STUDY ON THE SWELLING POTENTIAL OF SOME SELECTED ROCKS

Svellekarakter/svelleegenskaper til noen utvalgte skifrige bergarter

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SUMMARY

For clay minerals the swelling mechanisms and factors influencing on the swelling potential is widely explained and confirmed through comprehensive research. When it comes to intact rocks there are questions regarding both swelling potential and main reasons for swelling in the different rock types. It is therefore important to better understand the swelling behaviour of different rocks rich in clay minerals when in contact with water.

In this pretext, an extensive laboratory work has been performed to address a study on the expansive character of intact rock. Three different rock types have been tested; alum shale, greenschist and tuff, and the rocks vary in both structure and mineral composition.

Three traditional test methods consisting swelling pressure determination using dust powder, rock cylinders and free swelling have been used. In addition, recently developed new test apparatus at NTNU/SINTEF lab has also been used. The benefit of this method is that it gives possibility to look on the swelling strain of rock cubes when submerged in all three directions. When exposed to water the displacement in all three directions is recorded over time.

Results of all swelling test methods are compared. Further discussions are made on the swelling impact based on mineralogical composition. The applicability of this new method in comparisons to the other test methods is also discussed.

SAMMENDRAG

For leiremineraler finnes det omfattende forskning og utallige forklaringer på svellemekanismene og de faktorer som påvirker svellepotensialet. Når det kommer til intakt berg er det fortsatt en del spørsmål knytte til både svellepotensialet og hovedårsaker til svelling for de ulike bergarter. Det er derfor viktig med en bedre forståelse av svelleegenskapene til ulike bergarter rike på leirmineraler i kontakt med vann.

I denne sammenheng har et omfattende laboratoriearbeid har blitt utført og omhandler en studie på intakt bergs ekspansjonskarakter. Tre forskjellige bergarter er testet; alunskifer, grønnskifer og tuff, og bergartene varierer i både struktur og mineralsammensetning.

Tre tradisjonelle testmetoder bestående av svelletrykk bestemmelse ved bruk av pulver, intakt skiver og fri svelling; har vært brukt. I tillegg har en nylig utviklet testapparatur ved NTNU/-SINTEF laboratoriet blitt brukt. Fordelen ved denne metoden er at den gir muligheten for å studere ekspansjonen av intakt kuber etter at de er nedsenket i alle tre retninger . Ved eksponering av vann vil forflytningen i alle tre retninger registreres over tid.

Resultatene fra alle svelletestene er sammenlignet. Videre diskusjoner er utført på svellepåvirkningen basert på mineralogisk sammensetning. Anvendbarheten av denne nye testen sammenlignet med de andre testmetodene er også diskutert.

INTRODUCTION

This article is based on a master thesis (Skippervik, 2014) with the research topic *"Study on the swelling potential of some selected rocks"*. This implies a research of the swelling potential of intact rocks that have an expansive character, compared to the more comprehensive research of swelling potential for clay minerals. The swelling potential of intact rock might have an adversely effect on the stability of tunnels, slopes and foundations if the potential is mobilized. Figure 1 shows a photo of the collapsed area in the Hanekleiv tunnel in December 2006, which was an incident that led to an increase in the demand for testing of swelling properties.

Figure 1. Photo of the collapsed area in the roof of the Hanekleiv tunnel and the material from the cave-in on the floor of the tunnel (Nilsen, 2012).

There exists more research on the swelling potential of clays and gouge materials than for intact rock. In recent years, the focus on the latter case has however increased, and this entails both the development of already existing test methods, as well as an adjustment to the new methods. The knowledge on the cause and how this swelling potential may affect stability insitu is still inadequate, so a new and improved test apparatus and methods have been developed at NTNU/SINTEF lab (Dahl. et. al, 2013).

The study has been based on extensive laboratory work including swelling tests, various rock mechanical tests and mineralogical and petrographic analyses. The new swelling test method called 3D free swelling was one of the major focus areas of the MSc thesis. Therefore, comprehensive discussions and comparison of the testing results have been carried out and presented.

The selected rocks for this thesis are alum shale, greenschist and tuff. Testing methods used in determining the swelling potential are free swelling, swelling pressure by oedometer and swelling strain by newly developed 3D free swelling apparatus. In addition, mineralogical test and some other rock mechanical test were also carried out.

Sample preparation is one of the major tasks, which involves drilling, slicing, cutting and crushing of the selected rock material that provides cores, cored cylinders, cubes, pieces and milled dust.

SWELLING TEST METHODOLOGY

Previously performed swelling tests involved the use of specimens of dust powder prepared from clay minerals. The test methods and standards for clay minerals are however not adequate for testing of intact rock and the determination of the swelling potential for intact rock has hence involved development of a new methodology. This new method, which includes a combination of swelling strain measurements and mineralogy analysis, has been performed on rock cubes prepared from the intact rock specimens.

The test methods used for determination of swelling behaviour of rock mass are free swelling, swelling pressure index by oedometer and swelling strain by the new 3D free swelling apparatus. Free swelling testing is performed on loosely packed dust powder and the swelling pressure index is performed on remoulded rock specimens prepared as dust powder and intact rock material prepared as rock discs. Undisturbed and unconfined rock specimens prepared as rock cubes are used in the determination of swelling strain. The latter test method enables for a three dimensional swelling measurement as opposed to the one direction measurements for the former test methods.

Free swelling determination – measuring cylinder

A measuring cylinder is filled with 45 ml of distilled water before 10 ml of loosely packed milled powder is carefully added. The powder volume is recorded after sedimentation. The free swelling index number is the relation between this volume, V_1, and the original volume, V_0, of the milled powder (Mao et.al, 2011 and Dahl et.al, 2013).

The free swelling index number, Fs is calculated from the formula:

$$\text{Fs} = \frac{V_1}{V_0} \times 100\%$$

Swelling pressure index determination – Oedometer

This test method is used in the determination of the relative swelling potential of a material and potential instability caused by the swelling (Mao et.al, 2011). It is also used in the characterization and quantification of the swelling properties of the material (Dahl et.al, 2013).

Figure 2 shows the oedometer used for the swelling pressure index determination and a close up of the test cell components.

