

A novel method for predicting the swelling potential of clay-bearing rocks

Mahdi Moosavi* and Saleh Ghadernejad

School of Mining Engineering, The University of Tehran, Tehran, Iran

(Received April 27, 2020, Revised September 9, 2021, Accepted November 10, 2021)

Abstract. The main objective of this study is to present a fast and reliable approach to predict the swelling potential of clay-bearing rocks. Investigations showed that there is a good correlation between the swelling potential of a rock and its desire to absorb water due to its clay content which could be measured using the “Contact Angle” test as one of the most common ways to determine the wettability. In this test, the angle between a water drop and the flat rock surface on which it rests is measured. The present method is very fast and returns repeatable results and requires minimal sample preparation. Only having a saw-cut surface of a sample with any shape is all one needs to perform this test. The logic behind this approach is that the swelling potential of a rock is a function of its mineral content and molecular structure, which are not only distributed in the bulk of the sample but also reflected on its surface. Therefore, to evaluate swelling behavior, it is not necessary to wait for a sample to get wet all the way to its “internal structure” (which, due to the low permeability of clay-bearing rocks, is very slow and time-consuming). Instead, one can have a good sense of swelling potential by studying its surface. Parametric studies on the effect of moisture content, porosity, and surface roughness on the contact angle measurements showed that using a saw-cut oven-dried sample is a convenient way to evaluate the swelling potential by this method.

Keywords: clay-bearing materials; contact angle test; swelling strain; swelling test; wettability

1. Introduction

The swelling of clay-bearing rocks is often associated with damage to the surface and underground structures. In surface structures, during periods of increasing soil moisture, the swelling medium will heave and cause the lifting of structures such as buildings (Angin and Ikizler 2018). Afterward, reducing soil moisture during dry periods could result in a surface settlement, and damage can be extensive (AlZubaidi *et al.* 2013). On the other hand, in underground structures, swelling has different impacts. In unsupported tunnels, swelling usually expresses itself by invert heave and associated abutment movements (Einstein 1996). Furthermore, if support systems are used to prevent tunnel convergence, considerable swelling pressure would impose on the support systems. Moreover, in shallow tunnels, uplift of the entire tunnel section and the land surface above it may occur (Butscher *et al.* 2016). Many case studies have addressed such damages to the surface and underground structures (Grob 1976, Einstein 1979, Kovári *et al.* 1988, Olsen *et al.* 1989, Berdugo *et al.* 2009a, Berdugo *et al.* 2009b, Alonso *et al.* 2013, Alonso *et al.* 2015, Mao *et al.* 2015, Kong *et al.* 2018, Butscher *et al.* 2018, Ramon and Alonso 2018, Asghari-Kaljahi *et al.* 2019).

In Europe, during the construction of Wisenberg and Adler Tunnels under the main chain of the Jura mountains, numerous swelling-related damages were reported (Steiner

and Metzger 1988, Steiner *et al.* 1989). In Italy, passing through a heavily fissured claystone formation by the San Donato Tunnel, convergence and invert heaves of more than 1m were reported (Barla *et al.* 1986). Similar problems were encountered in Canada’s Dickson Dam diversion tunnel while passing through interbeds of limestone, sandstone, and shale (Phelps and Brandt 1989). Similar problems were observed in underground powerhouses, such as cracking of thick reinforced concrete and movement of the roof at Masjed Soleiman Dam in Iran due to swelling of claystone daylighting the cavern (Moosavi *et al.* 2006).

One of the problems with the design of tunnels to resist swelling pressure is the realistic evaluation of swelling pressure. While there are many laboratory tests devised for this, it has widely been reported that field measurements showed less swelling pressure than what was determined from laboratory tests. For instance, at the Belchen tunnel in Switzerland, the swelling pressure was reported between 0.2 - 0.3 MPa from field tests measured with contact pressure cells while associated laboratory results varied from 0.8 to 2.0 MPa (Grob 1979). For the construction of the Chamoise Tunnel in France, laboratory tests indicated swelling stresses between 3 and 8 MPa. However, swelling pressures between 0.15 - 2.5 MPa were measured in the field depending on the time of lining placement (Steiner 1993). Despite these differences between the laboratory and field results, still, laboratory tests are widely used due to their cost-effectiveness. However, sample preparation for traditional laboratory swell tests is challenging and usually results in sample disturbance and unrepresentative results. An overview of the available laboratory setups for swelling evaluation and their drawbacks are presented in the forthcoming sections. To avoid these problems, based on

*Corresponding author, Professor
E-mail: mmoosavi@ut.ac.ir

the sample's surface properties, a new method for fast and effective evaluation of free swelling strains is introduced, which requires minimal sample preparation.

