Laboratory swell tests on overconsolidated clay and diagenetic solidified clay rocks

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ABSTRACT: In order to the expected swell heaves due to excavation of the cuttings at the high-speed railway Nürnberg – Ingolstadt extensive swell tests on diagentic solidified clay rocks with different weathering grades and on overconsolidated clays were performed. The tests, carried out in different devices and under different loading conditions, are described. The results are shown, assessed and briefly summarized. The determined final swell heaves and their accompanying time-heave plots are described and analysed on basis of an one-dimensional swelling law. The advantages and disadvantages of the different test types are shown in order to provide realistic swell behaviour in situ.

1 INTRODUCTION

The high-speed railway from Nürnberg to Ingolstadt passes from north to south the Nürnberg Depression Area, the northern Alp Foreland, the Frankish Alp and the Ingolstadt Basin. Because of the considerable relief varieties and high requirements along the alignment, numerous embankments, cuttings, bridges and tunnels are necessary, at which complicated geological and hydro geological conditions must be accounted.

The alignment traverses regional in the northern Alp Foreland diagenetic solidified clay rock and in the Frankish Alp respectively in the Ingolstadt Basin sedimentations of tertiary, predominantly overconsolidated clays. Because of the potential swellability of these rocks and soils, swell heaves occur in the cutting subgrades due to excavation.

The high-speed railway is constructed as a slab track system, hence the tolerable deformation during the rail traffic is very low. Swell heaves after the installation of the concrete track must not exceed the correction value for the adjustability of the fastening system.

For this reason it is necessary to predict reliable swell heaves to control the swelling for the construction of the high-speed railway (von Wolffersdorff et al. 2002). These predictions of swell heaves include the final swell heaves and the time-heave plots. Both are founded on laboratory tests and on swell heave measurements in situ.

2 SWELL BEHAVIOUR

2.1 *Tertiary Clay*

Swell heaves caused by excavation in tertiary clays and diagenetic solidified clay rocks originates mainly from osmotic and mechanical swell processes (Fritzsche 2002). The swellability of the tertiary clay depends not only on the composition of the clay minerals, but also on the loading history, which usually results in an overconsolidation.

2.2 *Diagenetic solidified clay rocks*

Three different kinds of diagenetic solidified clay rock with distinctive swellability were found: Feuerletten, Opalinuston and Amaltheenton. The diagenesis in the clay rocks results, in difference to tertiary clays, in a solidification which counteracts to the swellability. The diagentic consolidation decreases with increasing weathering. A clear relationship between diagenesis, weathering grade and swellability could not be proved yet. For the swell characteristics of solidified clay rocks the following relationships were assumed at first.

- Higher weathering grade cause in higher swell values due to unloading.
- Higher weathering grade cause in lower swell potential, i.e. lower swell pressures at completely restrained volumetric expansion.
- Higher weathering grade cause in faster swell processes.

In the framework of the geological modelling the following 4 homogeneous areas with different swell characteristics have been defined depending on weathering grades:

- weathering grade w_2 and lower weathered
- weathering grade w_2-w_3
- weathering grade w_3
- weathering grade w_3-w_4 and stronger weathered

3 LABORATORY TESTS

3.1 *Type of swell tests*

For the investigation of the swelling in the cuttings all together 169 tests in 4 different laboratories has been carried out with the diagenetic solidified clay rocks and with the tertiary clay. With regard to the loading regime the tests differ as follows:

- combined swell pressure-swell heave tests,
- multi-stepped swell heave tests,
- Huder Amberg swell tests.

Table 1 gives an outline of all carried out swell tests ordered by the kind of soil and rock, laboratories and loading regimes.

Table 1. Swell tests.

	SP-SH test[1]	Swell heave test			Huder Amberg test		
	TU Karlsruhe	GH Kassel	Baugrund Dresden	TU München	GH Kassel	Baugrund Dresden	TU München
Feuerletten (kmF)	17	20			3	19	
Amaltheen Clay (lv)	13	7	3		3	6	
Opalinus Clay (al1)	6	4				15	
Tertiary Clay (tt, tk)	22		7	7			17

[1] Combined swell-pressure swell-heave test

In the following sections the test procedures and the loading regimes respectively the stress-strain curves are described.

3.2 *Experimental procedures*

Usually the swell behaviour is investigated with one-axial deformation tests (oedometric tests). The predictions of swell heaves, founded on an one-dimensional swelling-law (see Section 4) are supported mainly by one-axial deformation tests.

