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Experimental Investigation on the Influence of Swelling on Hydraulic Conductivity in Sulphate-bearing Rocks

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Abstract

Swelling in rock masses can significantly affect the serviceability of foundations and underground excavations. In sulphate-bearing 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 pressures 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 sulphate-bearing rock. Combined swelling-permeability tests were conducted on sulphate 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 compacted powder 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. Changes in mineralogical composition of the specimens were determined using X-ray diffraction (XRD).

The results indicate that swelling pressures 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 compacted powder specimens. The results indicate that precipitated gypsum occupies pore space during constrained swelling, leading to reduction in hydraulic conductivity. When deformation is allowed, no further pore volume is occupied, and hydraulic conductivity remains almost constant.

Keywords

Sulphate rock, Rock swelling, Rock permeability, Gipskeuper

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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; Steiner 2020).

The swelling of sulphate-bearing 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-to-gypsum transformation typically produces significantly higher swelling pressures compared to clay mineral hydration, although it occurs at a relatively slow rate. While anhydrite ($CaSO_4$) is known for its high strength, it is susceptible to dissolution when exposed to flowing water, leading to an increase in sulphate (SO_4^{2-}) concentration. When this concentration surpasses the saturation limit in pure water (approximately 2 g/L), gypsum ($CaSO_4 \cdot 2H_2O$) begins to precipitate and crystallize (Steiner 2020).

This study explores the interaction between swelling and permeability in sulphate rocks. Combined swelling-permeability tests were conducted on sulphate 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 anhydrite-bearing gypsum horizon, extending to the Bleiglanzbank and Dark Red Marl layers.

2.2 Testing apparatus

The 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 in 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 tests were performed in an acclimatized room under a constant temperature of 20°C.

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 initiate the test, a vertical load of 0.1 kN was applied to ensure proper contact between all components. Subsequently, a vacuum was 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 continuously used to refill the water container.

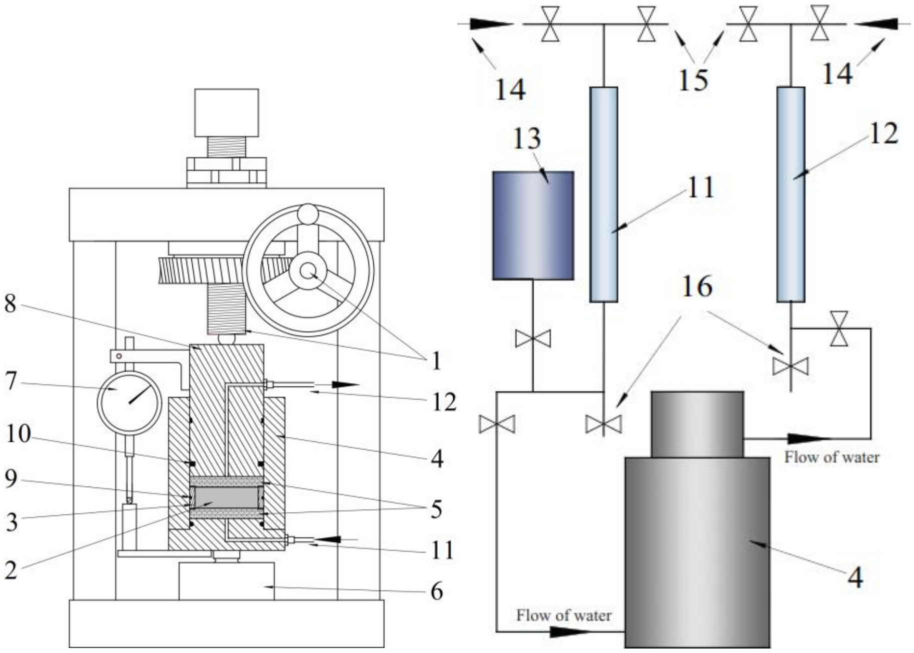

Fig. 1 Schematic diagram of the apparatus for the determination of the hydraulic conductivity of swelling rock specimens: a) Swelling test apparatus. b) Water injection system. (1) manual spindle, (2) rock specimen, (3) stainless steel oedometer ring, (4) pressure vessel, (5) porous discs, (6) load cell, (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:

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

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

For the preparation of the compacted powder specimens, the anhydritic rock material was ground using an agate stone mill and sieved to achieve 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, with a density of approximately 2.20 g/cm³.
The specimens measured 60 mm in diameter and 20 mm in height.

