The powder swelling test - advantages and limitations

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Abstract: During site investigations for tunnel projects in swelling rocks one of the major tasks is to determine the swelling potential and the mineral composition of the material. When carried out in the laboratory, the sampling procedure is the main problem.

Usually swelling rocks are very sensitive to changes in water content and stress state. Therefore it is more or less impossible to obtain undisturbed samples for proper laboratory testing. Even if treated with uttermost care, sample drawing produces tension release, small fissures, changes in water content etc. To avoid these problems, in 1993 Thuro suggested disturbing the samples completely by drying and grinding them. The generated powder is tested in a swelling cell called "Swellomat", measuring the swelling displacement of the material. One of the important advantages of this method is that, due to the consistent sample preparation, an almost perfect homogeneous material is produced. Moreover, compared with the original rock sample, the surface area of a powder is many times larger and, therefore, the test takes about ten times less time to obtain the desired results. On the other hand, some disadvantages are obvious: no natural undisturbed sample is used; therefore, no swelling pressures can be derived. Also, the comparability with the original rock mass may be difficult.

Extensive investigations have been carried out testing parallel series of a variety of swelling materials with different pressure swelling tests (Huder & Amberg 1970 and Henke, Kaiser & Nagel 1975) to calibrate the results of the powder swelling test. As a result of the study, a linear correlation could be proved. In this paper the testing procedure and possible factors influencing the results are described.

Résumé: Au cours d'études de sites pour des projets de tunnel dans des roches déformantes, l'une des tâches majeures est de déterminer le potentiel de gonflement ainsi que la composition minérale du matériau. Le principal problème de cette étude effectuée en laboratoire est lie à la procédure de prélèvement d'échantillon sur le terrain. Normalement, les roches « gonflantes » sont très sensibles aux variations de teneur en eau ainsi qu'aux variations de pression et de contraintes. Il est donc plus ou moins impossible d'obtenir des échantillons non perturbés afin de pratiquer des tests exacts en laboratoires. Même traités avec le plus grand soin, l'extraction d'échantillons entraîne un relâchement de la tension, la création de petites fissures, des variations de la teneur en eau etc. Afin d'éviter ces problèmes, Thuro proposa en 1993 de perturber complètement les échantillons en les séchant et en les meulant. La poudre résultant de ces opérations est testée dans une cellule de gonflement appelée un « swellomat », qui mesure le déplacement de gonflement du matériau. L'un des avantages importants de cette méthode est qu'en raison de la préparation logique de l'échantillon, un matériau homogène presque parfait est obtenu. De plus, comparé à l'échantillon d'origine, la surface de la poudre est bien plus grande et donc le test prend presque 10 fois moins de temps pour obtenir les résultats désirés. D'un autre côté, certains désavantages sont évidents: aucun échantillon naturel non perturbé n'est utilisé et aucune mesure de la pression de gonflement ne peut donc être définie. En outre, la comparaison avec la masse de la roche d'origine peut être difficile.

Afin d'étalonner les résultats des tests de gonflement de la poudre, des études poussées ont été menées, testant en parallèles des séries de différents matériaux gonflants avec des pressions différentes de gonflement (Huder & Amberg 1970 and Henke, Kaiser & Nagel 1975). Une corrélation linéaire peut être dégagée comme résultat de cette étude. La procédure du test ainsi que les facteurs pouvant influencés les résultats sont décrits dans ce papier.

Keywords: clay minerals, sedimentary rocks, laboraty studies, expansion, tunnels, site investigation.

INTRODUCTION

The swelling behaviour of clay rocks is normally determined by laboratory tests. In-situ tests are only possible in rarely built special research tunnels or in investigation adits. Also common are mineralogical investigations to estimate the swelling capacity. The results of the swelling tests are required to model and plan the tunnel design and construction. If the tests are made during site investigation, the biggest problem is to get undisturbed and proper sample material. When the swelling tests are carried out during construction of the tunnel, time is most important. These two main problems can be solved by the powder swelling test (Thuro 1993).

