International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Experimental Investigation on the Influence of Swelling on Hydraulic Conductivity in Sulfate Rocks

Maximiliano R. Vergara
gbm Gesellschaft für Baugeologie und-meßtechnik mbH Baugrundinstitut, Ettlingen, Germany
Institute of Soil Mechanics and Rock Mechanics, Karlsruhe Institute of Technology KIT, Karlsruhe, Germany
maxvergara@gmail.com

Abstract

Swelling in rock masses can significantly affect the serviceability of foundations and underground excavations. In sulfate rocks, swelling is driven by two key processes that lead to an increase in the rock's volume: the hydration of clay minerals and the transformation of anhydrite into gypsum. Generally, the swelling strains and stresses resulting from the anhydrite-gypsum transformation are considerably greater than those caused by the hydration of pure claystone.

This study investigates the interaction between swelling and permeability in sulfate rock. Novel combined swelling-permeability tests were conducted on sulfate rock specimens to estimate changes in permeability during swelling, which are attributed to gypsum precipitation within the rock.

Maximum swelling pressure tests were performed on both pulverized-compacted and intact rock specimens, with permeability measurements taken as the swelling pressure increased, equilibrating after approximately 600 days in the case of intact rock. In a subsequent stage, the specimens were unloaded, and the load was held constant while monitoring deformation and permeability over time. The changes in mineralogical composition of the specimens were determined using X-ray diffraction (XRD).

The results indicate that swelling stress increases alongside a reduction in hydraulic conductivity, with the effect being more pronounced in pulverized specimens than in intact rock specimens. The hydraulic conductivity stabilized at approximately 10^{-13} m/s in the intact rock specimens and 10^{-11} m/s in the powder specimens. The results show that precipitated gypsum occupies pore space during constrained swelling, leading to reduced hydraulic conductivity. Within a low swelling strain range, when deformation is allowed, no further pore volume is occupied, and hydraulic conductivity remains constant.

Keywords

Sulfate rock, Rock swelling, Rock permeability, Gipskeuper

ISRM

NBG

1 Introduction

Swelling rock masses can significantly impact the serviceability of foundations and underground excavations. In tunnel engineering, the presence of swelling rocks often leads to perimeter convergence, heaving of the tunnel floor, and damage to the tunnel lining. This is particularly severe in claystone containing anhydrite, commonly found in the Gipskeuper formation of southwest Germany, Switzerland, and France. Over the past decades, numerous instances of tunnel lining damage and construction difficulties in the Gipskeuper formation have been documented (Grob 1975; Kirschke 1987; Madsen et al. 1995).

The swelling of sulfate rocks results from two primary processes that increase the rock's volume: the hydration of clay minerals and the transformation of anhydrite into gypsum. Among these, the anhydrite-gypsum transformation typically induces significantly higher swelling strains and stresses compared to those caused by clay mineral hydration.

This study explores the interaction between swelling and permeability in sulfate rocks. Combined swelling-permeability tests were conducted on sulfate rock specimens to assess changes in permeability during swelling, attributed to gypsum precipitation within the rock matrix. Maximum swelling pressure tests were performed on both pulverized-compacted and intact rock specimens, with concurrent permeability measurements taken as the swelling pressure increased.

2 Material, specimen preparation and testing method

2.1 Material

The material used for the swelling tests was obtained from drill cores with a diameter of 100 mm, collected during exploration works for the rehabilitation of the Engelberg motorway tunnel, located west of Stuttgart, Germany. The tunnel intersects the Gipskeuper Formation.

The drillings were performed vertically from the ground surface, parallel to the tunnel section, reaching depths of up to 17 m below the tunnel floor level. The boreholes penetrated the anhydritic gypsum horizon, extending to the Bleiglanzbank and Dark Red Marl layers.

2.2 Testing apparatus

This testing apparatus, consisting of a pressure cell integrated into a modified swelling test device (Fig. 1), is an adaptation of the design by Pimentel (1999) originally developed for determining the permeability of bentonite and sand mixtures. In this device, horizontal deformation of the specimen is restricted, while vertical deformation or load can be accurately and easily controlled manually.