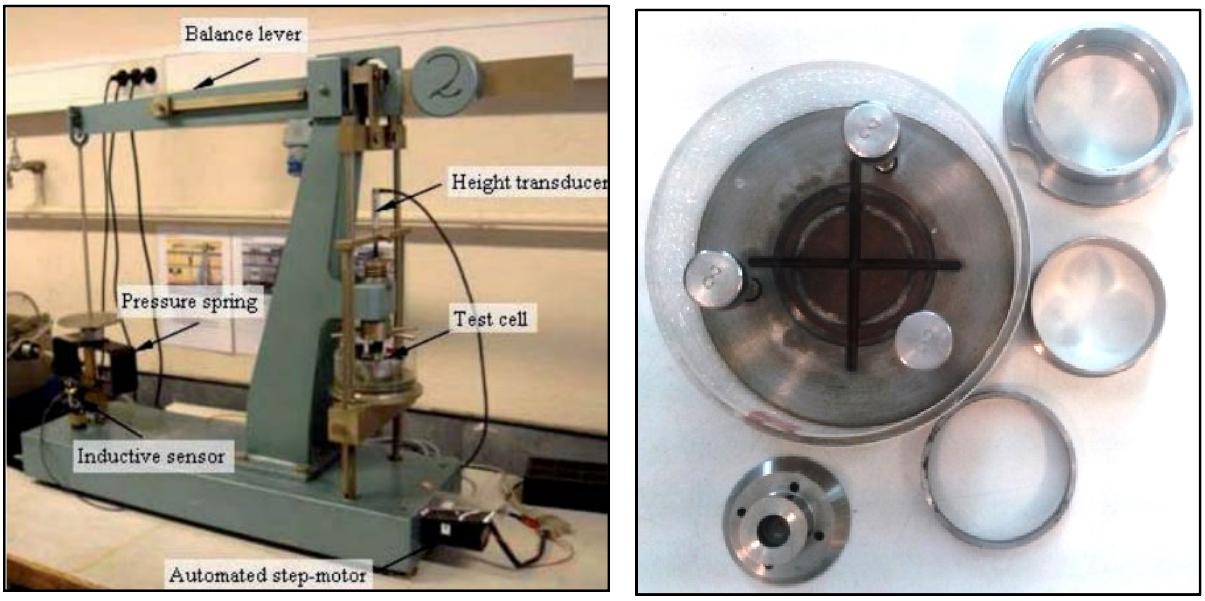

Figure 2. Photo of the updated Oedometer apparatus developed at the Norwegian University of Science and Technology for swelling pressure measurements, left, and test cell components, right.

The swelling pressure index is determined by performing 3 test stages; the compression stage, the unloading stage and the swelling stage. Dry powder is used in the compression stage where the height and hence volume of the sample is decreased to a certain level. In the unloading stage the dry powder sample is again allowed to regain height until a stable level is achieved. Finally in the swelling stage water is added to the dry sample and the height of the sample is now kept stable during the entire measurement (usually completed after 24 hours). Figure 3 gives a sketch of the three stages.

For testing of rock samples the 20/10 cm^2 cylindrical test cell is instead filled with 20 grams of finely milled powder or alternatively a rock disc.

The oedometer testing are performed according to the same procedure as stated by Mao and Dahl (Mao et.al, 2011 and Dahl et.al, 2013). However, there exists one difference that is instead of traditional 2 MPa pressure for milled sample a higher pre-consolidation pressure of 4 MPa was used for the rock samples.

Figure 4 shows the oedometer setup for the compression stage and the swelling stage.

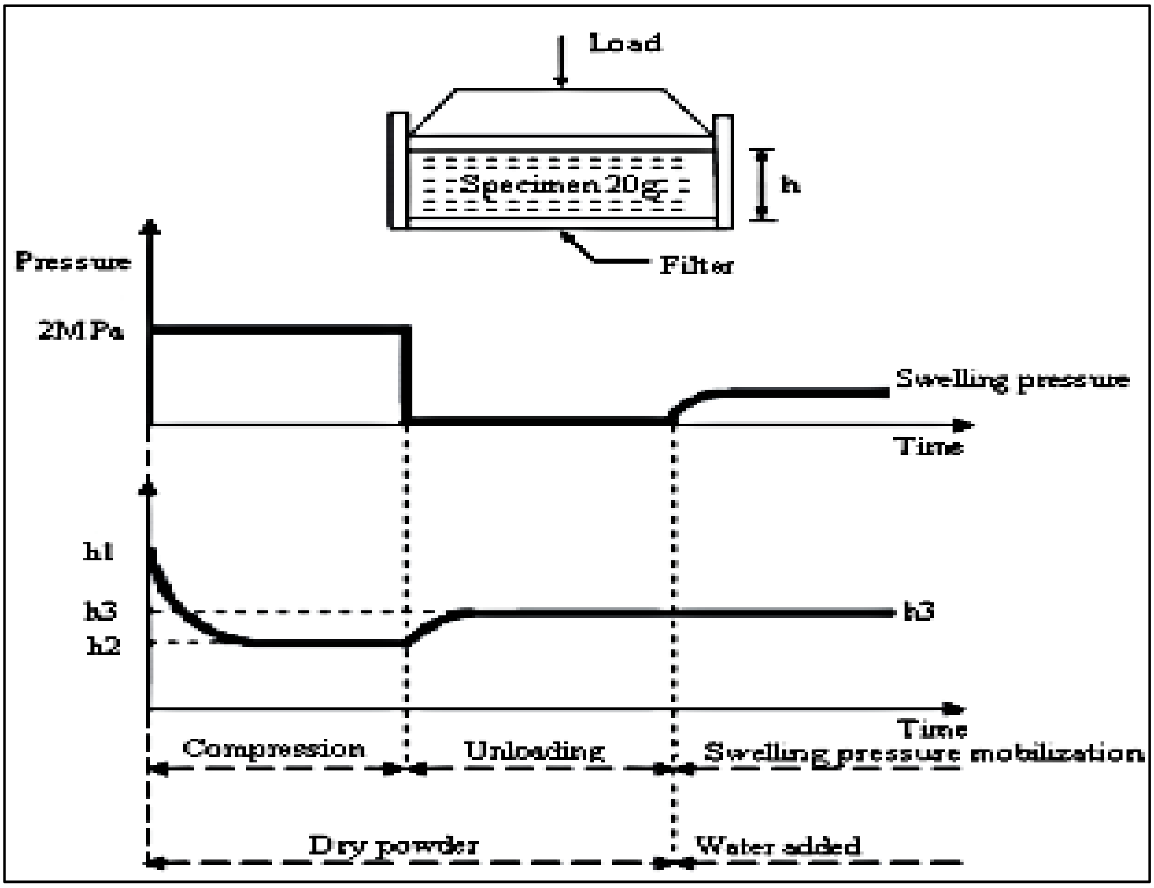

Figure 3. Sketch of the three stages in determining the swelling pressure index (Mao et.al, 2011).