2. Swelling mechanism

Swelling is a complex physiochemical phenomenon occurring in the presence of water and usually with stress relief. This phenomenon can be observed mainly in soils or rocks composing clays, shale, anhydrite, or pyrite. The mineralogical composition of the rock, water chemistry, and the level of stress relief are dominant factors controlling the extent of swelling (Butscher *et al.* 2016). In what follows, a brief review of the best-known mechanisms is presented.

In the chemical category, the transformation of anhydrite to gypsum (ATG) is a typical example of swelling. After anhydrite changes to gypsum, its initial volume can increase up to 60%. The extent and rate of this volume change depend on the degree of anhydrite disintegration and accessible water. Usually, this mechanism causes the highest swelling pressure but not always projects encounter such materials. The oxidation of pyrite and marcasite, which produces sulphates, and its further reaction with carbonate to produce gypsum could also result in a volume increase even without the presence of the water (Einstein 1996).

The physical mechanisms causing swelling are of different types, including mechanical, osmotic, and intracrystalline swelling (Einstein 1996). Mechanical swelling happens when a clay-bearing material is distressed, which, due to its low permeability, causes negative pore pressure. Over time, this excess negative pressure is reduced by absorbing more water or air bubbles, which results in a volume increase.

Osmotic swelling in clay-bearing materials originates from the difference in cation concentration between clay particles and pore water, a high concentration of cations held between two clay particles electrostatically and less cation concentration in pore water. To compensate for the difference in concentration, pore water enters the space between the clay particles (osmosis) and forces them apart. It would be easier for water to enter between clay particles at lower lateral stresses, push them apart, and cause swelling. Therefore, external stresses and chemistry of water control the osmotic swelling. This mechanism is believed to be the most significant mechanism causing swell for engineering applications.

Intracrystalline swelling is caused by the permeation of water molecules halfway between the clay sheets. This permeation is due to the hydration of the exchangeable cations. The amount of water molecules entering this space controls the amount of swell. This effect is very extent in smectite. Within the smectite group lays montmorillonites and vermiculites. They are consisted of very small sheet minerals and can absorb and release water proportional to the applied external pressure on them.

In nature, it is very seldom to happen only one of these mechanisms. Instead, most of the time, a combination of them is involved in swelling phenomena. This is why

prediction of swelling is not an easy task, and the best way to do that accurately is a laboratory (or field) test. Considering the above mechanisms, for tunnels resting in clayey rocks, osmotic swelling is the most relevant swelling mechanism.

3. Methods of measuring swelling potential

Over the last forty years, many suggestions and testing methods have been proposed to have a better sense of swelling phenomena. Most of them are reflected in three consecutive versions of ISRM Suggested Methods (ISRM 1979, 1989, 1999). In addition to these standard testing methods, researchers have introduced other methods that have proposed new testing setup to evaluate swelling potential such as indentation test (Mehranpour *et al.* 2012, Rassouli *et al.* 2012) or to evaluate swelling capacity based on other soil or rock properties such as plasticity index as explained by Klein (2001) or water content at dry-saturation stages as described by Yongxin *et al.* (1988). However, up to now, these methods have not yet been so widely utilized to be considered as a standard method.

Recommended tests by ISRM are basically arranged to measure the swelling of an undisturbed sample at unconfined (Free Swell) or semi-confined (Oedometric) or fully-confined (Zero Volume Change) conditions. The free swell test is intended to evaluate the expansion of a sample in three directions while absorbing water. This test yields the maximum possible strain for a sample. Due to the simplicity of this test, it is usually intended as the first step to evaluate the extent of swelling potential. When proved, more detailed experiments would be needed.