The rock specimen is placed within a stainless steel ring and installed in the pressure cell between two sintered stainless steel porous discs. The load on the specimen is measured by a load cell with a nominal capacity of 50 kN, while the axial deformation is recorded using a dial gauge attached to the loading piston.

The oedometer ring fits snugly within the pressure vessel and includes a packing on its outer side to isolate both faces of the specimen when inserted into the vessel. The piston is also equipped with packing to seal its interface with the cylinder. This allows the loading piston to move vertically, enabling precise control of the vertical load or deformation applied to the specimen.

The pressure vessel is connected to two graduated standpipes—upstream and downstream—and to a water supply. The volume of water flowing through the specimen over a given time interval is determined by monitoring changes in the water level within the standpipes. Pressure differences are applied using air pressure. The air pressure is regulated by an arrangement of three regulators in series.

To prepare the test, a vertical load of 0.1 kN was applied to ensure proper contact between all components. A vacuum was then applied to eliminate air within the cell. Under vacuum conditions, de-aired demineralized water was introduced from both sides of the specimen to begin the test. The downstream water was used to refill the water container.

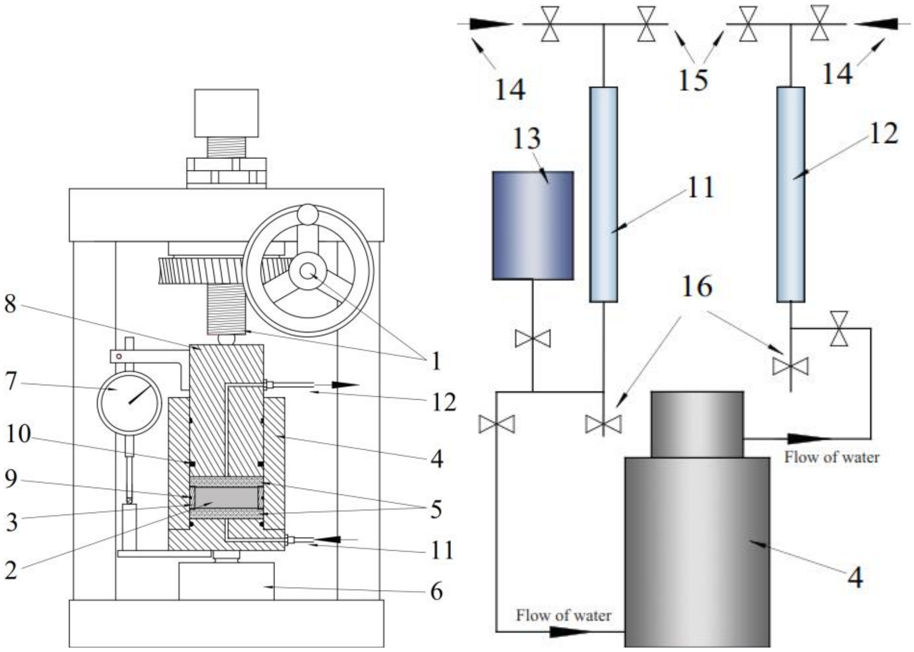

Fig. 1 Schematic diagram of the apparatus for the determination of the hydraulic permeability of swelling rock specimens: a) Swelling test apparatus. b) Water injection system. (1) manual spindle, (2) rock specimen, (3) stainless steel oedometer ring, (4) pressure vessel, (5) porous discs, (6) load cell, (7) dial gauge, (8) loading piston, (9) O-ring, (10) piston seal, (11) upstream graduated stand pipe, (12) downstream graduated stand pipe, (13) water supply, (14) air pressure/vacuum, (15) air bleed and (16) water outlet.

2.3 Determination of the hydraulic conductivity

The hydraulic conductivity (K) of the rock was derived from the one-dimensional form of Darcy's law for constant hydraulic head difference:

$$\mathrm{K} = \frac{QL}{A\Delta h} \tag{1}$$

In the following experiments, the cross-sectional area of the specimen (A), the hydraulic head difference (Δh), and the length of the specimen (L) were known parameters. The discharge (Q) was calculated based on the changes in water level observed on the upstream and downstream sides of the specimen over specified time intervals.

