Assessment of the swelling potential of anhydrite in tunnelling projects

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Abstract: The swelling capability of anhydrite can be one of the major problems during tunnel construction in such rocks. Sometimes the fear of anhydrite swelling was unfounded, since the material was not as reactive as assumed. On the one hand, this naturally depends on the great varieties of anhydrite bearing rocks for example in age, formation, concentration or layering. On the other hand, by excluding all these differences, it is interesting to investigate whether the pure anhydrite shows different swelling behaviour, too.

To answer this question a variety of mineralogical and geochemical investigations on anhydrite samples from a tunnel construction site, a quarry and a drilling core have been carried out. Simultaneously, the swelling potential of the samples were tested with the powder swelling test (Thuro 1993). With this testing method it is possible to test, exclusively, the pure anhydrite samples with identical preparation with regard to grain size, water content, homogeneity etc. Although the test was developed to obtain faster results, in some cases the swelling went on for years.

It seems that the swelling potential of pure anhydrite depends mostly on the crystallinity and thus on the former rock cover. The results presented in this paper will help to predict the swelling character of the different anhydrites in future projects.

Résumé: La capacité de gonflement de l'anhydrite peut être un des problèmes majeurs rencontrés lors de la construction de tunnels dans une telle roche. Quelquefois, les craintes de gonflement de l'anhydrite sont non fondées car le matériau n'est pas aussi réactif que ce que l'on pense. Cela dépend d'une part des grandes variétés d'anhydrite, par exemple en âge, en formation, en concentration ou en schistosité. Mais d'autre part, si l'on exclut toutes ces différences, il est intéressant de déterminer si l'anhydrite pure présente également différents comportements de gonflement.

Afin de répondre à ces questions, diverses études minéralogiques et géochimiques ont été menées sur des échantillons d'anhydrite provenant d'un site de construction de tunnel, d'une carrière et du cœur d'un forage. Les potentiels de gonflement de chaque échantillon furent mesurés simultanément à l'aide du test de gonflement de la poudre (powder swelling test). Avec cette méthode de test, il n'est possible de mesurer que de purs échantillons d'anhydrite avec une préparation identique, en terme de taille de grains, teneur en eau, homogénéité, etc. Même si le test a été développé afin d'obtenir des résultas plus rapides, le gonflement peut prendre plusieurs années dans certains cas.

Il semble que le potentiel de gonflement de l'anhydrite dépende essentiellement de la cristallinité et donc du recouvrement initial de la roche. Les résultats présentés dans ce papier pourront aider à prévoir le caractère de gonflement des différentes anhydrites lors de futurs projets.

Keywords: evaporates, sedimentary rocks, laboratory studies, expansion, tunnels, site investigations.

INTRODUCTION

Many tunnel projects of the present and the future have to deal with the swelling capability of anhydrite. The prediction of the swelling potential is often difficult. Normally there are two different approaches possible – calculating and/or testing.

The presented study deals with the testing methods and possibilities. Unfortunately swelling tests with natural anhydrite samples need a long time and often take up to several years. To avoid the time factor the faster powder swelling test was developed (Thuro 1993).

Another important topic of this paper is to compare different anhydrite rock types. It seems that some anhydrite bearing rocks have a higher swelling capability than others. The reasons for these differences were investigated. The investigations were focused on pure anhydrite layers whereas highly swellable fine distributed anhydrites in claystones (e.g. in Gypsum Keuper) were not investigated. Furthermore the question arose, which mineralogical or geochemical investigation methods can be used to accomplish this task.

ANHYDRITE

The name anhydrite was first used by A. G. Werner in 1804 (Frye 1981). He described an orthorhombic mineral with the chemical formula $CaSO_4$, a density of 2.89 to 2.98 g/cm^3, a Mohr's hardness of 3.0 up to 3.5 and a very good cleavage. The rare crystals normally look like a cube (cube spare). Anhydrite bearing rocks are much more common. These were seldom deposited directly from water (Langbein, Peter & Schwahn 1982). Instead, most of the anhydrite

rocks were recrystallised from gypsum rocks through diagenesis. With increasing overburden this process leads to a metamorphic anhydrite. The gypsum-anhydrite-gypsum cycle (Figure 1) proceeds when the anhydrite rock returns to the surface. With low rock cover and under humid conditions the anhydrite slowly alters to gypsum.