In the second test, the sample is radially confined in a stiff ring, and it can swell only in the vertical direction. This test can be performed with different surcharges to develop a relation between axial pressure and associated swelling strain. In the extreme case, when the sample is completely confined both laterally and axially, the volume change will be zero, so the resultant swelling pressure would be recorded instead of the swelling strain.

Obviously, for many engineering applications, where the rock mass is contacting a civil structure, the rock is not free to swell; rather, it builds up a swelling pressure proportional to the stiffness of the confining structure (Grob 1979). Rocks that swell more in the free swell test usually generate more pressure when they are confined. Therefore, to assess swelling strain and pressure, the primary test method, which is also the easiest, is a free swell test. This is why the same has been obtained for the present research.

One of the most critical and challenging stages of a laboratory swell test is sample preparation. The main aim here is to perform tests on "undisturbed" samples. For a proper test, one should ensure that the sample integrity and its water content are not changed during preparation. For the free swelling test, the specimen can be prepared as a square block with any specific size or a cylindrical sample (as mentioned in the latest ISRM suggestions) with any diameter. In order to do this, a conventional rock saw can be used. Care should be taken to avoid heating the sample via

fast cutting or cooling the blade with water since both will change the sample's water content. Air flushing and slow cutting should always be used in sample preparation to keep the sample's natural state.

For confined (Oedometric) tests, where the sample diameter may not necessarily fit the inner diameter of the confining ring, specimen preparation becomes more challenging. Since the sample should tightly fit into the ring, one may need to change the sample diameter (which is difficult) or make different rings for different samples (which is costly). For soft rocks, ISRM suggests to use a manual press and a trimming ring for sample preparation. Other methods like reducing the sample diameter with a lathe machine are hard and usually generate micro fissures in the sample. Redrilling a core with a smaller size is also not always feasible because the required reduction in size is often insufficient to satisfy overcoring conditions. According to the author's experience, although making new rings for different samples is costly, it may be the most conservative way of doing a proper test.

Some problems may arise in a free swelling test, especially in soft and active samples, such as early sample disintegration when exposed to water or the penetration of seating plates (under the gauge's tip) into the sample. As a result of these, sometimes the maximum swelling strain is overestimated in this test. Therefore, it is suggested to use a semi-confined test with a very low surcharge (about 5 KPa) to evaluate maximum axial strain more realistically (Pimentel 2015).

The semi-confined test also has some drawbacks, which results in the unrealistic evaluation of the swelling potential compared to the field conditions such as:

- Confining samples in a stiff ring is meant to inhibit its lateral strain. However, in the field, the stiffness of the rock mass and existing stresses control the extent of lateral swelling. Therefore, not always the stiffness of the ring can correctly resemble the in-situ stiffness of the ground.
- The amount of water that has access to the sample in the field has a limit and is not the same as inundation conditions in the laboratory. However, due to the lack of knowledge about the accessibility of water, this is a problem in any test. To be conservative about the swelling pressure, the worst scenario should be tested.
- In the laboratory, an individual cannot wait for a very long time to correctly simulate the lengthy life of an actual project.

As is clear from the above, performing a representative laboratory swelling test is an arduous task due to the softness of samples and being prone to disintegration when exposed to water. Also, the preparation of the exact sample diameter is very troublesome. The present paper introduces a new fast method for predicting free swelling strains with minimum sample preparation. The idea stems from the fact that the swelling-related properties of clays, including types of clays particles and their electrical charges and water absorption properties, are not only distributed inside the sample but also reflected on the sample's surface.

In other words, for finding out how much a clay-bearing material is willing to absorb water and swell, it is not mandatory to submerge the sample and wait for a long time

for water to penetrate this low permeability material; instead, a drop of water can be put on a flat surface of the sample and record how much the sample is willing to absorb the drop. This willingness is a function of those clay properties which control swelling. For an active clay, as soon as a water drop touches the sample surface, it is pulled by the sample, and its shape becomes very flat. On the other hand, the drop keeps its original shape and remains close to a sphere for a less active clay. Therefore, by performing a "Contact Angle Test," which is quite usual in "Wettability" studies, one can quickly evaluate the swelling potential of a sample. The beauty of this method is that it requires minimal sample preparation and being independent on the water to penetrate deep into the sample. In addition, this test can be repeated several times on one surface by putting the new drops a bit further away from the previous place and get new data. By doing so, one can get several data from one specimen in a matter of seconds and use the average to get better representative data. In summary, considering the important role of clay minerals and their surface properties both in swelling mechanism and wettability, it was decided to use the correlation of these two as a method for evaluating swelling potential.