2.4 Compacted powder specimens

The anhydritic rock material was ground in an agate stone mill and sieved to a maximum grain size of 0.04 mm. The resulting powder was then compacted into the oedometer ring using a piston in a uniaxial testing machine, with a maximum applied load of approximately 200 kN. The density of the prepared powder specimens was generally lower than that of the intact rock, which has a typical density of approximately 2.2 g/cm³. The specimens measured 60 mm in diameter and 20 mm in height.

The mineralogical composition of the materials, along with the semi-quantitative determination of the various clay mineral types, was analysed using X-ray diffraction (XRD) techniques. The mineralogical composition of the materials used in the preparation of the specimens is presented in Table 1.

Table 1 Mineral mass content (%) of the tested rock specimens

Specimen	Swelling clays	Illite	Kaolinite	Gypsum	Anhydrite	Quartz	Feldspar	Calcite	Dolomite
DA3, DA4	-	-	12	8	78	-	-	1	1
P13A	5	11	4	1	77	2	-	-	1
P13B	2	34	1	0	48	4	2	-	10

One test (DA3) was conducted under conditions of restricted axial deformation until a swelling stress of 1 MPa was achieved after 25 days. Following this, the stress was maintained constant, and the resulting swelling deformation was monitored.

A second test (DA4) was carried out under similar restricted axial deformation conditions, with the axial load being measured continuously over time.

2.5 Rock specimens

Cylindrical specimens, approximately 60 mm in diameter and 20 mm in height, were drilled from the core samples. Disks were cut from the drill cores and trimmed using a lathe to ensure the specimen faces were flat and parallel, enabling precise fitting into the oedometer ring.

The specimens were drilled perpendicular to the bedding, allowing the axial deformation and permeability to be measured in this direction during the tests (Fig. 2).

The mineralogical composition of the specimens was determined using X-ray diffraction (XRD). The material for analysis was collected from the rim of the drilled hole, taken from the same core section as the tested specimen. This approach ensures a more accurate estimation of the actual mineralogical composition. The analysed samples revealed a high concentration of anhydrite and a very low gypsum content (Table 1).

Both tests were performed under conditions of restricted axial deformation, with the axial load measured continuously over time. In the second test stage, both specimens were unloaded, and the swelling stress was kept constant while measuring the strain.

Fig. 2 Drill core from which specimens P13A and P13B were extracted (diameter 60mm)

3 Test results

3.1 Compacted powder specimens

The results of the tests on the compacted powder specimens are presented in Fig. 3. In specimen DA3, the swelling strain increased over time, while the hydraulic conductivity decreased. This indicates that a portion of the volume generated by gypsum precipitation contributed to the specimen's expansion, while the remaining volume occupied the pore space.

In specimen DA4, the swelling stress increased progressively over time, reaching a maximum of approximately 3.5 MPa after 150 days. Similar to DA3, the hydraulic conductivity of DA4 also decreased significantly, within the same order of magnitude, from 10^{-8} to 10^{-11} m/s.

The mineralogical composition after testing is summarized in Table 2. For both tests, the fraction of anhydrite decreased by approximately 5% of the total mass, while the gypsum content increased by about 2% (relative to the new mass). This small increase in gypsum content was sufficient to reduce the hydraulic conductivity of the specimens by several orders of magnitude.