THE PROBLEM USING CLAYSTONE SAMPLES

On the surface, claystones samples are more or less always disturbed. Under humid and atmospheric conditions the material alters immediately. First of all, there is a tension and stress release due to the extraction from its natural bedding. This produces expansion and thus small fissures. Secondly, the material changes its natural water content in contact with air and humidity. This behaviour is observed with almost every sample. Therefore it is nearly impossible to obtain undisturbed material from the ground as a testing sample.

The process of alteration also happens to the natural claystone rocks near the surface. Due to the low overburden and low restraint the material can absorb water and changes its consistency. In this case the claystones do not swell. Under certain rock cover the restraint increases the swelling pressure of the material and it can not absorb any more water. Only claystones with a relatively high density and low water content in the core of the hill underneath the "clay-swelling-level" are able to swell. The depth and distribution of this level should be investigated for each tunnelling project. Figure 1 shows a schematic cross section through a claystone hill.

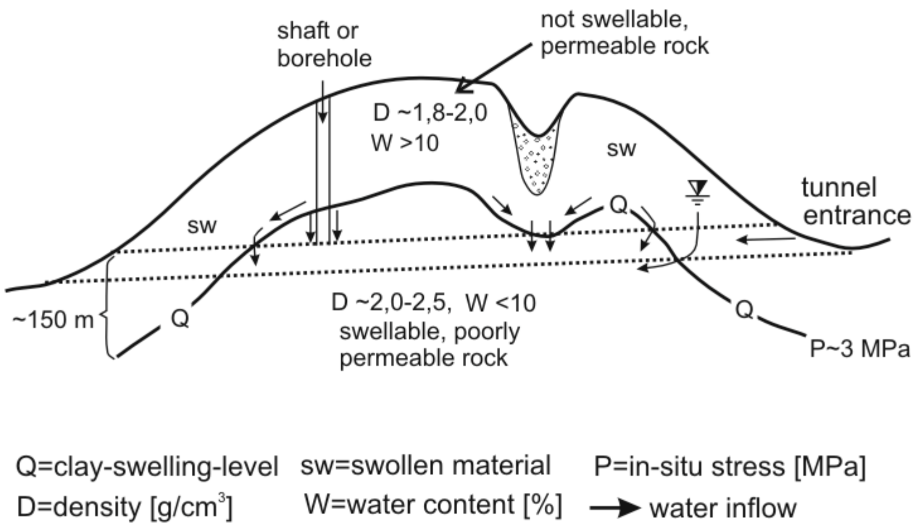

Figure 1. Rock characteristics and water inflow positions for a tunnel tube in a swellable claystone rock mass. Estimated max. swelling pressure for claystone = 3 MPa (schematic cross section).

SWELLING TESTS

There are two swelling characteristics that can be determined by laboratory testing. On the one hand the strain of the material and on the other hand the occurring pressure. Therefore two main testing procedures are possible:

- Strain-swelling-test: only displacement is measured with no axial and/or radial restraint (zero pressure change)
- Pressure-swelling-test: only pressure is measured with rigid radial and axial restraint (zero volume change)

These testing principles were often mixed. The most common testing procedure is with radial restraint and axial measuring (Paul 1986, ISRM 1989). The displacement can be analysed with or without a constant axial pressure. The swelling pressure is normally investigated with the swelling test after Henke *et al.* (1975) or Huder & Amberg (1970). The list below shows a selection of different common testing procedures for swelling tests which will be discussed in the following.

- Swelling strain test with radial restraint and free axial displacement (e.g. powder swelling test according to Thuro 1993)
- Swelling strain test with radial restraint and axial displacement under a constant pressure (e.g. powder swelling test according to Thuro 1993, Paul 1986, ISRM 1989)
- Swelling test according to Huder & Amberg (1970)
- Swelling test according to Henke *et al.* (1975)
- Swelling test according to Kirschke (1987) and Kirschke, Kovari & Prommersberger (1991) (not used in this study)

Unfortunately these testing procedures are very seldom applied to the same samples. Therefore it is difficult to compare the results of these tests. Generally the result of each test has to be interpreted differently because the swelling pressure of identical samples is not similar in the different tests.