4. Wettability and contact angle

There exists a surface tension between a fluid and a solid, an example of which is a drop of water hanging from the tip of a needle without falling. Chemical bonds are the attractive forces between atoms in a molecule and between adjacent molecules in a substance. These are the forces that hold things together. When molecules are in close proximity with a liquid or solid, the atoms arrange themselves to satisfy the bonding forces with nearby neighbors optimally. The idealized solid is illustrated in Fig. 1.

An atom in the interior has satisfied bonds in all directions: four in this 2-D drawing and six in the real 3-D world. However, the atoms in the top row do not have one bond satisfied because there is no neighbor above. These unsatisfied bonds constitute surface energy; a potential energy in the sense that another object brought up close might satisfy some of these "dangling" bonds. These bonds are the sources of willingness to wetting and adhesion.

Wettability describes the preference of a solid to be in contact with one fluid rather than another. "Contact Angle"

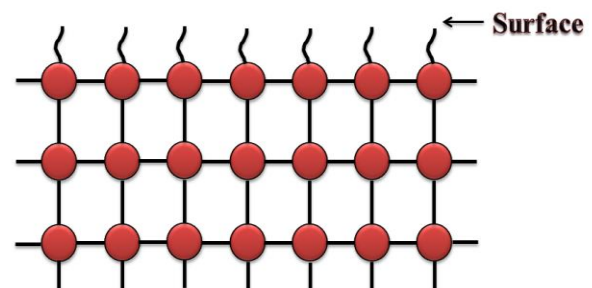


Fig. 1 Schematic of an idealized solid surface (Vijapurapu 2002)

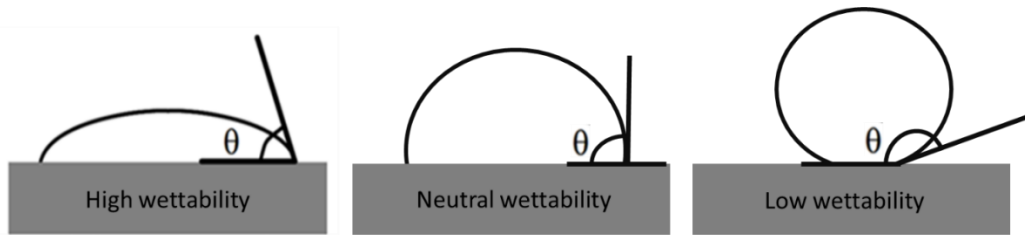


Fig. 2 Drop shape and its contact angle for different wettability

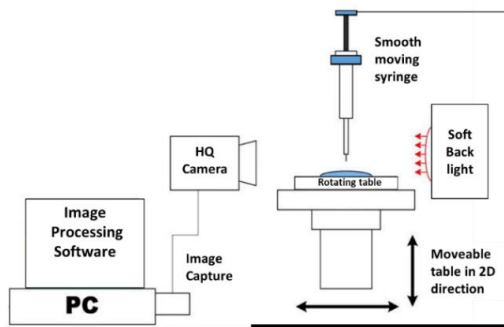


Fig. 3 Contact angle setup

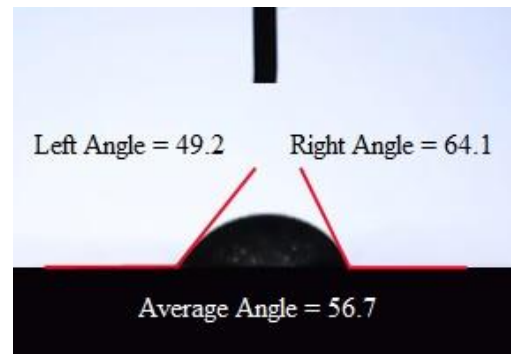


Fig. 4 Measured Contact angle method

is usually used to estimate the nature and strength of these bonds. Contact angle describes the shape of a liquid drop, usually water, at rest on a solid flat surface. The contact angle is the internal angle measured between a tangent drawn on the drop's surface at the resting point and a tangent to the supporting surface. Small contact angles, less than 90° , correspond to high wettability and vice versa (Fig. 2.). The shape of the drop reveals information about the chemical bonding nature of the material. This property is very much controlling the swelling of the material too.