A test is called swell heave test, if the axial swell expansion ε_z^q is determined by a predetermined axial compressive stress σ_z (see Fig. 1). It is force-controlled and can be carried out with conventional devices (oedometer).

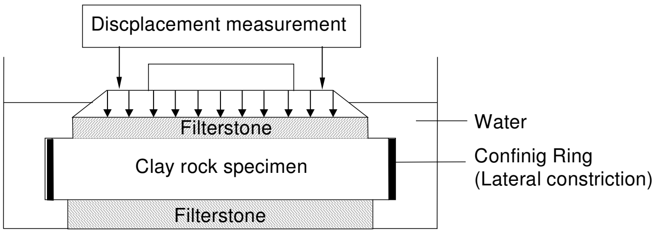

Figure 1. Force-controlled swell heave test.

In contrast a test is called swell pressure test, if the maximum stress σ_{z0} is determined by a fixed boundary in axial direction (see Fig. 2). It requires a deformation control system, which is generally not available in conventional devices.

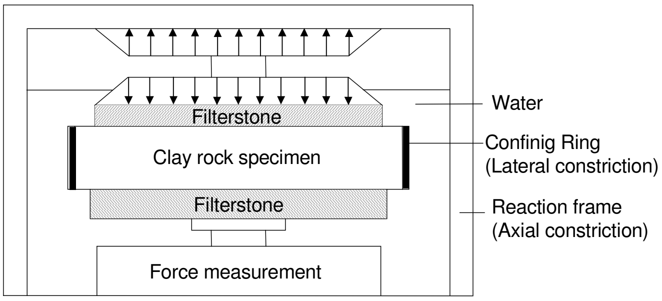

Figure 2. Deformation-controlled swell pressure test.

Experimental conditions of the combined swell-pressure swell-heave tests are much more complicated. Therefore an electronic control system is required to predetermine both, axial forces and axial displacements.

3.3 *Sample preparation and stress-strain curves*

The swell characteristics in situ of diagenetic solidified clay rock and predominantly overconsolidated clays are significantly different from these, which are ascertained in laboratory tests on prepared sampling material. Therefore it is necessary to place in the samples widely undisturbed, before the swelling process starts. The origin material has not to be exposed to a loading as possible. Otherwise the diagenetic bonds will be destroyed or the overconsolidated stresses will be changed.

The combined swell-pressure swell-heave test is characterized by a fixed boundary in axial direction after the widely undisturbed samples is placed in. Subsequently water is admitted and the swelling starts, i.e. the compressive stress σ_z increases until the swelling pressure σ_{z0} is reached. These increasing of stress describes a horizontal line in a stress-strain chart (see Fig. 3).

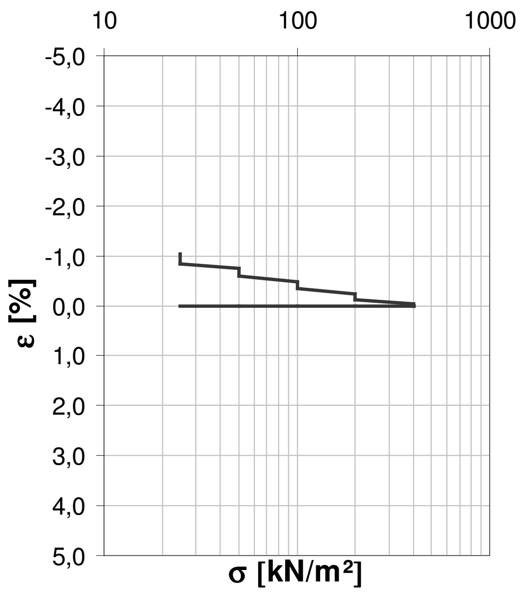

Figure 3. Stress-strain curve of the combined swell-pressure swell-heave test (several steps of heaves).

During the following heaving stage, the axial stress is reduced to a defined value, whereas a spontaneous heave occurs. Afterwards the stress is kept constantly and a swell heave develops. The swelling process is observed until the swell heave fades widely away, thus the final swell heave is reached. The stress-strain-curve for this stage has the shape of a step (increasing curve with decreasing stress and subsequently a vertical line). The heaving stage of the combined swell-pressure swell-heave test, shown in Figure 3, includes those 5 steps.