Swelling test after Huder & Amberg (1970)

This test is a combined pressure and swelling strain test. Figure 2 shows a typical test procedure. After the first loading (A) an unloading (B) and a reloading (C) procedure follows. Each step has to be held as long as the settlement (or displacement) changes. Afterwards distilled water has to be added to start the swelling process (E). The settlement (D) occurs because the powder sample consolidates in contact with water under high axial pressure. The maximum displacement has to be achieved before unloading the pressure again. The possible maximum pressure can be determined from the graph.

The tests where carried out in a common compression apparatus. The specimen height was approx. 20 mm and the diameter of the oedometer cell was 70 mm. The minimum load of 5 kN/m^2 was followed by 10 kN/m^2, 25 kN/m^2, 50 kN/m^2, 100 kN/m^2, 200 kN/m^2, 400 kN/m^2 and a maximum load of 800 kN/m^2 (Figure 2). The tested material was a homogenised powder of 10%, 25% and 40% swellable Sodium-Bentonite mixed accordingly with 90%, 75% and 60% Quartz (Figure 3). These samples were used to ensure an exact mineralogical definition and absolutely identical samples for all tests. The grain size of the powder varied between clay and fine sand with a maximum in the coarse silt range.

The swelling pressure correlated to the content of swellable clay minerals (Sodium-Bentonite) due to the swelling test according to Huder & Amberg (1970) can be seen in Figure 3.

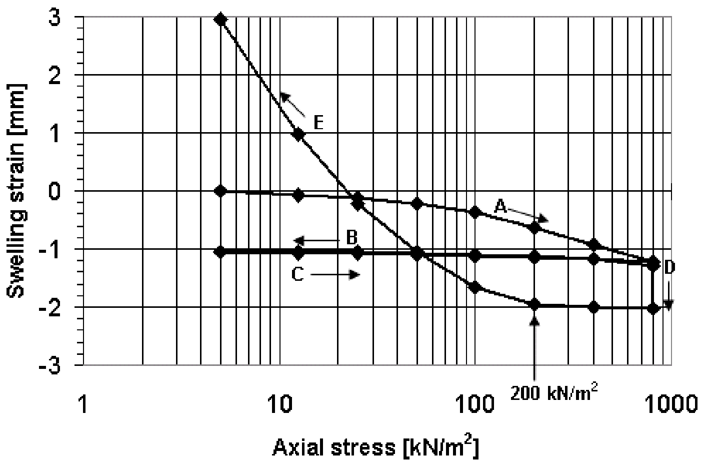

Figure 2. Testing procedure and interpretation of a swelling test according to Huder & Amberg (1970). The sample was mixed from 25% Sodium-Bentonite and 75% Quartz. The material has a swelling pressure of 0.2 MPa.

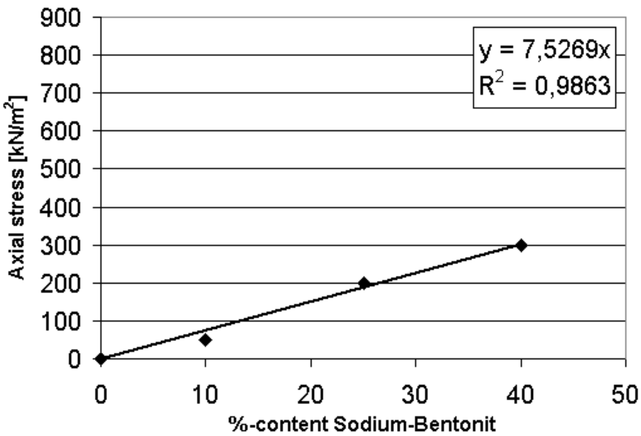

Figure 3. Interpretation of a swelling test series according to Huder & Amberg (1970). A very good linear dependency between swelling pressure (axial stress) and content of swellable clay minerals (%-content Sodium-Bentonite) is visible.