The wettability test is widely used in the petroleum industry and has been discussed in detail elsewhere (Yuan *et al.* 2013, McPhee *et al.* 2015, Abdallah *et al.* 2007) since, in petroleum-related applications, not only do both oil and brine exist, but also temperature and pressure have elevated values compared to geotechnical applications. As a result, there are several methods devised for determining the wettability of rock to various fluids. The main ones are:

- Microscopic Observation which involves direct observation and measurement of wetting angles on small rock samples. There are so many subgroups in this class such as advancing and receding contact angle methods (Johnson 1964), Captive Bubble Method (Taggart *et al.* 1930), Tilting Plate Method (Adam *et al.* 1863), and so many other methods (Yuan 2013). This class of methods is usually referred to as Goniometry.
- Amott Wettability Measurements is a macroscopic means for wettability measurement of a rock core to given fluids, usually brine and oil (Amott 1959). This method is further revised and known as the Amott-Harvey method.
- USBM (U.S. Bureau of Mines) method. It is similar to the Amott method in which it compares the work necessary for one fluid to displace the other but considers the work required to do a forced fluid displacement.

Other wettability methods also exist, which would not

be discussed here for brevity. In the present paper, the simpler version of the wettability test, microscopic observation, is applied. Hence, the procedure explained in the ASTM standard (ASTM 2013) is followed.

Usually, the contact angle test is used as one of the popular wettability methods. A detailed discussion on different contact angle test methods is presented by Neumann *et al.* (1979). In this test, the equipment consists of an adjustable table on which the sample is located and leveled (Fig. 3). A camera takes films from the sample when an accurate syringe releases a drop of water on its flat surface. Afterward, using a computerized image processing program, the contact angle is measured later on from a snapshot taken from the film at the correct time when the drop rests on the surface. The picture should contain both sides of the drop, and the average of angles measured at both sides should be used (Fig. 4). Usually, at least three drops are located on each sample, and an average of six measurements are used.

The followings summarize the tests performed on different swelling samples to determine the correlation between free swelling and associated contact angle.

5. Test program

The present test program is a continuation of previously performed tests at the Rock Mechanics laboratory of the University of Tehran (Moosavi and Samani 2017). The equipment used in this research has been modified to increase the measurement accuracy, and the number of samples has been increased. Samples were selected from various formations and locations (Table 1), which mainly include claystone, siltstone, marl, and schist. It should be noted that, in these rocks, mechanical or osmotic swelling are activated, and no chemical swelling occurs.

Table 1 Specifications of rock samples

Rock Type	Project Name and Location	Code	Sample Diameter (mm)	Sample Height (mm)	Specific Weight (gr/cm ³)
Claystone	Masjed Soleiman Dam, Iran	A	61	48	2.12
Claystone	Ghadir Tunnel, Iran	B	54	46	2.28
Siltstone	Ragun Dam, Tajikistan	C	61	46	2.70
Marl	Silon Dam, Iran	D	54	33	2.38
Claystone	Qom Formation, Iran	E	50	32	2.13
Schist	Meydook Mine, Iran	F	54	41	2.24

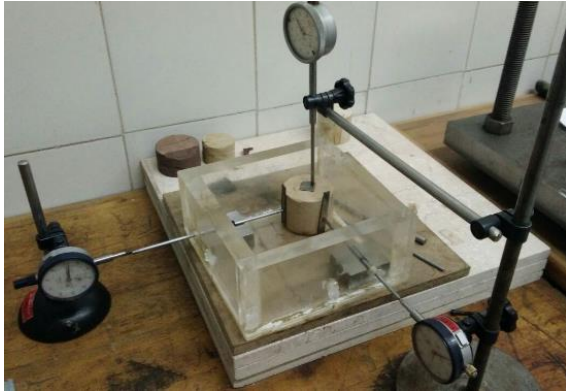


Fig. 5 Laboratory equipment for free swell strain measurement

To determine the correlation between the free swelling strains and contact angle, the contact angle and free swelling tests were performed on each sample. As explained before, on each specimen, it is possible to do a large number of contact angle tests then the same specimen can undergo swelling tests. Therefore, the average of all contact angle measurements for one sample was used to correlate with swell test results on the same sample.