The mineralogical composition of the rock, 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 material used in the preparation of the compacted powder 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 (rock powder)	-	-	12	8	78	-	-	1	1
P13-A (rock)	5	11	4	1	77	2	-	-	1
P13-B (rock)	2	34	1	0	48	4	2	-	10

One test (DA3) was conducted under conditions of restricted axial deformation until a swelling pressure 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 resulting swelling load being measured continuously over time.

2.5 Intact rock specimens

Cylindrical specimens, approximately 60 mm in diameter and 20 mm in height, were drilled from the core samples. 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). Disks were then cut from the drill cores and carefully trimmed using a lathe to ensure a precise fit into the oedometer ring and to achieve flat and parallel faces on both sides of the specimen.

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 initially conducted under conditions of restricted axial deformation, with the axial load measured continuously over time. In the second stage of the tests, both specimens were unloaded, and the swelling pressure was maintained constant while the swelling deformation was measured.

Fig. 2 Drill core from which specimens P13-A and P13-B 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 pressure 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 associated with a significant reduction in the hydraulic conductivity of the specimens by several orders of magnitude.

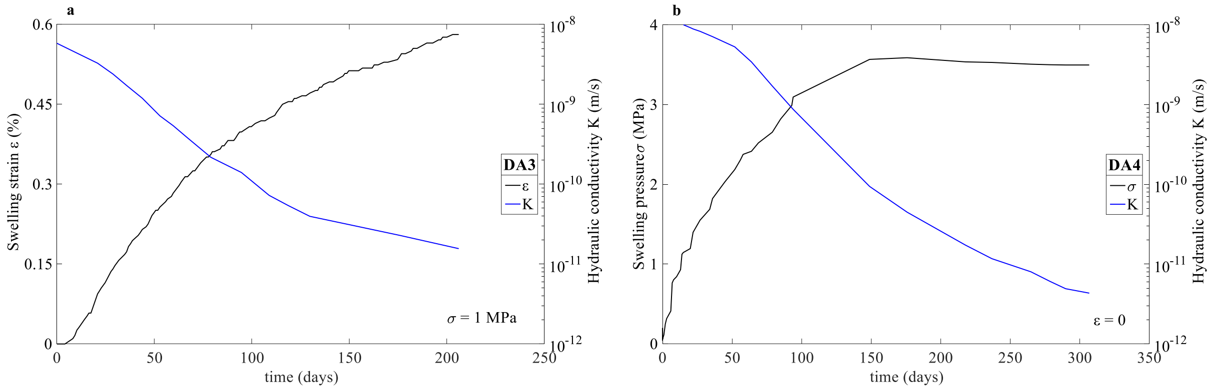

Fig. 3 Hydraulic conductivity vs time of powder specimens in oedometric swelling test. a) Swelling strain under constant stress of 1 MPa. b) Swelling pressure under restricted deformation ε = 0.

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 pressure achieved under restricted deformation corresponds to the maximum swelling pressure (Madsen, 1999). It was observed that specimen P13-B, which had a lower anhydrite content, reached a maximum swelling pressure of approximately 7.7 MPa. In contrast, specimen P13-A, with a higher anhydrite content, did not reach the maximum swelling pressure during the testing period, which lasted about 600 days, indicating a slower rate of the anhydrite-gypsum transformation.

The relationship between swelling pressure and hydraulic conductivity was also observed. As the swelling pressure increased, the hydraulic conductivity decreased. Specimen P13-B exhibited a faster reduction in hydraulic conductivity compared to P13-A.

In the second stage of testing, both specimens were unloaded, and the swelling pressure was kept constant at 3 MPa for P13-A and 5 MPa for P13-B, while the swelling deformation was measured. During this phase, the hydraulic conductivity remained unchanged despite the increasing strain, as shown in Fig. 5. Ultimately, the hydraulic conductivity of both specimens stabilized, with P13-A reaching approximately 1.3×10^{-13} m/s and P13-B stabilizing at around 0.8×10^{-13} m/s.

The observed 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 is in contrast to the behaviour observed in the powder specimen DA3, where the hydraulic conductivity decreased as swelling strain increased. In powder specimens, the continued decrease in hydraulic conductivity indicates that pores were being filled, likely due to their higher initial porosity. It is important to note that the swelling deformation measured in the intact rock specimens during the test was relatively low, and that intact rock typically has low porosity. Therefore, this behaviour cannot be directly extrapolated to higher swelling deformations, which may lead to an increase in void volume and, consequently, an increase in hydraulic conductivity.