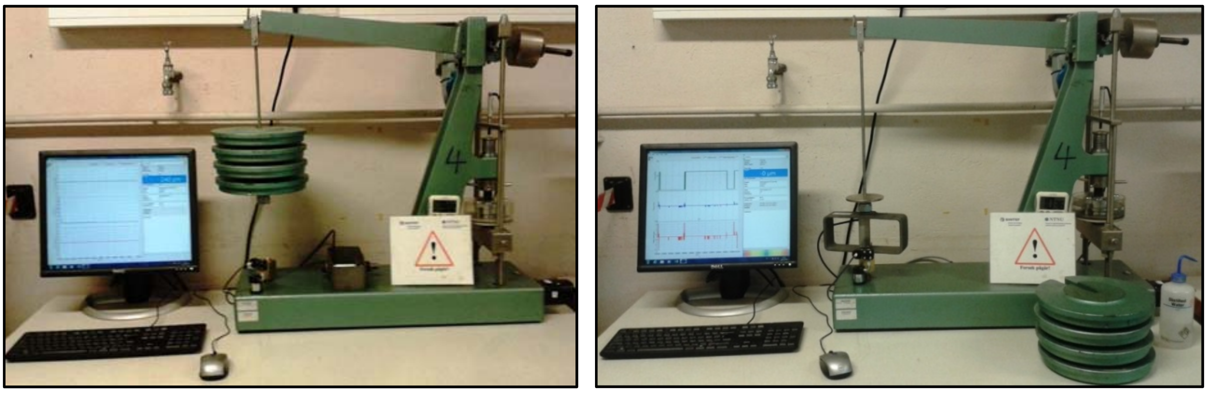

Figure 4. Oedometer setup for the compaction step, left, and the swelling stage, right.

Swelling strain determination – 3D free swelling apparatus

The sides of the prepared rock specimen consisting of a cut cube are marked with three gauge points that corresponds to the respective axis of the cube. Initial dimensions of the specimen are measured and registered and the plexiglass plates are fixed at each of the gauge point. The rock cube is placed into the apparatus (Figure 5) before it is covered with distilled water and allowed to swell freely.

The 3 dimensional expansion of the prepared rock cube is measured and logged continuously by using digital distance gauges during the entire test. The continuous electronic logging of measurements does also include registration of water temperature by a digital thermometer. The swelling displacement as a function of elapsed time is recorded until a constant level is reached or a peak is passed according to as suggested by ISRM (1977).

Figure 5: Photo of 3D measuring cell and apparatus for free swelling in 3 directions developed at SINTEF/NTNU in 2013.

The swelling strain is calculated for three directions, x, y and z and the measurement in direction x is equal to the formula:

$$\frac{d}{L} \times 100\%$$

Where; x is a direction relative to the bedding or foliation, d is the maximum swelling displacement recorded in direction x during test and L is the initial distance between gauge points in direction x (ISRM, 1977).

SELECTION OF ROCK SAMPLES AND PREPARATION

Three different rock types were selected; alum shale, green schist and tuff. Figure 6 shows photos of the selected rocks.

Figure 6: Photo of the three rock type, from left to right; alum shale, greenschist and tuff.

These three rock types were chosen due to their high degree schistosity (particularly prevailing for alum shale and green schist) and clay mineral content, two factors which normally are associated with the expansive character of the rock mass.

Samples of the rock types were prepared as milled dust, cored rock cylinders and rock cubes. The milled dust samples were applied for free swelling testing, swelling pressure testing using the oedometer and mineralogical analysis using the XRD technique. The cored rock cylinders were applied for swelling pressure testing using the oedometer and the rock cubes were used for 3D free swelling test using newly developed apparatus.

Dust powder

To prepare the dust powder samples representative parts of the rock were crushed, by hand with a geological hammer, giving rock piece sizes of approximately 10-15 mm. The crushed bulk material, a total of 40 g, was then placed in the coil mill for 2 minutes, resulting in milled powder for each of the rock specimens and for each of the testing methods. The dust powder was then dried in a heating cabinet at 105º C for 24 hours and then followed by an additional milling in a porcelain mill for 15 minutes. Figure 7 shows photos of the prepared dust powder from the selected rocks.

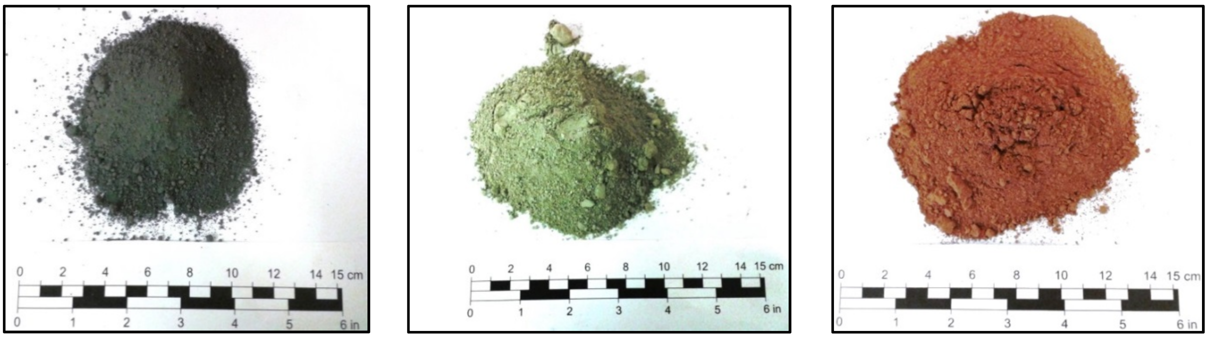

Figure 7: Photos of prepared dust powder for free swelling, swelling pressure and XRD analysis, from left to right; alum shale, greenschist and tuff.

Cored rock cylinders

The preparation of the discs involved drilling (under dry condition using compressed air instead of water as cooling aid) of cores from intact rock material with a diameter of approximately 35 mm followed by slicing of the rock cores into discs with thickness 5 mm. The discs were drilled and cut with respect to the stratification allowing potential swelling perpendicular to the cleavage (Brattli and Broch, 1995). Photo of prepared discs are shown in figure 8.