Swelling test according to Henke et al. *(1975)*

This swelling test is also a combined strain and pressure test (Figure 4). After the usual loading (A) and unloading (B) procedure the sample is wetted and the complete swelling displacement (C) at a pressure of 5 kN/m^2 is recorded. Afterwards the sample is loaded again (D). The determined swelling pressure is the pressure which is necessary to reduce the primary swelling displacement to zero and can be determined from the graph.

The tests were carried out in a normal compression apparatus. The specimen height was approx. 20 mm and the diameter of the oedometer cell was 70 mm. The minimum load was 5 kN/m^2, followed by 10 kN/m^2, 25 kN/m^2, 50 kN/m^2, 100 kN/m^2, 200 kN/m^2, 400 kN/m^2 and a maximum load of 800 respectively 1000 kN/m^2 (Figure 4). The tested material was a homogenised powder of 10%, 25% and 40% swellable Sodium-Bentonite and 90%, 75% and 60% non swelling Quartz (Figure 5). The grain size of the powder varied between clay and fine sand with a maximum in the coarse silt range.

The swelling pressure correlated to the content of swellable clay minerals (Sodium-Bentonite) due to the swelling test according to Henke *et al*. (1975) can be seen in Figure 5.

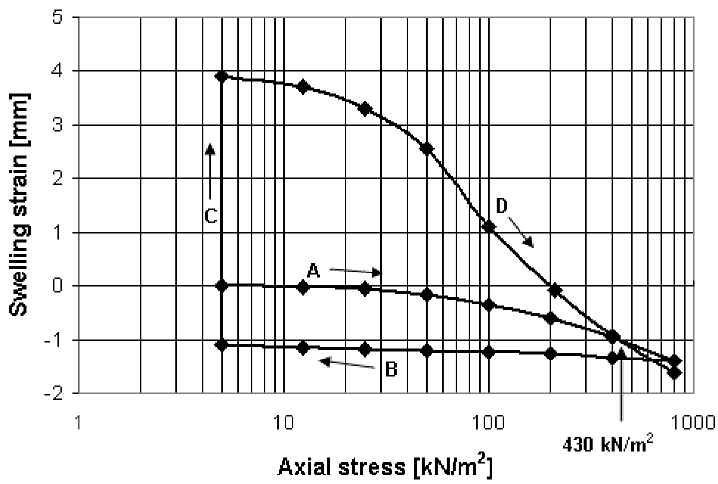

Figure 4. Testing procedure and interpretation of a swelling test according to Henke *et al.* (1975). The sample was mixed from 25% Sodium-Bentonite and 75% Quartz. The material has a swelling pressure of 0.43 MPa.

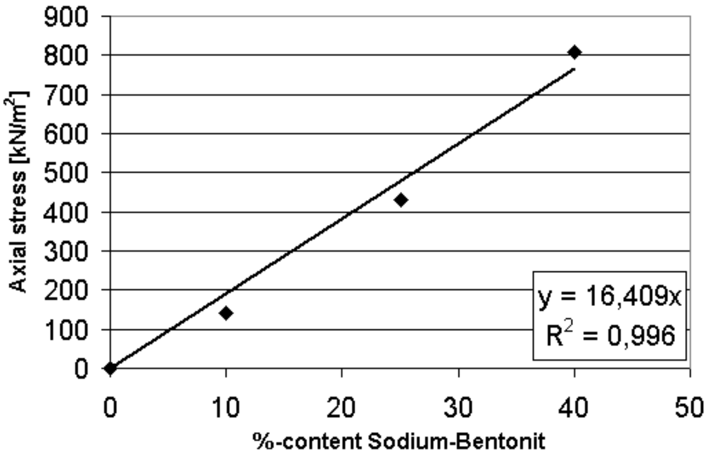

Figure 5. Interpretation of a swelling test series according to Henke *et al*. (1975). A very good linear dependency between swelling pressure (axial stress) and content of swellable clay minerals (%-content Sodium-Bentonite) is visible.