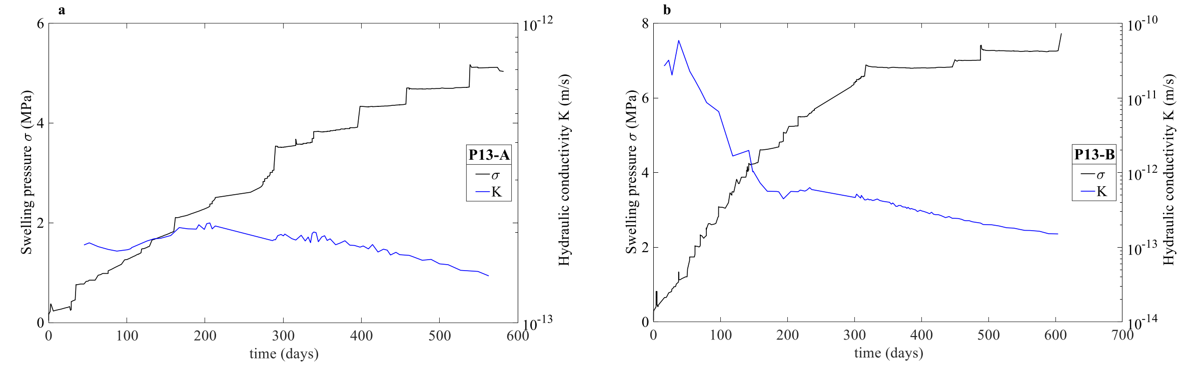

Fig. 4 Swelling pressure and hydraulic conductivity vs time of rock specimens in oedometric swelling test (ε = 0).

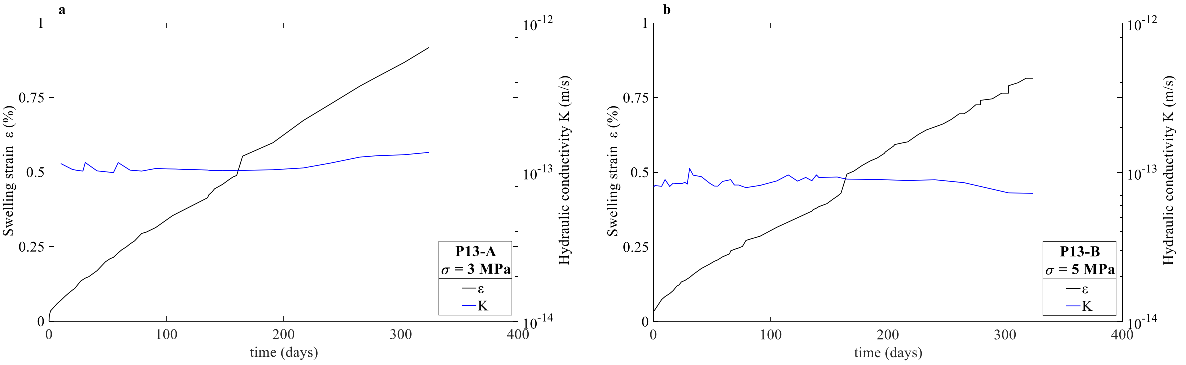

Fig. 5 Swelling strain and hydraulic conductivity vs time of rock specimens in oedometric swelling test under constant stress.

4 Conclusions

This study investigated the swelling behaviour and permeability changes of sulphate rock specimens using combined swelling-permeability tests. The results confirm, as expected, a relationship between swelling stress and permeability, with the swelling process, particularly gypsum precipitation, playing an important role in reducing rock permeability.

In compacted powder specimens, hydraulic conductivity decreased as swelling strain and stress increased, indicating that pore space was being filled. In contrast, in natural rock specimens, permeability initially decreased with increasing swelling stress but remained constant once the swelling stress stabilized. This difference is likely due to the rock's lower porosity and the absence of significant pore volume changes within the swelling strain range tested.

The intact rock specimens reached swelling pressures of up to 7.7 MPa, which is not unusual in laboratory tests on sulphate-bearing rocks. However, in-situ measurements indicate that the loads acting on tunnel linings typically are substantially lower, reaching only up to 2 MPa (Steiner and Schwalt 2019). This significant reduction can be attributed to rock deformation and fracturing around the tunnel opening prior to lining installation. Additionally, unlike controlled laboratory conditions, in-situ conditions may limit the extent of gypsum precipitation, likely due in part to changes in rock mass permeability, further limiting the buildup of stress.

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.

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