A detailed look at an alteration zone from anhydrite to gypsum in a rock body is given in Figure 2. Underneath the surface lies a completely leached material which consists mostly of clay and silt. This zone has relatively low density and high water content. Its base is marked by the gypsum level. Further down gypsum remains next to clay and silt. This area has medium density and water content. Underneath this layer follows the anhydrite level. The centre of the hill is still built up of unaltered and more or less dry anhydrite rock.

Swelling can only appear if there is a contact between the anhydrite and water. Normally there is no water conductivity in the intact and dry anhydrite body. This situation changes with the construction of the tunnel. Beside the natural inflow many new water channels like boreholes, shafts or the tunnel entrances are developed (Figure 2).

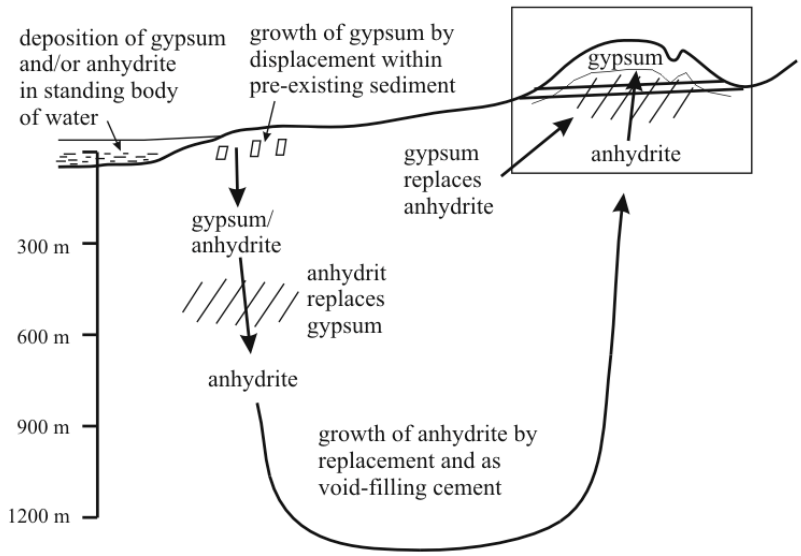

Figure 1. Schematic diagram illustrating gypsum-anhydrite-gypsum cycle (according to Murray 1964). The rectangle on the upper right side is shown in detail in Figure 2.

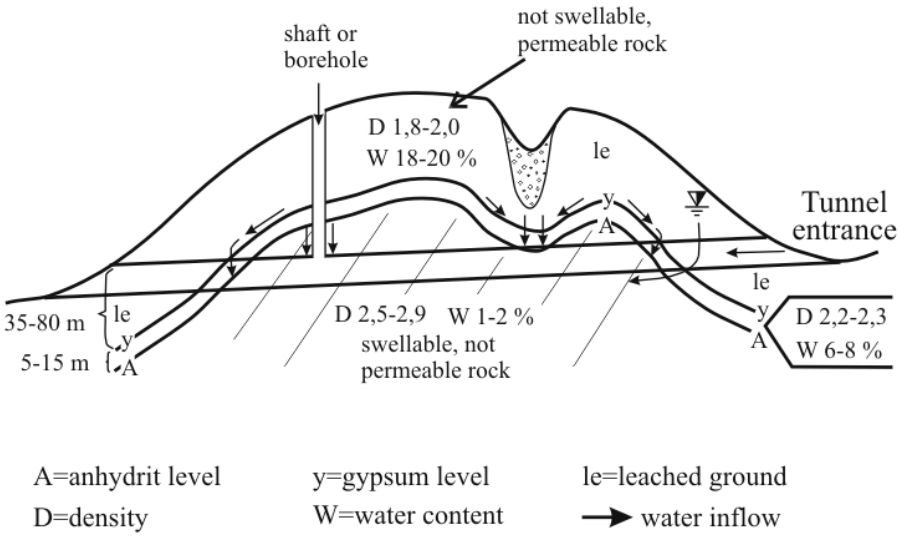

Figure 2. Rock characteristics in a sulphate containing rock mass. Also shown are areas of potential water inflow into a tunnel tube (Schematic cross section, modified according to Spaun 1979 and Amstad & Kovari 2001).