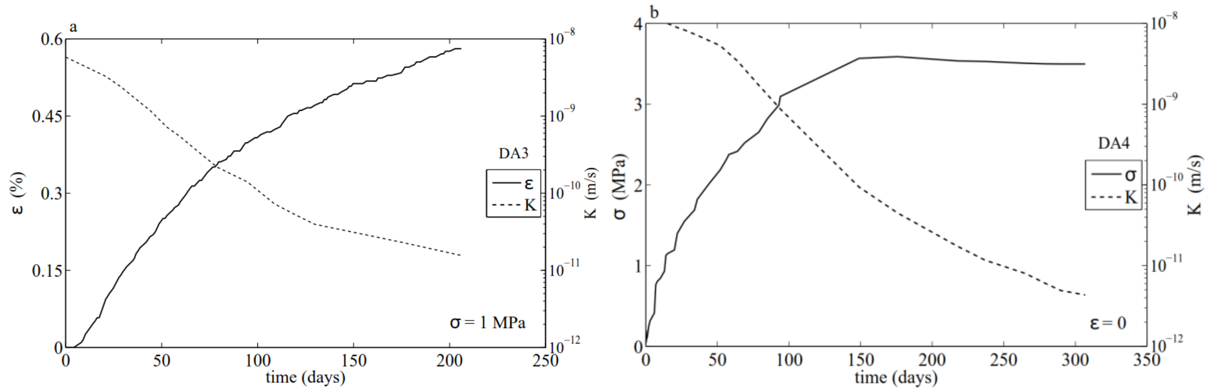

Fig. 3 Swelling strain under constant stress (a), swelling stress σ = 1MPa under constant strain ε = 0 (b) and hydraulic conductivity vs time of powder specimens in oedometric swelling test.

Table 2 Mineral mass content (%) of the specimens after testing

Specimen	Swelling clays	Illite	Kaolinite	Gypsum	Anhydrite	Quartz	Feldspar	Calcite	Dolomite
DA3	-	-	13	10	73	-	-	3	1
DA4	-	-	14	10	73	-	-	2	1

3.2 Rock specimens

The results of the tests on the intact rock specimens are presented in Figs. 4 and 5. The swelling stress achieved under restricted deformation corresponds to the maximum swelling stress (Madsen, 1999). It was observed that specimen P13B, which had a lower anhydrite content, reached a maximum swelling stress of approximately 7.7 MPa. In contrast, specimen P13A, with a higher anhydrite content, did not reach the maximum swelling stress during the testing period, which lasted about 600 days, indicating a slower development of the anhydrite-gypsum transformation.

The swelling stress increased as the hydraulic conductivity decreased. The reduction in hydraulic conductivity was faster in specimen P13B. Ultimately, the hydraulic conductivity stabilized at approximately 10^{-13} m/s.

In the second test stage, both specimens were unloaded, and the swelling stress was maintained constant while measuring the strain. During this phase, the hydraulic conductivity did not change with increasing strain and remained stable, as shown in Fig. 5.

This behaviour suggests that the precipitated gypsum occupies pore volume during swelling under constrained deformation, resulting in a reduction of hydraulic conductivity. However, when deformation was allowed the hydraulic conductivity remained constant.

This observation differs from the behaviour of powder specimen DA3, where the hydraulic conductivity decreased with increasing swelling strain. In the powder specimens, the continued decrease in hydraulic conductivity indicates that pores were being filled, likely due to their higher initial porosity. However, the swelling strain measured during the test was relatively low, and this behaviour cannot be extrapolated to higher swelling deformations, which could lead to a significant increase in void volume.