Swelling test according to Kirschke (1987) and Kirschke et al. *(1991)*

In 1987 Kirschke first published an attempt at a combined swelling strain and swelling pressure test. These tests were necessary to examine the swelling potential of rocks from the Middle Keuper (consisting of claystone, marlstone, gypsum and anhydrite) for the design of the Freudenstein-Railwaytunnel between Mannheim and Stuttgart in Germany. This tunnel is constructed with yielding support. Thus the laboratory tests were focused on a simultaneous testing procedure for swelling strain and pressure. Therefore the swelling pressure was first measured without axial strain. After reaching a certain point (e.g. 4 MPa) the pressure was reduced and some displacement was allowed before restraining the displacement again. As shown in Figure 6 the sample regained the maximum pressure several times. Even under a maximum pressure of 8 MPa the sample regained the same swelling pressure, after allowing some displacement.

Since simultaneous measuring of swelling strain and swelling pressure (a) is quiet difficult the swelling behaviour under natural conditions by two different swelling test procedures was extrapolated (Figure 7). One procedure allowed some swelling displacement (c_1) and afterwards measured the pressure reached (c_2). The other procedure allowed the swelling pressure to develop (b_1) and afterwards measured the following swelling displacement (b_2).

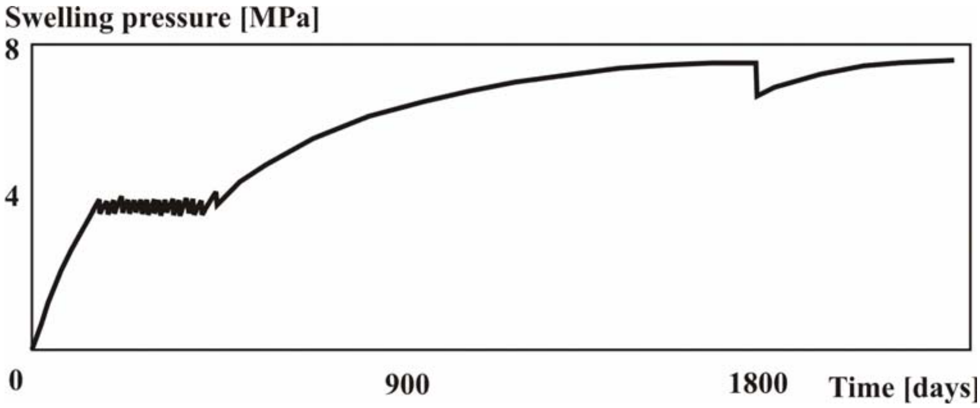

Figure 6. Testing procedure for a swelling test according to Kirschke *et al.* (1991). There are several pressure release and displacement sequences shown. After each sequence the sample regained its swelling pressure again.

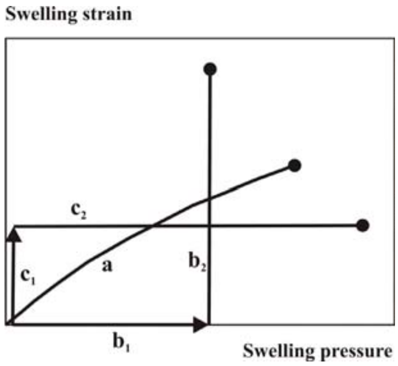

Figure 7. Two testing procedures (c = allowed swelling displacement (c_1) and measured swelling pressure (c_2) & b = allowed swelling pressure (b_1) and measured swelling displacement (b_2)) to determine and extrapolate the expected natural swelling behaviour (a) of the sample (according to Kirschke *et al*. 1991).

Powder swelling test (according to Thuro 1993)

A new approach to the swelling problem in laboratory testing was undertaken by Thuro in 1993. The target was to obtain data quickly. Therefore he dried and ground the natural sample and put it into a modified oedometer cell (Figure 9). A maximum of six cells can be put in a so called “Swellomat” (Figure 8). The measured swelling displacement occurs very fast (days to weeks) because the surface of the sample powder is many times larger than the original sample in natural conditions.

Another advantage of this method is the possibility to test all kinds of material. The size, water content, disturbance etc. of the sample is irrelevant for the test.