The anhydrite swelling principles

In contact with water the anhydrite alters to gypsum. The 61% volume increase from anhydrite to gypsum can be calculated from the solids. This chemical change is shown in Figure 3. It is irreversible under atmospheric conditions.

	Anhydrit	Wasser		Gips
	1 mol	2 mol		1 mol
	$CaSO_4$	+ $2H_2O$	⟷	$CaSO_4*2H_2O$
G [g]	136.14	36.0		172.14
D [g/cm^3]	2.95	1.0		2.32
V [cm^3]	46.2	36.0		74.3
V [%]	100.0	77.9		160.8

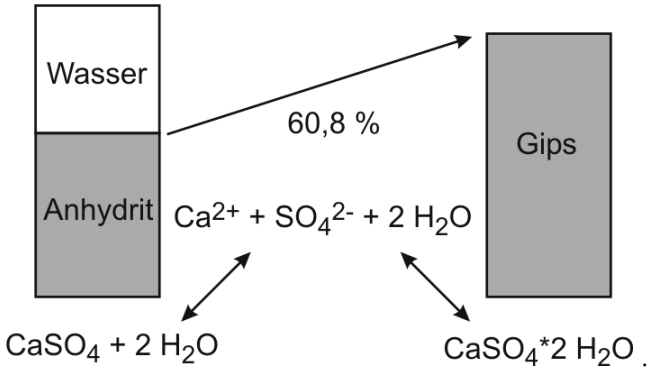

Figure 3. Chemical and physical basics of the of anhydrite-gypsum conversion. The reaction goes through a solution and crystallisation phase (modified after Amstad & Kovari 2001).

Looking closer, this equation is quite simplified, since the reaction involves a solution and a crystallisation process. Therefore we have to deal with 2 processes. The first step is the solution of anhydrite; the second step is the crystallisation of gypsum (Figure 3). Both steps are triggered through the different saturation concentrations of anhydrite and gypsum. Their value is dependent on temperature, pressure and foreign ions. This only applies to a closed system, where no calcium or sulphate ions are lost and always the perfect amount of water is available. In nature there is always an open system where the substances can move freely.

Anhydrite bearing formations

The investigations focused on anhydrite bearing formations in southern Germany and in the eastern alps. Table 1 shows a brief overview in chronological order (from the youngest to the oldest).

Table 1. Overview of the anhydrite bearing formations in the study area. The formations written bold are described in detail below.

Formation	Age	Former rock cover (estimated)	Outcrop
Pechelbronner formation	Oligocene	~1000 m*	Rhine Valley graben
Gipskeuper (Gypsum Keuper)	Upper Triassic	~1000 m*	NW Bavaria and Baden-Wuerttemberg
Mittlerer Muschelkalk (Middle Triassic)	Middle Triassic	~1200 m*	NW Bavaria and Baden-Wuerttemberg
Reichenhaller formation	Middle Triassic	~5000 m†	Northern calc. alps
Haselgebirge	Permotriassic	~6000 m†	Northern calc. alps
Zechstein	Permian	~1550 m*	NW Bavaria and Baden-Wuerttemberg

* According to Geyer & Gwinner (1968)
† According to Gwinner (1971)

Tested Material

Because of the instability of anhydrite under humid conditions, it is not easy to get fresh material from the ground surface. It was possible to collect underground samples from the following formations:

- **Haselgebirge**: This permian massive anhydrite is bluish-grey and coarse grained. It is quarried near Golling in Austria. A very good description of this anhydrite gives Wiesheu (1997). He found that this anhydrite is slightly metamorphic due to the former rock cover and stresses.
- **Reichenhaller formation**: This triassic anhydrite from the northern calcareous alps appears in massive breccias and laminated variations. It is dark grey and medium grained.
- **Gypsum Keuper**: This dark grey and fine grained anhydrite is interlayered with black claystone. The layers are between 1 and 5 cm thick. The samples were taken from a borehole near Stuttgart at a depth of around 50 m. Therefore the material is fresh and unaltered.

INVESTIGATIONS

The anhydrite was mechanically separated from the original rock. This procedure guarantees pure and unmixed anhydrite samples. The material was then prepared for each test.

Swelling capacity

Powder swelling test

The swelling capacity was tested with the powder swelling test according to Thuro (1993) where the swelling displacement of a powdered sample is measured. The separated anhydrite samples were dried, fractured and grinded to a homogeneous powder with a defined grain size between fine sand and clay. The material then was inserted in a testing cell (Figure 4). It is necessary to produce a constant density of around 1.5 g/cm^3. The height of the inserted material is around 2.0 cm. The axial surcharge was minimised and consisted of the upper porous plate and the cap (together 72 g is equivalent to 0.18 kN/m^2 pressure). Distilled water was added to start the swelling. A dial gauge measuring the vertical displacement is read off once a day.

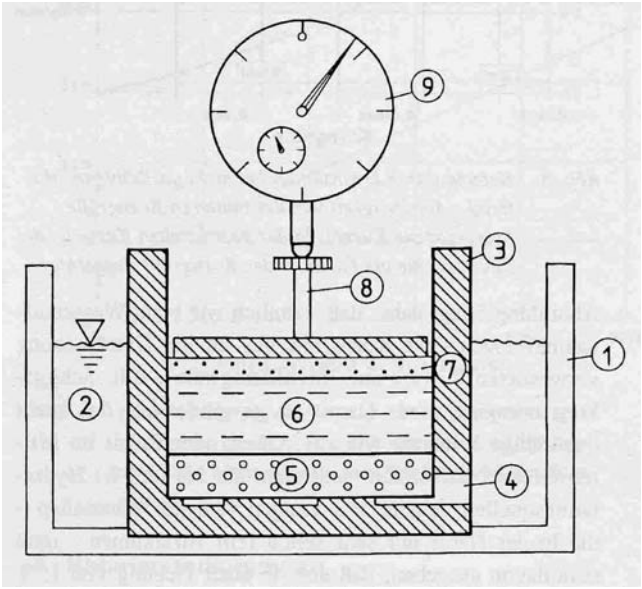

Figure 4. Drawing showing the test setup ("Oedometerzelle") for the powder swelling test. 1=water tray, 2=water, 3=swelling cell, 4=drainage hole, 5=lower porous plate, 6=sample, 7=upper porous plate, 8=cap, 9=dial gauge (according to Thuro 1993).

The results of the swelling ability tests after approximately one year are shown in Figure 5. The absolutely identically prepared and assembled anhydrite samples have very different swelling capacities. The swelling has still not finished and continues in a constant rate. Beside an interesting fact is that all 3 samples showed proportional swelling in the last ½ year.