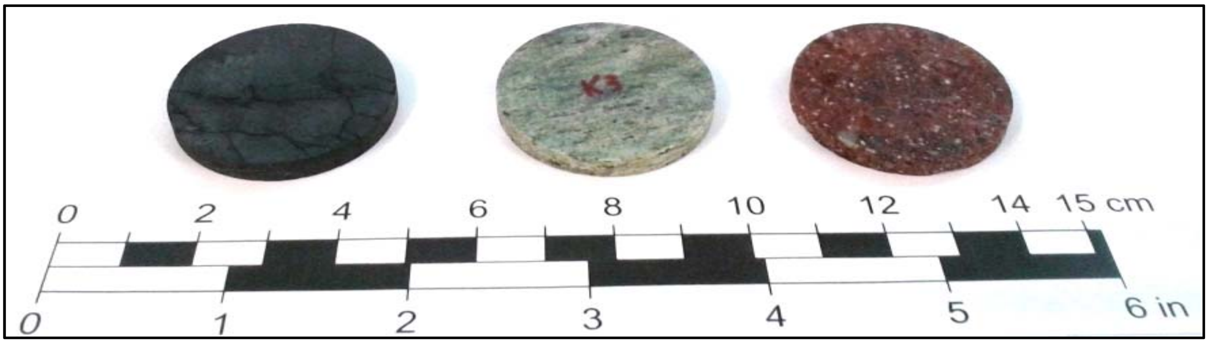

Figure 8: Photo of prepared discs for swelling pressure testing.

Rock cubes

Preparations of the rock cubes involved sawing out the specimens using a cutter machine equipped with a diamond blade. The dimensions of the rock cubes were initially set to 50x50x50 mm, and the cubes were prepared so that the cube axis was perpendicular to the foliations and beddings of the rock (ISRM, 1977). Difficulties in preparing the rock cubes made it impossible to obtain the standard dimensions resulting in plotting of new dimensions for the rock samples. Figure 9 shows the prepared rock cubes for the 3D free swelling.

Figure 9: Photos of prepared rock cubes for 3D free swelling, from left to right; alum shale, greenschist and tuff.

SWELLING TEST RESULTS

Swelling pressure index – dust powder

Figure 10 shows the swelling pressure curve for the tuff and table 1 gives classification of the swelling pressure index and the free swelling for all three rock samples according to NBG, 1985 (modified after Dahl et.al, 2013).

As seen in Table 1, for all three rock samples the free swelling lies in the level of moderate and the swelling pressure ranges from low to moderate. No duplicate tests were performed and only three rock samples were tested, making it difficult to confirm a correlation between the free swelling and the swelling pressure for other rock types.

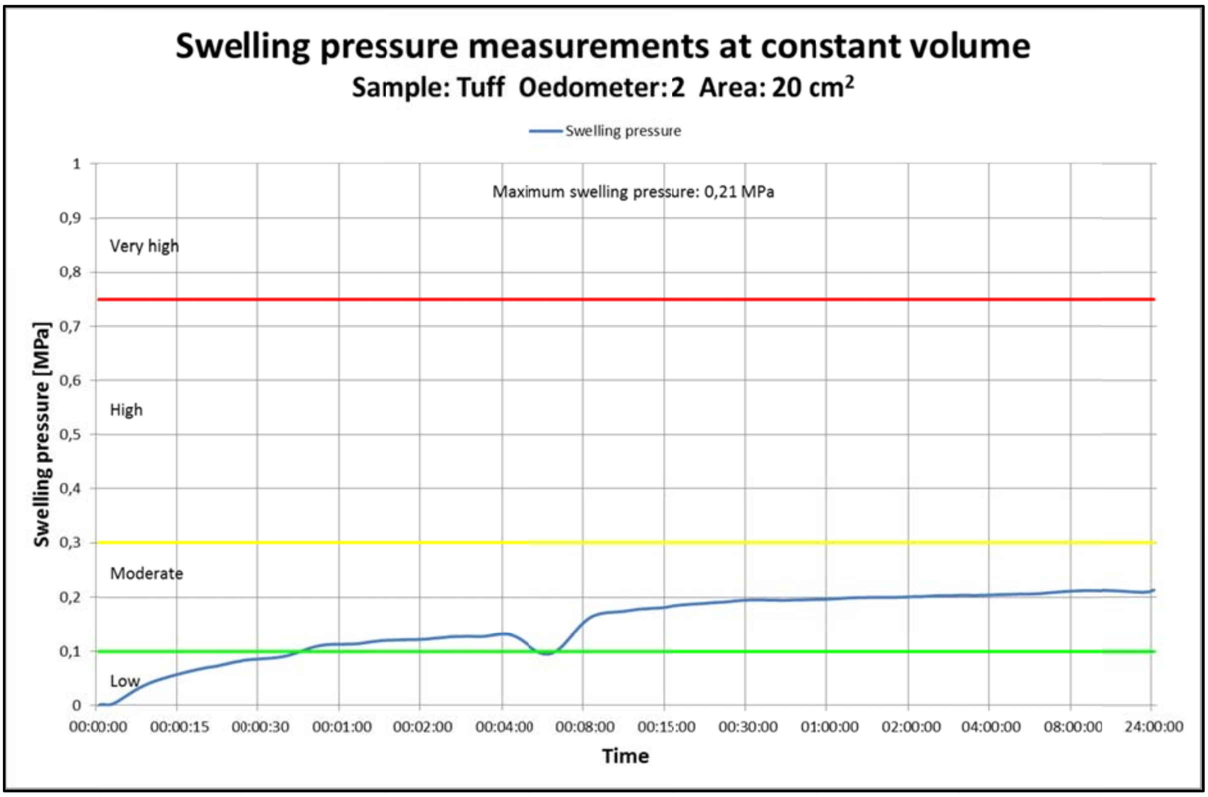

Figure 10: Swelling pressure chart for the tuff showing the maximum swelling pressure measured.

Table 1: Classification of the free swelling and the swelling pressure index of the rock samples.

Sample	Free swelling		Swelling pressure	
	[%]	Classification	[MPa]	Classification
Alum shale	130	Moderate	0,03	Low
Greenschist	100	Moderate	0,02	Low
Tuff	135	Moderate	0,21	Moderate

The rock sample with the highest free swelling value, the tuff, has the highest value for swelling pressure and the rock sample with the lowest free swelling value, the greenschist, has the lowest value for swelling pressure. This corresponds well to the fact that both test methods are used in the quantification and classification of swelling properties and the relative swelling potential of gauge and bulk material (Dahl et.al, 2013).