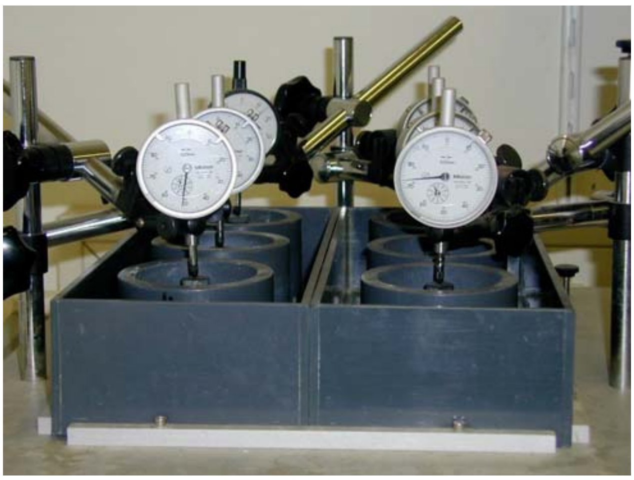

Figure 8. “Swellomat” according to Thuro 1993. Two water basins with 3 swelling cells (“Ödometerzelle”) each. The displacement is measured manually or by displacement probes.

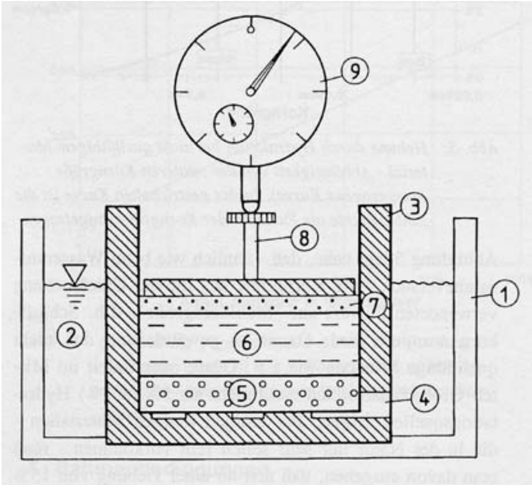

Figure 9. Drawing showing the test setup ("Ödometerzelle") for the powder swelling test. 1=water tray, 2=water, 3=swelling cell, 4=drainage hole, 5=lower porous plate, 6=sample, 7=upper porous plate, 8=cap, 9=dial gauge (according to Thuro 1993).

Method and sample preparation

The powder swelling test is a normal swelling strain test with rigid radial restraint. It was carried out with and without an axial load (axial pressure) on the sample (Figure 11). The most important difference to other swelling tests concerns the sample preparation. The sample is dried and ground to a powder. In this study the material was generated from swellable Sodium-Bentonite and non swelling Quartz. Therefore the samples were always well-defined and identical for each test. The powder is placed in the oedometer cell (Figure 9) which has a diameter of 70 mm. The sample height should be around 18 mm to obtain a density around 1.5 g/cm^3.

A usual test run is shown in Figure 10. The swelling displacement is expressed in percent correlated to the original sample height. The swelling strain is plotted against the time in minutes. Most of the swelling displacement occurs in the first third of the test. After around 14 days the curve begins to flatten and reaches a level after around 6 weeks.

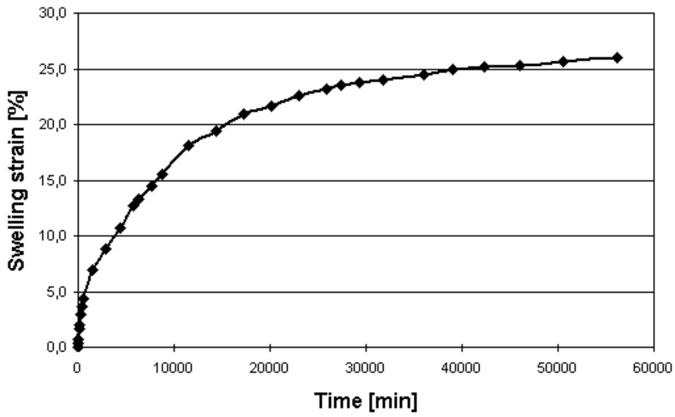

Figure 10. Trend of a typical powder swelling test (according to Thuro 1993). The sample was mixed from 25% Sodium-Bentonite and 75% Quartz. The axial pressure was 5 kN/m^2. The material has a swelling strain of 26% (from the primary height).