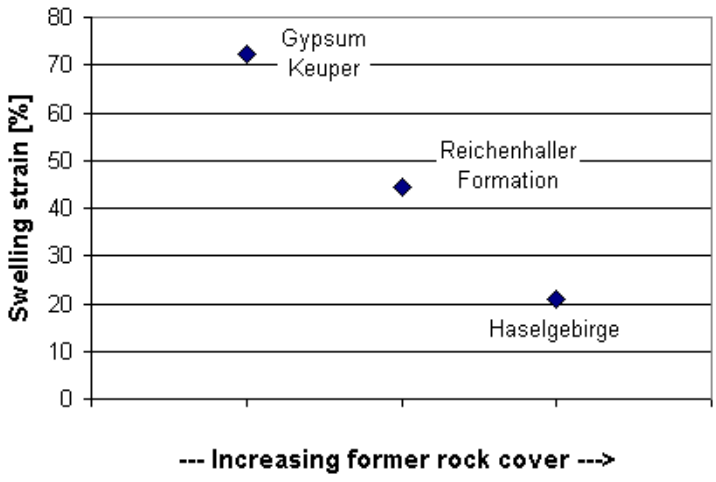

Figure 5. Decreasing swelling capacity against increasing former rock cover after around 1 year of swelling. The swelling in percent is related to the sample height at the beginning of the test.

Mineralogy and geochemistry

Thin section analysis

The thin section analyses confirmed the macroscopic observations. The anhydrite crystals get coarser as the former rock cover increases. This simplified coherence is not always admissible but it seems valid in general. Generally speaking, the coherence can also be seen at Reimann (1991) who gives a large overview of anhydrite deposits around the world. In Figure 6 a thin section of a relatively fine grained anhydrite from the Gypsum Keuper is shown. At the same enlargement the anhydrite from the Haselgebirge shown in Figure 7 has much coarser crystals.

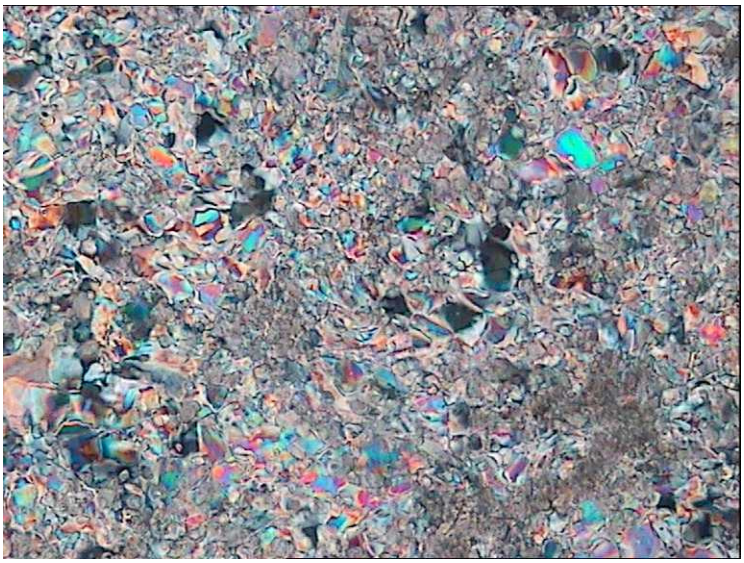

Figure 6. Thin section image of the Gypsum Keuper sample with small anhydrite crystals. Crossed nicols, picture width approx. 0.65 mm.

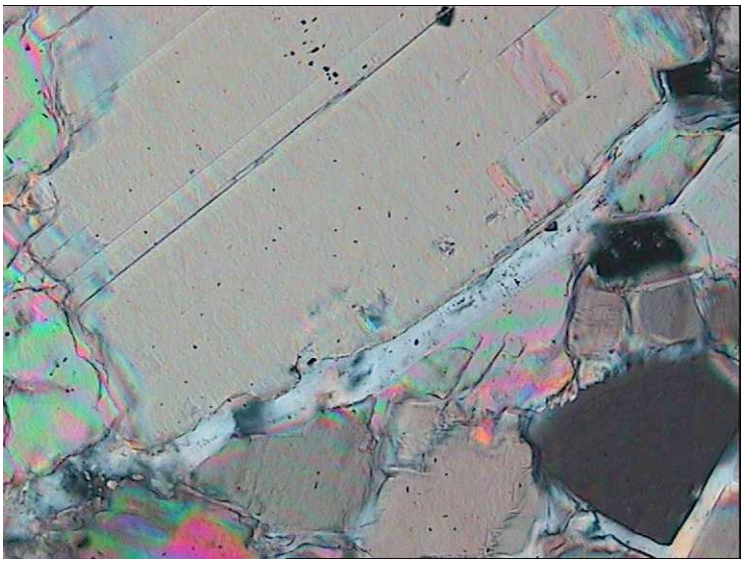

Figure 7. Thin section image of the Haselgebirge sample with large anhydrite crystals. Crossed nicols, picture width approx. 0.65 mm.