Swelling pressure index – rock discs

Figure 11 shows the swelling pressure curve for the greenschist and table 2 gives the classification of the swelling pressure for all three rock samples on the basis of the test results and the gauge material according to NBG, 1985 (modified after Dahl et.al, 2013).

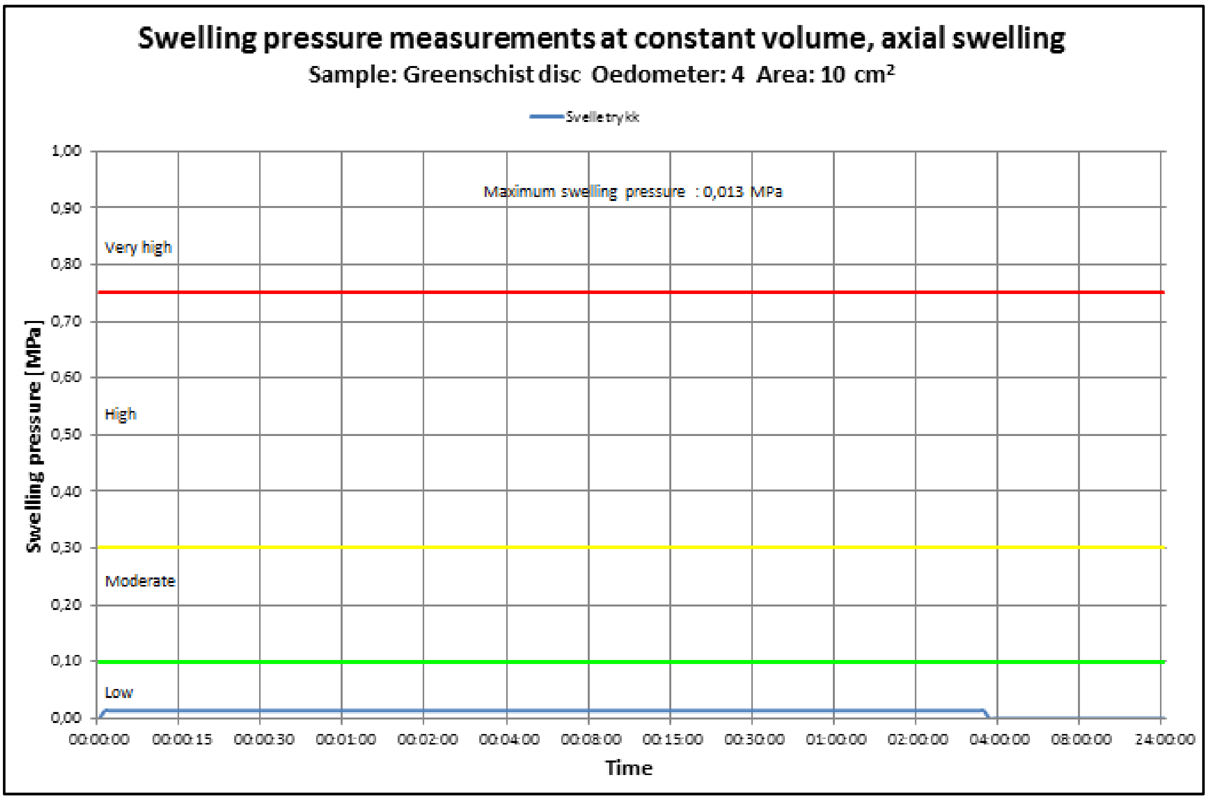

Figure 11: Swelling pressure chart for the tuff showing the maximum swelling pressure measured.

Both alum shale and tuff is showing zero swelling pressure, indicating an inactive rock material. The greenschist shows the greatest swelling pressure of the three rocks. The test values of rock discs correlate to the test values of bulk material expect for the greenschist that is showing a significant deviation between the two values.

Table 2: Swelling pressure results of the three rock samples.

Sample	Swelling pressure	
	[MPa]	Classification
Alum shale	0,00	Inactive
Greenschist	0,01	Low
Tuff	0,00	Inactive

Swelling strain - rock cubes

In figure 12 the swelling curve for the tuff is shown and in table 3 the highest measured swelling strain in x-, y- and z-direction is given, both in percentage and in mm.