Application of an axial surcharge

Two different testing setups were used. Firstly a test series with a static axial load on the sample was carried out. The load had a weight of 1.96 kg which is equivalent to 5 kN/m^2 static axial pressure on the sample. In the second test series only a minimum load of porous plate and cap (together 72 g, equivalent to 0.18 kN/m^2) was used. The results of the different series are shown in Figure 11. Both series show a good linear correlation between swelling strain and percentage content Sodium-Bentonite. The swelling strain with minimal restrictions is around 3 times larger than the swelling strain with the constant axial surcharge.

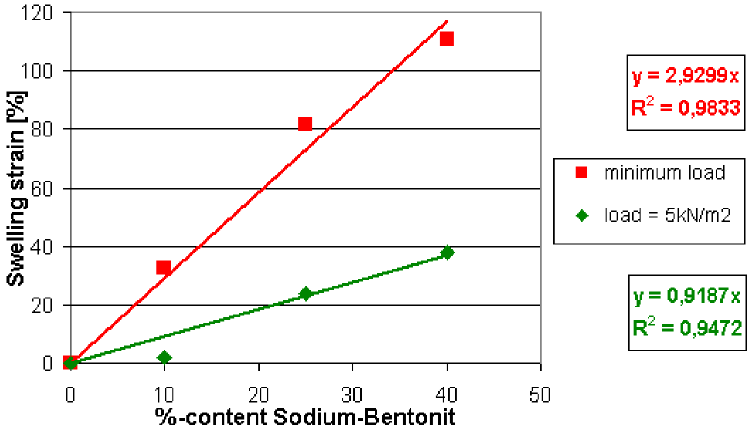

Figure 11. Comparison of different testing setups for the powder swelling test. Red rectangles show the swelling strain with minimum load whereas the green rhombs represent the swelling strain with 5 kN/m^2 axial load. The displacement is correlated to different %-content of Sodium-Bentonite.

CORRELATION

The results of the powder swelling tests (according to Thuro 1993) in comparison to the different swelling pressure tests can be seen in Table 1. All tests have been carried out with identically prepared samples with defined Sodium-Bentonite contents (10%, 25% & 40%) accordingly mixed with Quartz (90%, 75% & 60%).

It appears very interesting that the test procedure according to Henke *et al.* (1975) gives on average 2.0 to 2.5 times larger values than the test procedure according to Huder & Amberg (1970) (see also Figures 3 & 5).

Table 1. Correlation between Sodium-Bentonite content, swelling strain (powder swelling test (PST) according to Thuro 1993) and Swelling pressure (swelling tests according to Huder & Amberg 1970 & Henke et al. 1975)

Sodium-Bentonite content (%)	Swelling strain (PST) (minimum axial load) (%)	Swelling strain (PST) (5 kN/m^2 axial load) (%)	Swelling pressure (Huder & Amberg) (kN/m^2)	Swelling pressure (Henke *et al.*) (kN/m^2)
10	32.7	2.1	50	140
25	81.8	23.8	200	430
40	111.0	38.0	300	830

The result of the tests carried out are plotted in Figure 12 and Figure 13. It seems that they all have a good linear correlation. Therefore swelling strain results of the powder swelling test can be related to an axial stress from swelling pressure test after Huder & Amberg (1970) (Figure 12) and Henke *et al*. (1975) (Figure 13).