Scanning electron microscope analysis

The scanning electron microscope was used to examine the micro-structure of the samples. Small plates in the size of approx. 1 cm^2 were glued on specimen holders and were vaporized with gold to increase the conductivity. The SEM-analyses where made with a LEO 1525 SEM with SE-, InLens- and QBSD-Detector at the Zentrum für Werkstoffanalytik Lauf, Germany. Interesting details were recorded (Figure 8 & 9). Special attention was paid to the texture. Noticeable is the more porous Gypsum Keuper sample. These pores are possible water channels and weak points concerning the crystal stability. In contrast to that the sample from the Haselgebirge appears very compact and impervious.

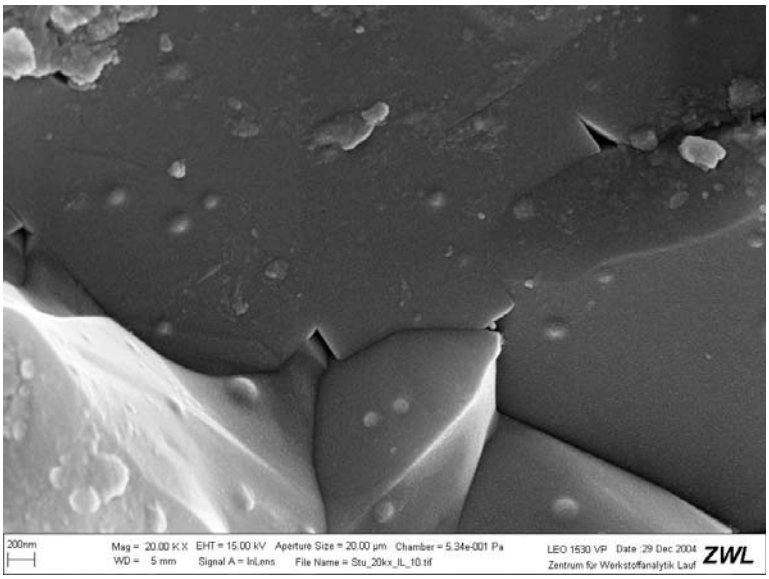

Figure 8. SEM image of the Gypsum Keuper anhydrite sample. Please notice the pores between the single crystals. Picture width approx. 5000 nm.

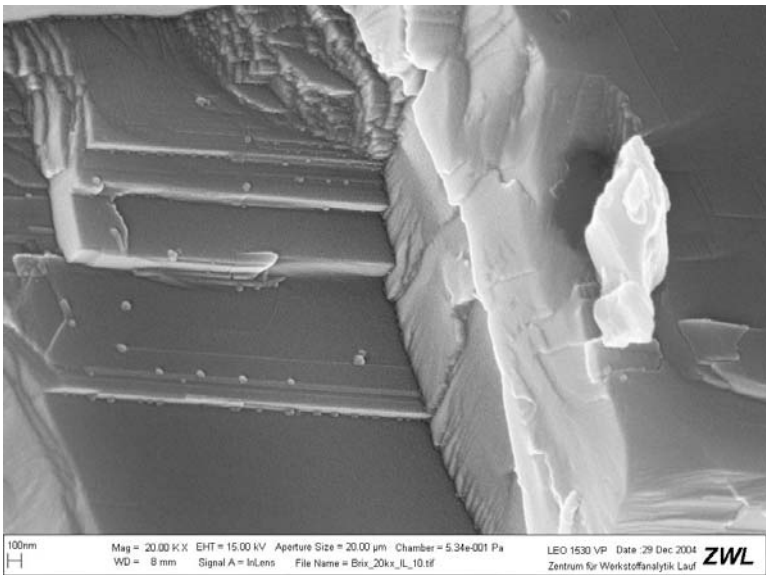

Figure 9. SEM image of the Reichenhaller formation anhydrite sample. The material looks very compact and impervious. Picture width approx. 5000 nm.