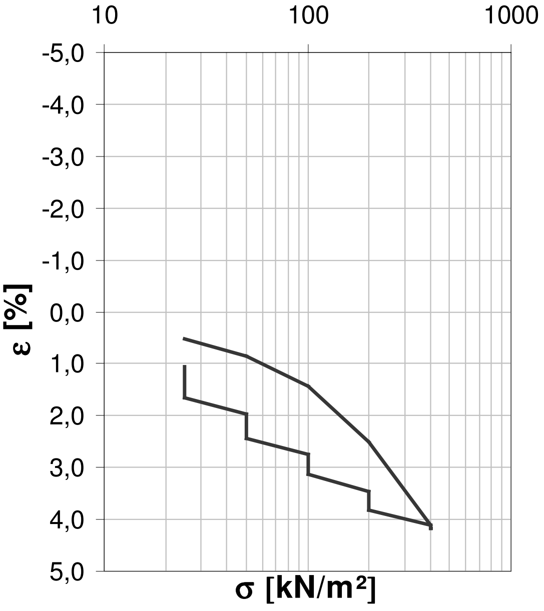

Figure 4. Stress-strain curve of the swell heave test (several steps of heaves).

In Figure 3-5 it is obvious, that in all 3 kinds of tests the 5 stepped heaving stages are the result of the same experimental procedure. The experimental procedure of the swell heave test, the Huder Amberg swell test and the combined swell-pressure swell-heave test differ only in the initial state before the swelling starts.

Before admitting water and heaving start, the conventional swell heave test is characterized by an one-axial compression (oedometric loading) until a defined compressive stress is reached. This compressive stress is assumed empirical and should approximate the swelling pressure σ_{z0}.

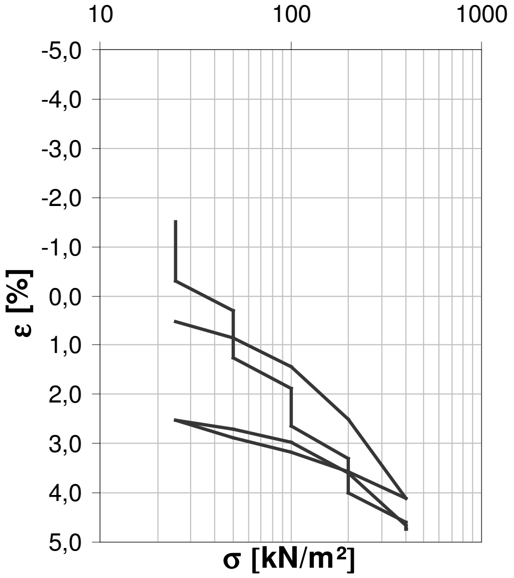

Figure 5. Stress-strain curve of the Huder Amberg test (several steps of heaves).

The Huder Amberg test differs only from the conventional swell heave test in a complete loading-unloading-reloading cycle before the swelling starts.

Both the conventional swell heave test and the Huder Amberg swell test have the following disadvantages:

- Besides the inevitable structural changes as the result of sampling and placement the specimen gets additional disturbed by the preloading to a more than less arbitrarily selected compressive stress.
- The swelling pressure σ_{z0}, which compensates the swell heave completely, cannot be experimentally determined.

The analysis of the swell tests is based of an one-dimensional swelling law, which is briefly described in the following section.

4 1D SWELLING MODEL

4.1 *Final swell heave*

The logarithmic approach according to Grob is used here for the presented one-dimensional swelling model (Grob 1972). It is shown in Figure 5.

The stress σ_{z0} of Figure 5 is a maximum value, which over presses the swelling completely. The stress σ_c is a minimum value. The swelling does not increase for lower compressive stresses than σ_c. The swell heave coefficient C_b describes the dependence between the swelling and the vertical stress σ_z. The both parameters C_b and σ_{z0} of the swelling model are determined by laboratory tests.

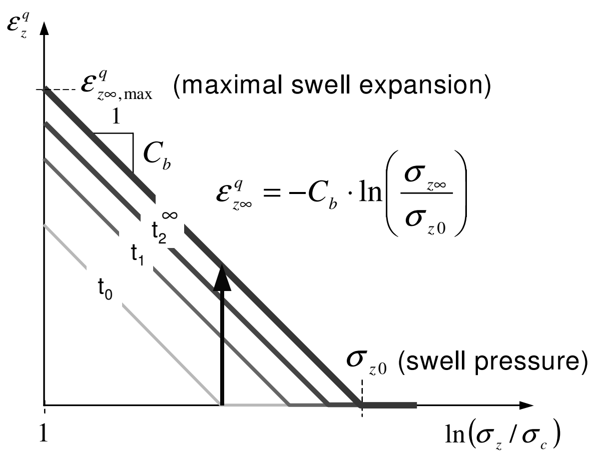

Figure 5. 1D swelling model.