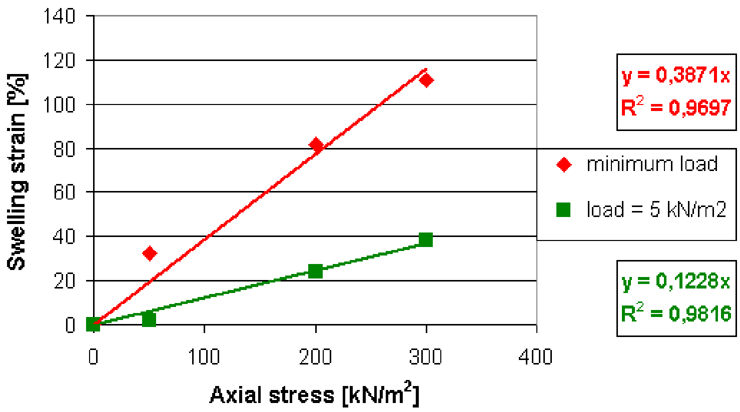

Figure 12. Correlation between swelling strain [y] (powder swelling test according to Thuro 1993) and the axial stress [x] (swelling pressure test according to Huder & Amberg 1970). The red rhombs correspond to swelling strain with minimum axial load whereas the green rectangles correspond to swelling strain with 5 kN/m^2 axial pressure.

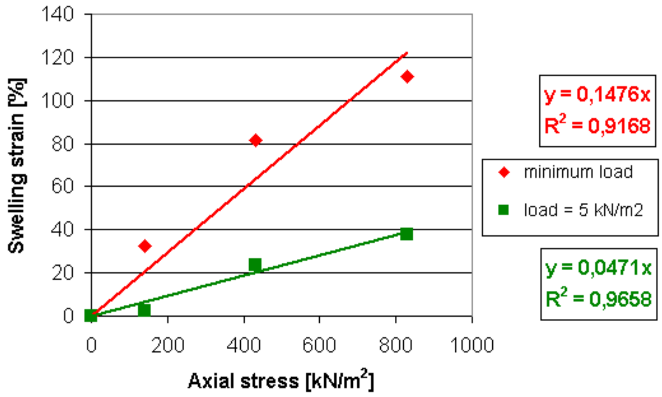

Figure 13. Correlation between swelling strain [y] (powder swelling test according to Thuro 1993) and the axial stress [x] (swelling pressure test according to Henke *et al.* 1975). The red rhombs correspond to swelling strain with minimum axial load whereas the green rectangles correspond to swelling strain with 5 kN/m^2 axial pressure.

CONCLUSIONS

In the future it is possible to correlate three common laboratory swelling test methods. It is a first approach to gain fast laboratory test results for swelling pressure by means of the powder swelling test. To prove the results presented here, comparative studies on natural sample material have to be carried out. Furthermore a correlation to the swelling tests according to Kirschke (1987) and Kirschke *et al.* (1991) should be investigated. It is also planned to extend the study on identical samples with a swelling pressure test with zero volume change (ISRM 1989).

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REFERENCES

HENKE, K. F. & KAISER, W. & NAGEL, D. 1975. Geomechanische Untersuchungen im Gipskeuper. *Strassenbau und Strassenverkehrstechnik*, **184**, 149-169. (in German).

HUDER, J. & AMBERG, G. 1970. Quellung in Mergel, Opalinuston und Anhydrit. *Schweizerische Bauzeitung*, **88**(43), 975-980 (in German)

ISRM 1989. Suggested methods for laboratory testing of argillaceous swelling rocks. *Int. J. Mech. Min. Sci. & Geomech. Abstr.*, **26**(5), 415-426.

KIRSCHKE, D. 1987. Laboratory and in situ swelling tests for the Freudenstein tunnel. *Proc. 6th Int. Congr. Rock Mech.,* Vol. 3, 1492-1496, Montreal.

KIRSCHKE, D., KOVARI, K. & PROMMERSBERGER, G. 1991. Bemessungsgrundlage und Konstruktion der Sohle des Freudensteintunnels. *Ibw 7 - Der Freudensteintunnel*, 40-57. (in German)

PAUL, A. 1986. Empfehlung Nr. 11 des Arbeitskreises 19 – Versuchstechnik Fels – der DGEG – Quellversuche an Gesteinsproben. *Bautechnik*, **63**(3), 100-104 (in German)

THURO, K. 1993. Der Pulver-Quellversuch – ein neuer Quellhebungsversuch. *Geotechnik*, **16**(3), 101-106 (in German).