X-ray diffraction analysis

X-ray diffraction analysis was used to determine the qualitative mineralogical composition of the samples. In this method the diffraction of monochromatic X-rays on the surface of a crystal lattice produces varying reflection intensities (X-ray reflexes) at varying angles. These reflexes are measured and typical reflexes can be determined for each mineral, depending on the dimension of the spacing from the lattice plane (d-value). The experiments were done with a fully automatic X-ray diffractions apparatus (Philips-PW 1800 with monochromator; CuKα) at the chair of Engineering Geology, Technische Universität München.

For this purpose subspecimens were extracted from the samples. They were dried approx. 24 hours at 40° degrees Celsius until a constant mass was reached. Afterwards the material was homogenised and pre-grinded in a ring-shaped agate stone mill. The milling < 40 µm was done by manual work in an agate-mortar. From this extracted material texture-free powder-samples were prepared. The overview scans (Figure 10) were made in an angular range between 0° and 70° (2Θ). The identification of the mineral associations contained in the sample occurred by the means of the d-values and the characteristic lines of the diffraction (reflex) via an identification program (Philips-IDENTIFY).

All three anhydrite samples in Figure 10 show similar peaks for anhydrite (06-0226). They do not differ in their mineralogical character concerning X-ray diffraction.

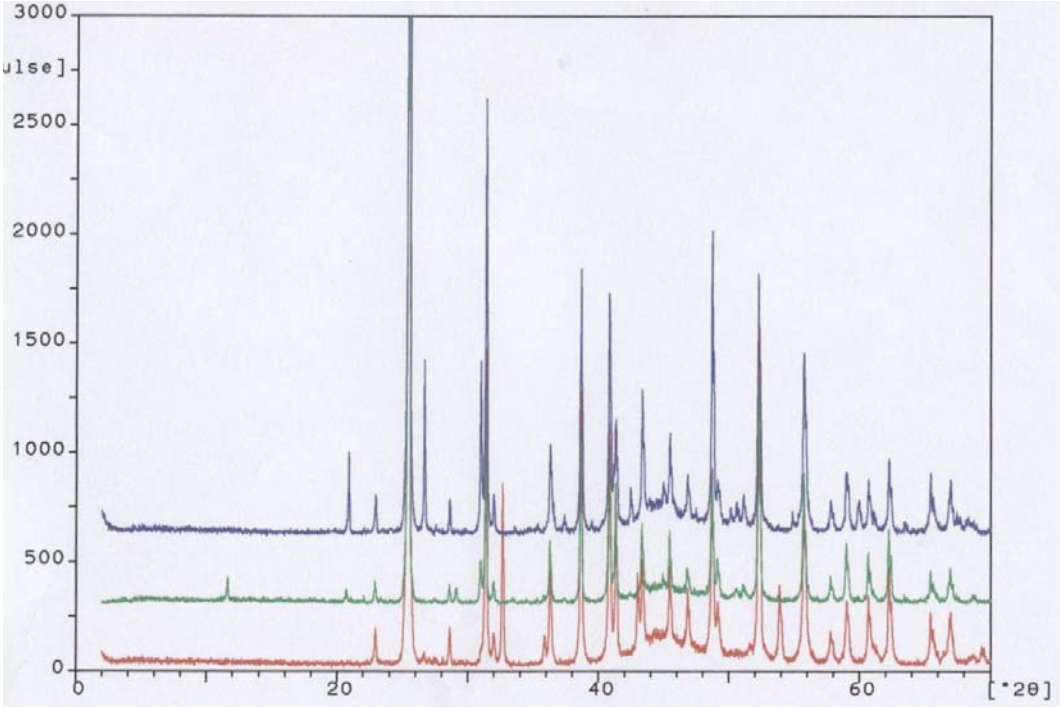

Figure 10. Relation and analogy between the mineralogical RDX data of the different anhydrite samples. Blue (upper graph) = Gypsum Keuper, green (middle graph) = Haselgebirge, red (lower graph) = Reichenhaller formation.

