INE constitutive law for crushed salt was used as published in /2/. It is based on a formulation described in /9/ and contains a modified material function h_1 and some parameters fitted to the INE measurements on the reference backfill material:

$$\dot{\varepsilon} = A \cdot e^{-Q/R/T} \cdot (h_1 \cdot p^2 + h_2 \cdot q^2)^2 \cdot (h_1 \cdot p/3 \cdot \mathbf{1} + h_2 \cdot \mathbf{S})$$

$$h_1(\eta) = a / (((\eta_0/\eta)^c - 1)/\eta_0^c + d)^m$$

$$h_2(\eta) = b \cdot h_1(\eta) + 1$$

where

$\dot{\varepsilon}$:	tensor of the inelastic strain rate	T :	absolute temperature
p :	mean normal stress	η :	porosity
S :	tensor of the deviatoric stress	η_0 :	initial porosity (31 %)
q :	deviatoric stress invariant	**1** :	unit tensor
Q :	activation energy	R :	universal gas constant

and $A = 1.09 \cdot 10^{-6}$/s/MPa^5
$Q/R = 6520$/K
$a = 0.01648$
$b = 0.9$
$c = 0.1$
$m = 2.25$
$d = 0.0003$

The additional parameter d is not included in the formulation reported in /2/. It was introduced in the numerical calculations to remove the singularity at zero compaction. With the small values used here it has no significant influence in the interesting range of consolidation.

Under the hydrostatic stress conditions of the Benchmark test, the function h_2 and the parameter b do not have any effect on the result.

The comparison of this calculation with the test results is shown in Fig. 17 for the mean strain. The main features are a relatively good agreement in the consolidations reached at the end of each of the 3 cycles as well as a noticeable discrepancy in the development with time: In the experiments the strain rises faster during the load raising periods and more slowly during the creeping periods. This result is not unexpected, because the constitutive law used in the calculation does not take into account the grain displacement mechanisms and the visco-plastic and transient creep effects which are believed to be significant during stress raising periods and at high consolidation rates. These effects are small at the low consolidation rates as they are expected in nuclear waste repositories ($<10^{-8}$/s) and that is why it was renounced to use more complex constitutive law formulations accounting for these effects.

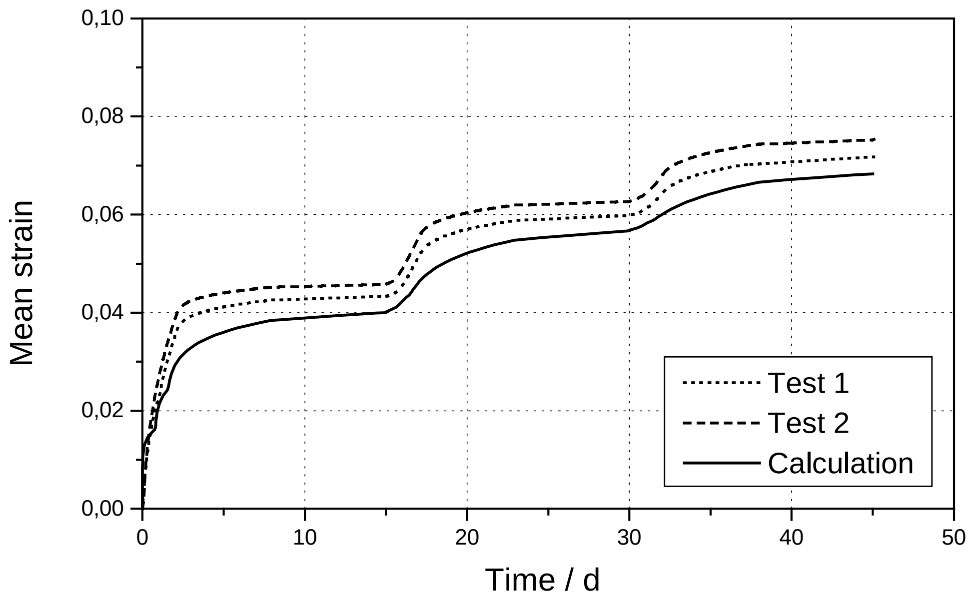

Fig. 17 Comparison of predictive calculation and test results (OMB method)

The lower compaction rates in the experiments during the creeping periods then may be explained by the stronger consolidation of the material already reached during the stress raising periods.

It should be stated here, however, that a somewhat better agreement between experiment and calculation would result too from using a constitutive law fit with a higher stress exponent and a stronger dependency on the porosity.

A better comparison between experiment and calculation or constitutive law is possible when experimental strain rates are related directly to those calculated with the constitutive law for the consolidation actually reached in the experiment. This procedure presupposes, as does the constitutive law used, that the compaction rate depends only on the actual stress, temperature and porosity, but not on the loading or deformation history.

These comparative results are shown in Tables 5 and 6 for the times at the end of the creeping periods of the two tests.