4.2 *Time plot of the swell expansion*

Kiehl proposed a time-depended extension of the swelling model that is shown in Figure 5 (Kiehl 1990). With assumption of constant unloading stress values the following equation can be written.

$$\varepsilon_z^q(\hat{t}) = -C_b \cdot \ln\left(\frac{\sigma_{z\infty}}{\sigma_{z0}}\right)\left[1-\exp\left(-\frac{\hat{t}}{\eta_q}\right)\right] \tag{1}$$

The parameter η_q describes a time reference unit and is determined by using the time-heave curves of the swell tests.

In Equation 1 the new variable $\hat{t}$ is introduced, which defines a modified time to obtain time-plots independent of the layer thickness. The following power approach describes the relationship between the modified time, the real time and the thickness of swelling layer as well as of the sample,

$$\hat{t} = t \cdot \left(\frac{d_{\text{specimen}}}{D_{\text{layer}}}\right)^n \tag{2}$$

The exponent n of (2) adjusts the influence of the thickness dependence on time-swell behaviour. This exponent is calibrated by an approximation to preliminary heave measurements in situ, e.g. extensometer measurements.

5 ANLAYSIS OF THE TEST DATA

5.1 *Purpose of the analysis*

Both parameters of the swelling model C_b and σ_{z0} and the time reference unit η_q according to (1) and (2) were determined by using of above named extensive test series. Various calibration procedures were developed and applied to determine representative parameters and to verify the applicability of the swelling model.

Furthermore the mentioned relationships between weathering grade and swellability were quantified and checked by using the test series on the diagenetic solidified clay rocks.

5.2 *Final swell heave*

A few basic results are selected from the extensive analysis of the test series and are presented in suitable charts. Figure 6 shows the results of a series of conventional swell heave tests on tertiary clay in an ε-logσ-chart.

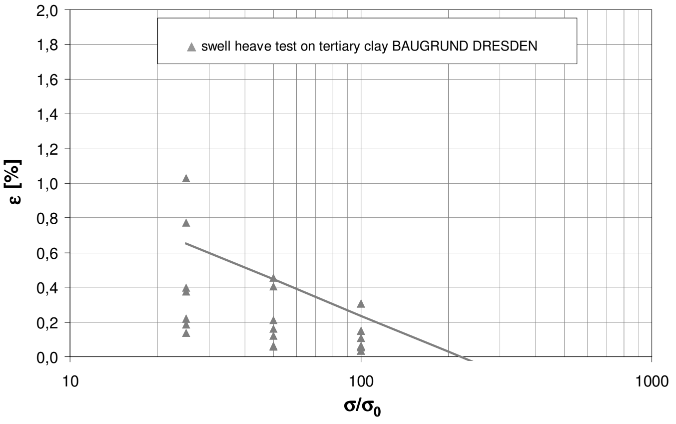

Figure 6. Representative swell-strain straight-line as the result of swell heave tests on tertiary clay.

In Figure 6 is shown, that the test results scatter significantly. But the stress dependence of the swell heaves relating to every individual test is described very well by means of the above named swelling model.

The swell-strain straight line shown in Figure 6 is the result of a representative calibration procedure of C_b and σ_{z0} from the test results. Because the representative swelling pressure σ_{z0} cannot be determined directly, the calibration for both parameter is very sensitive and should not carried out by using statistical methods only.

The scatter of the test results of diagentic solidified clay rocks is still greater than the results of tertiary clay, although samples of the 4 homogeneous areas with different swell characteristics were separately analysed. The calibration procedures of the swell parameters were more difficult because additional correlations between the swell parameters C_b and σ_{z0} and the weathering grade had to be accounted.

The swell-strain straight lines demonstrate the relationship between swellability and weathering grade for the 4 weathering grades of Feuerletten, which is described in Section 2 (see Fig. 7). The represented 4 swell strain straight-lines are the results of the predominantly empiric calibration procedure of the swell parameters C_b and σ_{z0} (Fritzsche 2002).