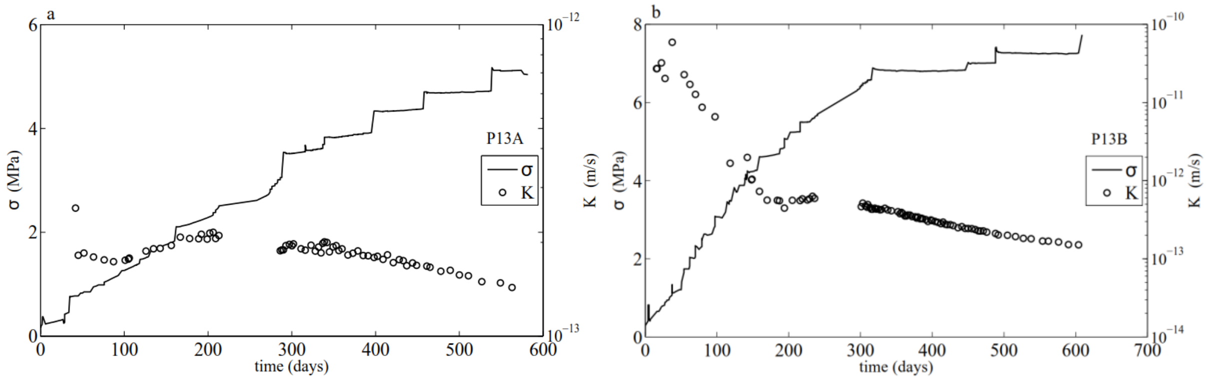

Fig. 4 Swelling stress and hydraulic conductivity vs time of rock specimens in oedometric swelling test (ε = 0)

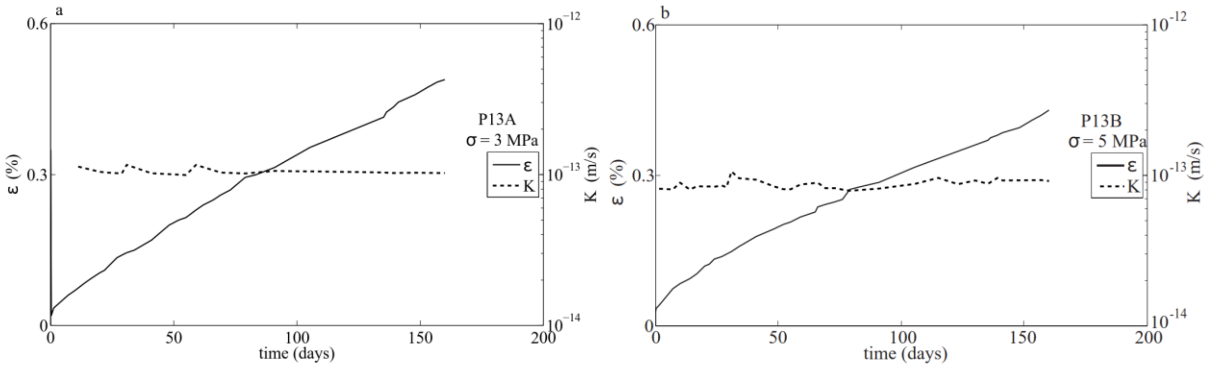

Fig. 5 Swelling stress and hydraulic conductivity vs time. Rock specimens in oedometric swelling test under constant stress

4 Conclusions

This study investigated the swelling behaviour and permeability changes of sulfate rock specimens using combined swelling-permeability tests. The results demonstrate that swelling stress and permeability are closely related, with the swelling process, particularly gypsum precipitation, playing a key role in reducing permeability.

In compacted powder specimens, permeability decreased with increasing swelling strain and stress, suggesting pore space filling. However, in natural rock specimens, permeability decreased with increasing swelling stress but remained constant once swelling stress stabilized. This is likely due to the rock's lower porosity and the absence of significant pore volume changes.

The results provide valuable insights into the interactions between swelling, permeability, and mineralogical composition. Future studies could focus on expanding these tests to a broader range conditions to refine our understanding of swelling rock behaviour and the associated mineralogical changes during the swelling process.

References

Grob H (1975) Swelling and heave in swiss tunnels. Bulletin of Engineering Geology and the Environment, 14(1):55-60.

Kirschke D (1987) Laboratory and in situ swelling test for the Freudenstein tunnel. 3:1492-1496,1987.

Madsen FT, Fluckiger A, Hauber L, Jordan Po, and Vögtli, B (1995) New investigations on swelling rocks in the belchen tunnel, switzerland. In Proceedings of the 9th Congress of the International Society for Rock Mechanics, Tokyo, Japan, September 1995.

Madsen FT (1999) Suggested methods for laboratory testing of swelling rocks. International journal of rock mechanics and mining sciences, 36(3):291-306.

Pimentel E (1999) Swelling and permeability tests on high compressed bentonite and mixtures of bentonite and sand. In Proceedings of the 9th Congress of the International Society for Rock Mechanics, Paris, France, August 1999.