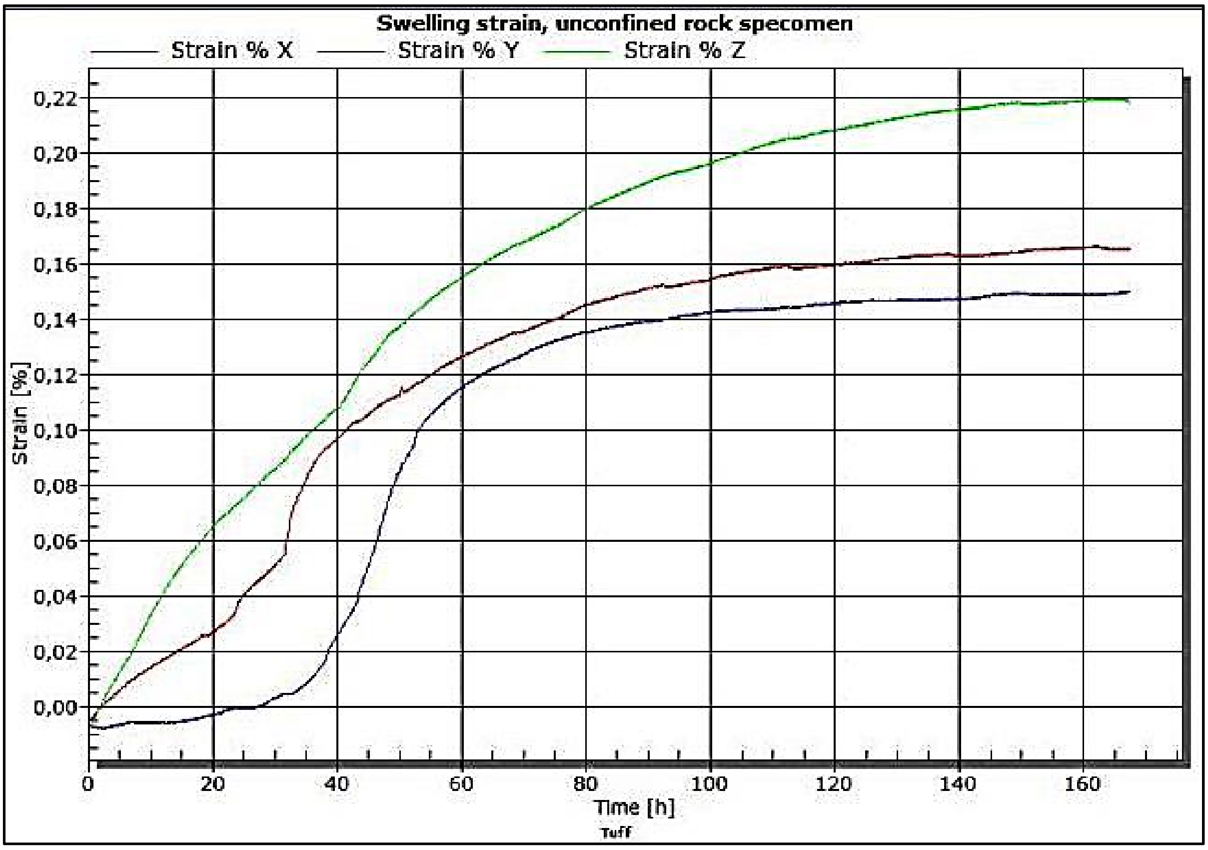

Figure 12: Swelling strain chart for the tuff.

The alum shale shows greatest swelling strain in the x-direction, as opposed to the greenschist and tuff with the greatest swelling strain in the z-direction. The tuff also shows significant swelling strain in the x- and y-direction and these values correspond to values calculated for the free swelling and the swelling pressure index.

Table 3: Swelling strain results of the three rock samples.

Sample	Swelling strain x-direction		Swelling strain y-direction		Swelling strain z-direction	
	[%]	[mm]	[%]	[mm]	[%]	[mm]
Alum shale	0,125	0,0602	0,055	0,0241	0,060	0,0295
Greenschist	0,008	0,0035	0,006	0,0026	0,048	0,0209
Tuff	0,165	0,0826	0,145	0,0770	0,220	0,1122

DISCUSSION

A comparison in relation to dust powder, rock cylinders and rock cubes was carried out in order to find correlations between the test methods, figures 13-15. The results from the swelling tests were also compared to the results from the petrographic and mineralogical tests and the rock mechanical tests to find correlations that might explain swelling. Table 4 gives a compilation of the rock mechanical test results for point load strength, slake-durability index and density.

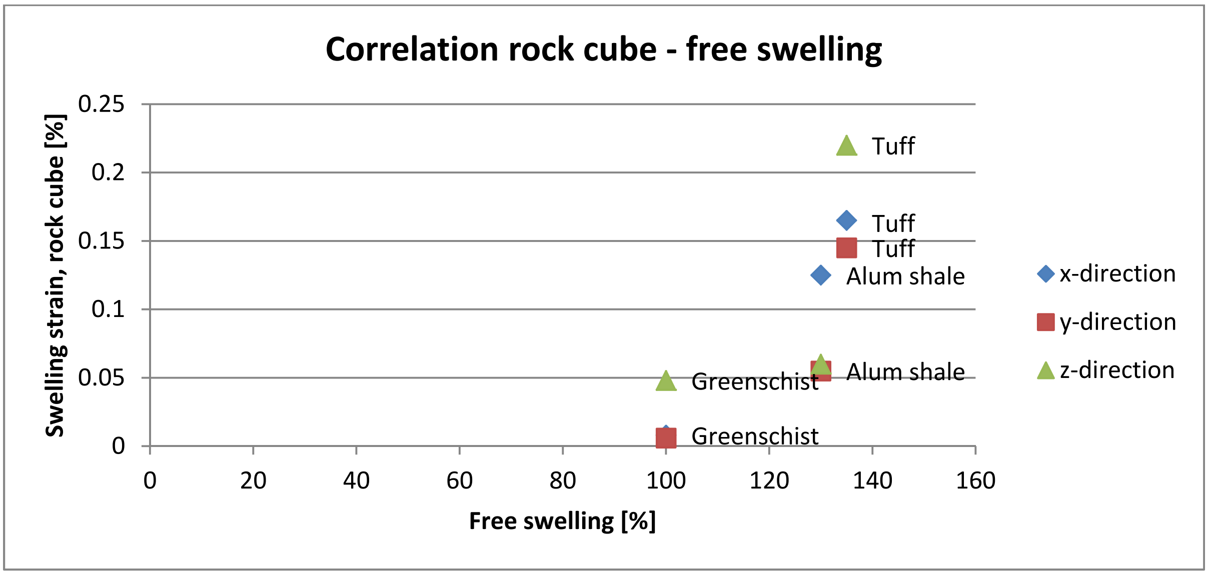

Figure 13: Correlation between swelling strain for rock cube and free swelling.

There is an evident correlation between the test method for rock cube and free swelling; an increase in the free swelling indicates an increase in the swelling strain. A correlation between swelling pressure for dust powder and swelling strain for rock cube are also seen, which indicates that the higher the swelling pressure the higher the swelling strain.

Figure 15 shows the swelling pressure for rock discs classified as inactive even though expansion in all three directions has been measured. The greenschist shows low values for both measurements in contrast to the tuff which show significant swelling strain in all three directions and no swelling pressure for the rock cylinder. Deviations in the values for the tests imply difficulties in finding correlation between the methods; nevertheless the determination of swelling strain for rock cubes is a very good indication on the swelling characteristic of intact rocks. The determination of swelling pressure and swelling strain appear thus as two independent test methods.