To ensure that different water content in the samples do not adversely affect the test results, all samples were oven-dried before doing the tests (both for contact angle and swelling potential). For the contact angle test, a saw blade was used to cut a flat surface from the sample. No special polishing or extra treatment was done on the surface. These conditions were arranged in a way that the proposed correlation between swelling strains and contact angle can be used with minimal effort for situations where there is no access to complicated equipment facilities.

5.1 Free swelling test

For swelling tests, cylindrical samples were used, and displacements were measured by three dial gauges with 0.01 mm resolution. A picture of the free swelling test setup is shown in Fig. 5.

The results of free swelling tests in three orthogonal directions are summarized in Table 2. The results of free swelling tests on the samples are also shown in Fig. 6.

5.2 Contact angle test

The test setup consists of a moving table in longitudinal and vertical directions to locate the specimen in line with the camera and the light source. The base can also rotate to

Table 2 The result of free swelling tests

Code	Vertical strain (%)	Lateral strain 1 (%)	Lateral strain 2 (%)	Volumetric strain (%)
A	1.11	0.59	0.72	2.44
B	1.26	1.19	1.37	3.87
C	0.50	0.38	0.39	1.28
D	4.35	1.94	2.02	8.31
E	6.37	3.02	2.86	12.25
F	0.27	0.07	0.06	0.40

speed up performing several contact angle tests on one specimen by rotating the base table for each new drop (Fig. 7).

The light source is an LED type that does not generate any heat to affect the water drop adversely and cause vaporization. Also, the light is dispersed by an intermediate mate sheet to provide a soft distributed light source. A high-quality camera (50 fps) takes a film from the whole test procedure, facilitating the selection of a proper frame for contact angle measurement. The film can be processed by any digital film processing software. Before starting the camera, its lens is focused on receiving a clear shot from the drop.

The syringe has a screw-type feeding system to generate the drop in a controlled manner. Also, the whole syringe can move up and down to place the needle tip at a proper distance from the sample surface (about 3 mm). When the sample has been placed on the base table and moved to its correct position with respect to the needle, the test starts by starting the camera to film. A drop of water is carefully put on the sample, and a few seconds is waited before the table is rotated to provide new place for the next drop. This procedure is continued until enough drops have been placed on the specimen surface. The camera is filming during all these stages, which will be saved and processed on the computer for contact angle measurements later on.

After a test is done, the drop analysis requires film processing and deciding on the right time for measuring the contact angles at both sides of the drop. When a drop falls on the sample surface, its shape undergoes some changes for a short period of time as a result of interactions between the surface tensions and gravity force. It is only after a while, in order of a second, where the shape of the drop stabilizes. It is of prime importance that the angle measurement is done at the right time. An early snapshot might be suffering an unstable drop shape, and a very late snapshot might be erroneous because of water being sucked by the sample. An analysis of drop shape has been done in this test program to develop the best timing for obtaining the snapshot.