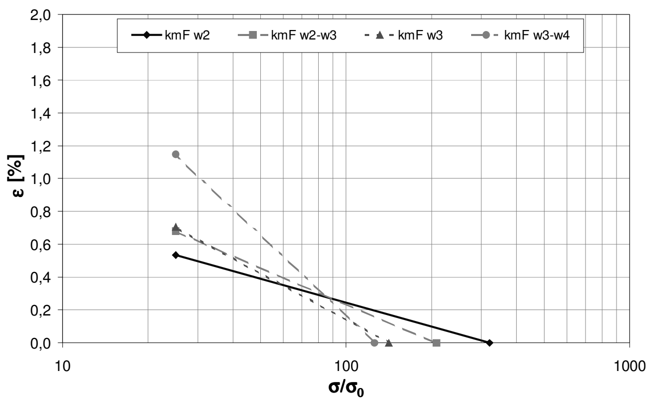

Figure 7. Swell-strain straight-lines for the different weathering grades of Feuerletten as the result of a representative analysis of the swell parameter C_b and σ_{z0}.

Although the test series were carried out on material from the same homogeneous area with similar loading regime, and in one and the same laboratory the results scatter also considerably. These scatters are greater than these, which occur by the determination of shear strength parameters φ and c using a comparable data basis.

5.3 *Time-heave plots*

The time heave-plots of the swell tests are analysed both to determine the reference time unit η_q and to separate the swell heaves from other heave parts.

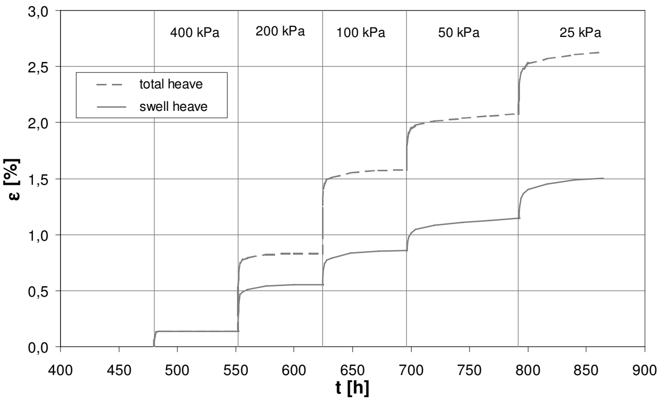

Figure 8. Time-heave plot and time-swell heave plot of a conventional 5-stepped swell heave test.

Figure 8 shows the time-heave plot and the time-swell heave plot of a conventional swell heave test with 5 steps. The separation of the swell heave from the total heaves is more than less arbitrarily.

The time at which spontaneous heaves due to unloading are faded away depends on the material structure and the previous loading history. For instants a pore water pressure balance can occur in terms of a reverse consolidation after the maximum compressive stress is applied. Thus arising heaves occur already within a very short time.
These effects were considered in Figure 8 by the separation of the time-heave plot in a swell part and a further heave part.

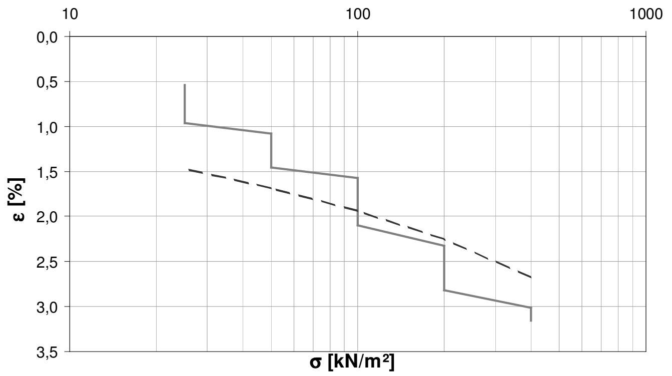

Figure 9. Stress-swell strain curve of a 5-stepped swell heave test and stress-strain curve of a conventional oedometer test

The magnitude of the spontaneous heaves due to unloading can be also estimated on the basis of the unloading in oedometer tests on the same material. Figure 9 shows the stress-swell strain curve of a 5-stepped swell heave test and the unloading of an oedometer test. The determined slopes of the spontaneous heave steps should agree with the tendency of the unloading curve of a conventional consolidation test.