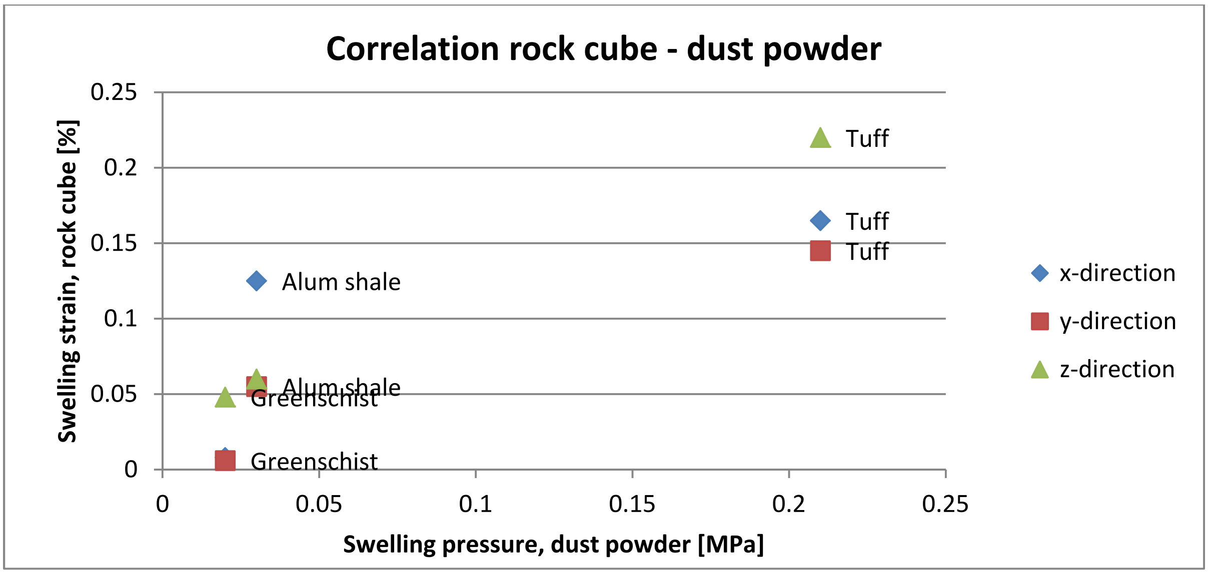

Figure 14: Correlation between swelling pressure for dust powder and swelling strain for rock cube.

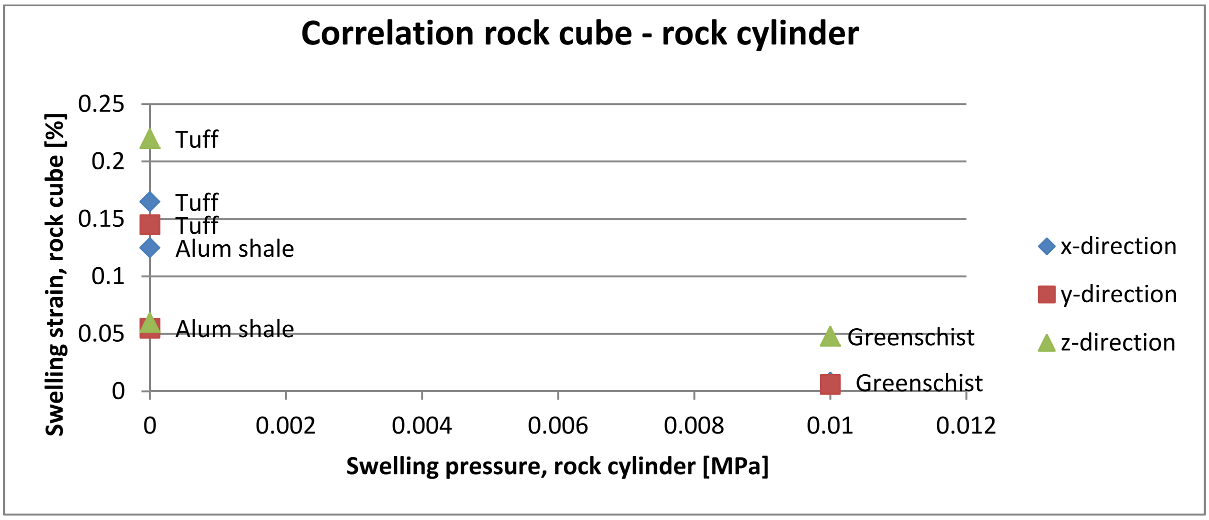

Figure 15: Correlation between swelling pressure for rock disc and swelling strain for rock cube.

Table 4: Compilation of rock mechanical test results for point load strength, slake-durability index and density.

Rock type	Test method							
	Point load strength [MPa]			Compressive strength [MPa]	Tensile strength [MPa]	Slake-durability index [%]		Density [g/m^3]
	I_s	I_{s50}	Classification	σ_c	σ_t	I_{d2}	Classification	
Alum shale	2,9	2,3	Medium	31,7	1,8	94,3	High	2,59
Green schist	8,0	7,1	High	142,1	5,6	98,1	Very high	2,86
Tuff	4,3	3,3	Medium	46,4	2,7	99,0	Very high	2,65

Alum shale:

Swelling test results show moderate free swelling, insignificant swelling pressure, both dust powder and rock cylinder, and greatest swelling strain in the x-direction; x > z > y. For alum shale there is a good correlation between low classified swelling pressure and swelling strain, and greatest expansion is in the x-direction. This very fine grained rock shows a distinct foliation and schistosity, which may be a reason for swelling due to capillarity (Dahl et.al, 2013). The highest value for swelling strain was however recorded in x-direction and this might be inconsistent with the assumptions of swelling due to capillarity.

The XRD analysis show a content of 86 % calcite and this is confirmed by thin section analysis. Relatively large calcite veins, some with mineral coating, were observed parallel to the foliation. This mineral coating might fill the fractures in alum shale and swelling normal to the foliation is decreased. In order to compensate for swelling pressure build up a volume increase parallel to the foliation might occur and thus greatest swelling strain in x-direction. Small amounts of two types of iron sulphides were found; sphalerite and pyrite. The quantity of sulphides indicates a low impact on the swelling potential. Small amounts of mica and gypsum were also found. For the same reason mentioned above effect on the swelling potential is insignificant.

Rock mechanical test results show medium point load strength, high slake-durability index and σ_c and σ_t values indicate medium strong rock.

Greenschist

Swelling test results show moderate free swelling, insignificant swelling pressure, both dust powder and rock cylinder, and greatest swelling strain in z-direction; z > x > y. Greenschist shows lowest values for both swelling pressure (classified as low) and swelling strain. Measured expansion is slightly higher in z-direction compared to x- and y-direction. This rock consist distinct foliation and schistosity, which, as for the alum shale, may be a reason for swelling due to capillarity.

The XRD analysis shows high content of numerous sheet silicates and this is confirmed by thin section analysis. Structure of the distinct sheet silicates (Prestvik, 2005) may be a reason for swelling due to various lengths of interlayers and capability of holding exchangeable cations and water molecules (Nilsen, 2010; The Cooperative Soil Survey, 2014).