Stress (MPa)	Time (d)	Volume Strain	Porosity	Exp. Strain Rate (%/d)	Calc. Strain Rate (%/d)	Exp./Calc.
5.0	7.8	.1227	.2135	.0381	.0692	.551
4.25	15.0	.1250	.2114	.0099	.0258	.384
10.0	22.8	.1676	.1711	.0472	.0899	.525
8.5	30.0	.1705	.1682	.0137	.0328	.418
15.0	37.0	.1988	.1388	.0553	.0838	.660
12.75	45.	.2030	.1343	.0199	.0280	.711

Table 5: Measured mean strain rates (OMB method) compared to calculation for actually reached consolidations (Test 1)

Stress (MPa)	Time (d)	Volume Strain	Porosity	Exp. Strain Rate (%/d)	Calc. Strain Rate (%/d)	Exp./Calc
5.0	7.95		.2075	.0312	.0404	.772
4.25	15.0	.1313	.2057	.0085	.0160	.531
10.0	23.0	.1751	.1639	.0433	.0542	.799
8.5	30.0	.1771	.1615	.0110	.0210	.524
15.0	37.8	.2080	.1292	.0490	.0443	1.11
12.75	45.	.2106	.1259	.0131	.0167	.784

Table 6: Measured mean strain rates (OMB method) compared to calculation for actually reached consolidations (Test 2)

These results illustrate, that at least at low consolidation rates, i.e. during the creeping periods, the crushed salt used in the Benchmark test behaves similarly to the reference backfill material, for which the constitutive law was defined on the basis of similar tests performed with the same testing device. The averaged ratio of about 0.54 (Test 1) and 0.75 (Test 2) between experiments and constitutive model may be due to the less broad grain size distribution of the Benchmark material, which theoretically should in fact give rise to lower compaction rates.

The remaining question regarding possible systematic errors in these measurements is hoped to be answered through the comparative evaluation of the results of all participants of the Benchmark. From the test results presented here it may be argued, however, that the remaining uncertainties should be rather small (in particular in Test 2).

6. COMPARISON WITH RESULTS OF OTHER BENCHMARK PARTICIPANTS

Two other laboratories, BGR (Hannover) and GRS (Braunschweig), have participated with conventional triaxial devices in the experiment of the CSCS Benchmark. The detailed presentation and comparison of the results of the experiments performed there will be given in the final reports of the EC project BAMBUS. However, some features can be presented here on the basis of the preliminary results reported in the Benchmark meetings and in /10/:

The development of the compaction with time agrees well with the INE results except in the first stage of loading. Because of technical problems in the determination of radial strains, the results were renormalized with the use of the final compactions determined after the tests. These final compactions and the renormalized compaction curves are in satisfactory agreement with the INE results (the somewhat higher compactions resulting from the BGR experiment may be due to a deviatoric loading at the start and the higher test temperature of about 33°C). However, the precise determination of the compaction rates from these tests during the creeping periods is rather limited. In the BGR results the fluctuations due to temperature variations and other technical problems are too large to allow reliable information to be obtained on the compaction rates. The GRS data also show relatively much scatter, but can reasonably be evaluated and result in stress exponents of about 5-6.5, i.e. comparable to the INE results. There are, however, some open questions concerning the different behaviour of axial and radial strain rates.

No fast stress changes were performed by these participants for the determination of elastic compression moduli because of insufficient precision of the volume determination in these triaxial devices.

7. CONCLUSIONS

The experiment defined for the EC Benchmark CSCS on crushed salt was successfully performed twice with the INE true triaxial device. In the second test special measures were taken for further reduction of wall friction effects. Determination of the time depending compaction was performed with high accuracy using two independent measuring methods. For both tests compaction rates could be derived with good precision from the experimental data for the six creeping periods.

The high self-stiffness of the triaxial device and the good measuring precision allowed to determine elastic compression moduli from the fast load changes performed in Test 1.

The final compactions resulting from the in line measurements are in good agreement with the determination of the sample volumes and porosities after the tests.

The second test resulted in slightly higher compactions (21.06 compared to 20.15% at the end), which is believed to be due to the reduced wall friction effects. The sample geometry remained practically ideal in this test. The amount of the observed discrepancy agrees well with a theoretical estimate of the wall friction effect in the triaxial device.

Stress exponents of 5–6.5 were derived from the compaction rate changes during the stress reductions in Test 1, whereas values of about 7.5 resulted from Test 2. Several more recent tests performed by the author on the reference backfill material (applying only small and slow stress reductions) also indicated stress exponents in this range. From the Oedometer tests on the reference backfill material much higher stress exponents were derived /1/. However, because of the problems of interpreting Oedometer tests, these results may be questionable. Nevertheless, a constitutive law fitting on the basis of a stress exponent of 6 or 7 instead of 5 (used up to now in the INE model) should be examined at least. This would still be consistent with the stress exponent for the stationary creep of solid rock salt where values of 5 – 7 for medium stress levels are under discussion /11/. Of course it should be kept in mind that any fixed value for the stress exponent for crushed salt creep will only be a compromise, because strictly speaking it depends on the stress level, porosity, temperature, grain shape and grain size distribution, and others.

Like in most of the former tests performed with the true triaxial device, the compactions found vertically were higher than those in the horizontal directions, though the loading was hydrostatic. This effect is thought to be due to a certain anisotropy of the sample material in the test cell. This assumption will be examined in a special test with a testing material consisting of more or less cubic grains.

The compaction behaviour of the testing material as obtained by the Benchmark experiments is rather similar to that observed in numerous tests on the reference backfill material. This means that the differences in the grain size distribution (i.e. the removal of a coarse fraction above 8 mm grain size) has no great influence on the compaction behaviour.

It is shown that the experimental results obtained can be described fairly well by a viscoplastic constitutive model as proposed by Hein /9/ (modified in details /2/), which considers both volumetric and deviatoric strain rates under hydrostatic and shear stress conditions. Some apparent discrepancies are believed to be due to certain viscoplastic and transient creep effects that are partly relevant in such short term laboratory tests, but not under waste disposal conditions with very low consolidation rates.

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