Specific surface analysis (air permeability method after Blaine / DIN EN 196-6 (1990))

The air permeability method after Blaine was used to make a statement of the specific surface (quantity based surface) of the different anhydrite samples (DIN EN 196-6 (1990)). The test was performed at the material testing laboratory of the Technische Universität München.

The samples had to be prepared all at the same way before measuring the specific surface. For that purpose they had to be dried and milled in an agate mill for three minutes each. After that a mineral size fraction <40 µm was extracted by means of dry sieving. The density of the material was determined with the pycnometer (D = 2.94 g/cm^3). Samples of 2.455 g each were produced and filled into the testing cells. Then the samples were compressed to a volume of 1.67 cm^3.

During the test air flows through the bed of anhydrite and the time which a certain amount of air needs to pass the sample is measured. Using the measured time, the instrument constant K (2.39), the density of the material and the value 524.2 (derived from the porosity e = 0.5 and the surrounding temperature T = 20.5) the specific surface (Blaine-Value) can be calculated.

Table 2. Results of the Blaine-Value test.

Sample	Blaine-Value	Surface area	Swelling capacity
Gypsum Keuper	5680	large	high
Reichenhaller formation	3340	middle	medium
Haselgebirge	2240	small	low

CONCLUSIONS

The swelling capability of anhydrite depends on the crystallinity and therefore on the former rock cover. Fine grained anhydrites normally had a smaller overburden in their history. Coarse-grained anhydrites, on the other hand, had a larger former rock cover. The grain size can be determined by thin sections analysis. The main result of the powder swelling tests is that with increasing size of the crystals the swelling potential decreases. This observation is linked to size of the specific surface area. Naturally coarser crystals have less surface area. But even if cracked and milled to an identical grain size the former fine-grained material has a much higher Blaine-Value. This indicates a larger surface and therefore a higher swelling capability (Figure 11).

For future projects it is necessary to carry out powder swelling tests to obtain quick swelling data, in combination with an intensive thin section analyses and a surface examination (Blaine-Value). With these tests it is possible to get a quick idea of the swelling potential of pure anhydrite rocks.

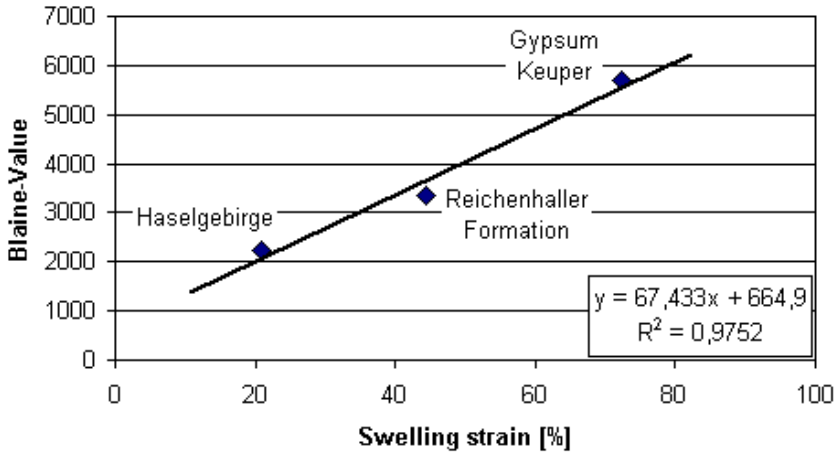

Figure 11. Linear correlation between Blaine-Value (specific surface after DIN 196-6 (1990)) and swelling capacity (from the powder swelling test according to Thuro 1993).

Acknowledgements: Many thanks to the Technische Universität München who financed the investigations with a scholarship for junior scientists in 2001 to 2003.

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