6 INFLUENCE OF THE TEST TYPE ON TEST RESULTS

6.1 *Diagenetic solidified clay rocks*

Swell tests with different loading regimes were carried out on same material to investigate the influence of the loading regime on the swell value before the swell process starts. An analysis is exemplary given for the Feuerletten. On sampling material of the homogeneous area „weathering grade w3“ combined swell-pressure swell-heave tests, conventional multi-stepped swell heave tests and Huder Amberg swell tests were carried out. Figure 10 shows the results of the 3 test series and the accompanying representative swell-heave straight lines. The outcome is a strong dependence between swellability and test type. Hence the following qualitative relationship results.

- Combined swell-pressure swell-heave tests
  ⇒ low swellability (low C_b and σ_{z0} values),
- Conventional swell heave tests
  ⇒ middle swellability (middle C_b and σ_{z0} values),
- Huder Amberg swell tests
  ⇒ high swellability (high C_b and σ_{z0} values).

The results of the actual heave predictions and heave measurements in situ prove, that the calculated swell heaves on the basis of the swell parameters C_b and σ_{z0}, determined by combined swell-pressure swell-heave tests, are close to reality. Against it, the swellability determined on the basis of the other two test types is too high in order to specify the swell behaviour of diagenetic solidifided clay rocks.

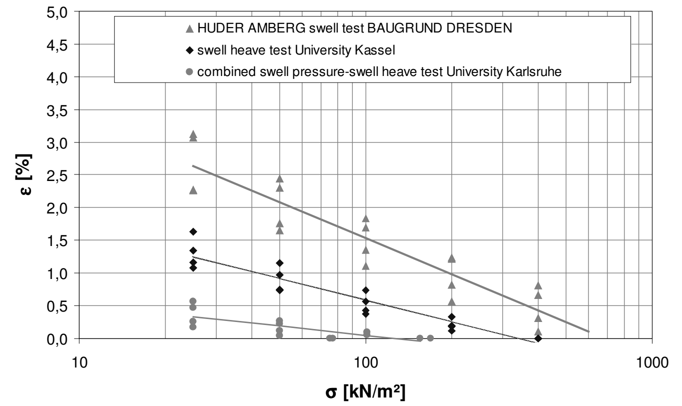

Figure 10. Results of 3 different test series on Feuerletten and corresponding representative swell-strain straight-lines

Conventional swell heave tests and Huderr Amberg swell tests are not suitable to assess the swell behaviour in situ of diagenetic solidified clay rocks under laboratory conditions. Due to the preloading before swelling starts the diagenetic bonds were destroyed, even if widely undisturbed samples were placed in.

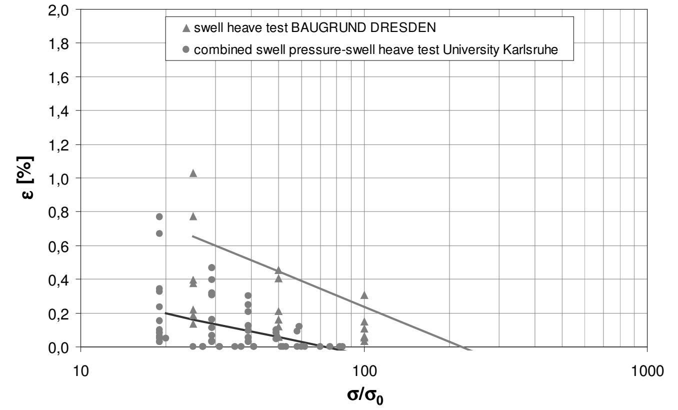

Figure 11. Results of 2 different test series on tertiary clay and corresponding representative swell-strain straight-lines

6.2 *Tertiary clay*

All 3 test types were also carried out on tertiary clay. Figure 11 shows the results of the combined swell-pressure swell-heave tests and the results of the conventional swell heave tests as well as the accompanying swell-strain straight lines. It is obviously, that the experimental determined swellability of the tertiary clays depends on the test type as well as the diagenetic solidified clay rocks do.

The swellability of tertiary clay determined with conventional swell heave tests and Huder Amberg swell tests does not agree with the swell behaviour in situ at all, because the clay structure gets strongly disturbed by the loading regime.

7 CONCLUSIONS

This paper shows, that combined swell-pressure swell-heave tests are more suitable to describe the in situ swell behaviour of diagenetic solidified clay rocks and tertiary clay under laboratory conditions, than the conventional swell heave test and the Huder Amberg swell test.

It is recommended to force the technical development of combined swell-pressure swell-heave-tests and emphasize the advantages in according technical standards for increased use.

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