Albite is a tectosilicate consisting of SiO_4-tetrahedrons in a three dimensional framework with 1:2 ratio between silicon and oxygen elements. Chlorite and phlogopite are phyllosilicates where SiO_4-tetrahedrons are bonded together in a parallel sheet structure with 1:2.5 ratios between the silicon and oxygen elements. Amphibole is inoslilicate meaning SiO_4-tetrahedrons are bonded together in a double chains structure. The ratio between silicon and oxygen elements is 1:2.75. Epidote is a sorosilicate where isolated SiO_4-tetrahedrons are bonded together and ratio between silicon and oxygen elements is 2:7.

The structure of tectosilicates, phyllosilicates and double chained inosilicates enable for a volume increase due to interlayer spacing between the unit layers. The swelling potential is mobilized provided that other factors influencing the swelling are fulfilled. Small amounts of mica and sulphide; chalcopyrite are also found. The quantity of minerals indicates a low impact on the swelling potential.

Rock mechanical test results show high point load strength and very high slake-durability index and σ_c and σ_t values indicate very strong rock.

Tuff

Swelling test results show moderate free swelling, moderate swelling pressure on dust powder, insignificant swelling pressure on rock cylinder and greatest swelling strain in z-direction; z > x > y. A good correlation between the two test methods for tuff is found; i.e. values for both swelling pressure and swelling strain. The tuff shows greatest expansion of all three rock samples and highest expansion is found in the z-direction. The rock is compact and fine grained and no distinct layering is observed.

The XRD analysis shows a high content of numerous sheet silicates and this is confirmed by thin section analysis. Structure of the distinct sheet silicates may be a reason for swelling, as above, due to the various lengths of interlayers and capability of holding exchangeable cations and water molecules.

Quartz and zeolites like wairakite and laumontite are tectosilicates consisting of SiO_4-tetrahedrons in three dimensional frameworks with 1:2 ratio between silicon and oxygen elements. The tree dimensional framework of zeolites consist of $(Al,Si)O_4$-tetrahedrons arranged in an open ring structure provides an easy flow of water molecules and cations in and out of the silicates (Prestvik, 2005). Changes in volume due to water content changes will affect swelling and shrinking behaviour (Pusch, 2012) and thus be a significant contributor to swelling potential of tuff. Chlorite and kaolinite are phyllosilicates where SiO_4-tetrahedrons are bonded together in a parallel sheet structure with a 1:2.5 ratio between silicon and oxygen elements. The kaolinite mineral is a nonexpansive clay mineral (The Cooperative Soil Survey, 2014) and thus will not affect the swelling potential.

The structure of the tectosilicates and phyllosilicates enable for a volume increase due to interlayer spacing between unit layers. The swelling potential is mobilized provided that other factors influencing welling are fulfilled. No sulphides were found by the XRD-analysis.

Rock mechanical test results show medium point load strength and very high slake-durability index; and σ_c and σ_t indicating medium strong rock.

CONCLUSION

Tunnelling in city areas is prone to many instability challenges since most of the cities are located in the valleys where fractured, weathered and faulted rock mass are under laying. This leads to the need for more research on topics that influences on the tunnel stability. One of such instability issues is off course swelling potential. Based on the swelling test carried out in three different rock types following conclusions are drawn:

- All three rocks show swelling potential of varying degree and some correlations between swelling potential and rock mechanical properties.
- The tested alum shale sample is classified as a medium strong rock and show moderate swelling pressure and highest swelling strain in the x-direction. Swelling of alum shale might be explained by various factors and the main reasons are most likely related to the distinct foliation and schistosity and presence of a considerable amount of calcite minerals. Calcite veins with mineral coating fill up the fractures in the rock and swelling pressure built up in z-direction is compensated by a swelling strain in the x-direction thus giving greatest swelling parallel to the foliation.
- The tested greenschist is classified as a very strong rock and show low swelling pressure. The maximum swelling strain is measured in the z-direction. Swelling of greenschist might be explained by distinct foliation/schistosity of the rock and also presence of various sheet silicates. The silicate minerals which have highest influence on the swelling potential are the tectosilicates, the phyllosilicates and the double chained inosilicates due to their distinct structure which enable for water molecules and exchangeable cation to enter through interlayers of the silicates causing a volume increase in the unit layers. This corresponds well to the recorded swelling strain in the z-direction.

- The tested tuff is classified as a medium strong rock and show moderate swelling pressure and highest swelling strain in the z-direction of all three rocks tested. This rock shows no distinct layering and a great amount of various sheet silicates are found. Tectosilicates and phyllosilicates are the sheet silicates that have greatest impact on the swelling potential. As for the greenschist, these silicate minerals will influence the degree of swelling. Difference in the recorded swelling strains for the rocks can be explained by the distinct structure of zeolites, wairakite and laumontite. These tectosilicates consist of a three dimensional framework of $(Al,Si)O_4$-tetrahedrons which are arranged in an open structure. This allows for a free flow of water molecules and cations in and out of the interlayers in the silicates providing a change in water content. An increase in water content entails an increase in swelling strain and thus contributes to the highest swelling in the z-direction.

- The testing methods for rock cylinders and rock cubes vary in both methodology and presentation of the test result. The differences are considerable according to test performances and the presentation of the test results. The testing method for rock cube is by far found to be the best to represent real situation as well as in terms of execution and presentation. This method is most tangible regarding criterias and behaviour of expansive rocks as it results in values for actual displacement of the rock mass.

On the basis of this research the following recommendations has been made for future researches:

- Proceed with a thorough research; a PhD., where several rock types in each category of sedimentary, metamorphic and igneous origin are compared. Several tests are needed to get swelling potential of each rock type.

- Replace the testing method for rock cylinders with the testing method for rock cube due to very low values for swelling pressure and high values for swelling strain and perform testing on rock cubes both parallel and normal to the layering. Also perform repeated drying and rewetting cycles to observe shrinkage and swelling behaviour.

- Include SEM and DTA analysis, to confirm the XRD results, in order to distinguish between various sheet silicates and study the mineral coating on the calcite minerals.

- Include more rock mechanical testing such as Poisson's ratio, young's modulus, UCS, sonic velocity and Brazilian tensile strength to get an even better understanding of the correlations between rock mechanical properties and swelling potential.

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