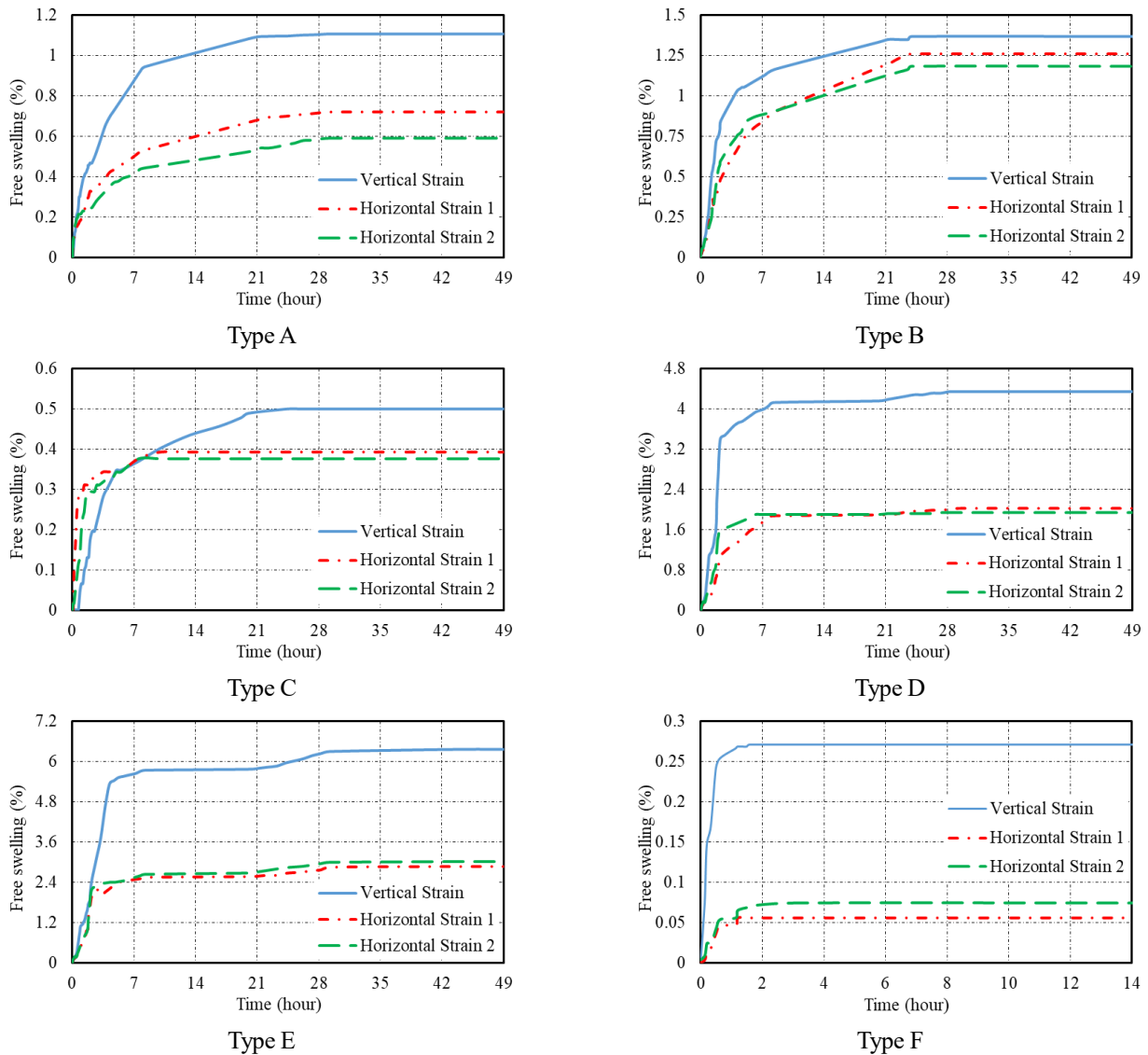


Fig. 6 Free swelling tests on the samples



Fig. 7 Contact angle measuring equipment

In Fig. 8, drop shape analysis results are shown in which the right and left contact angles and their average are measured. From the recorded data, the right to the left contact angles ratio is determined all during 2.6 seconds from the test initiation. In the following pictures, snapshots

of the drop resting on the sample surface are also shown.

As it is clear from the frames, the contact angle at the first touch is 120 degrees. From this moment until 1.5 seconds and afterward, the contact angle decreases to 60 degrees. During the first 0.5 seconds, the drop shape is unstable due to the balancing process between the acting forces. Approximately after 0.5 seconds, the difference between the right and the left angles reduces, and those become very close to the average angle, which is the correct number to report (Fig. 9). When the time elapses, the sample gradually absorbs the drop, and the contact angle decreases to zero when the rock completely sucks the drop. Studying the ratio between the right and the left contact angles on a drop can help come up with the time of drop stabilization. The following graph depicts one of such analysis where this ratio fluctuates between an average line and stabilizes after a while. The ratio of 1 means a complete symmetrical drop. As in Fig. 10, the values above the horizontal line represent a drop leaning towards the right side of the screen and vice versa.

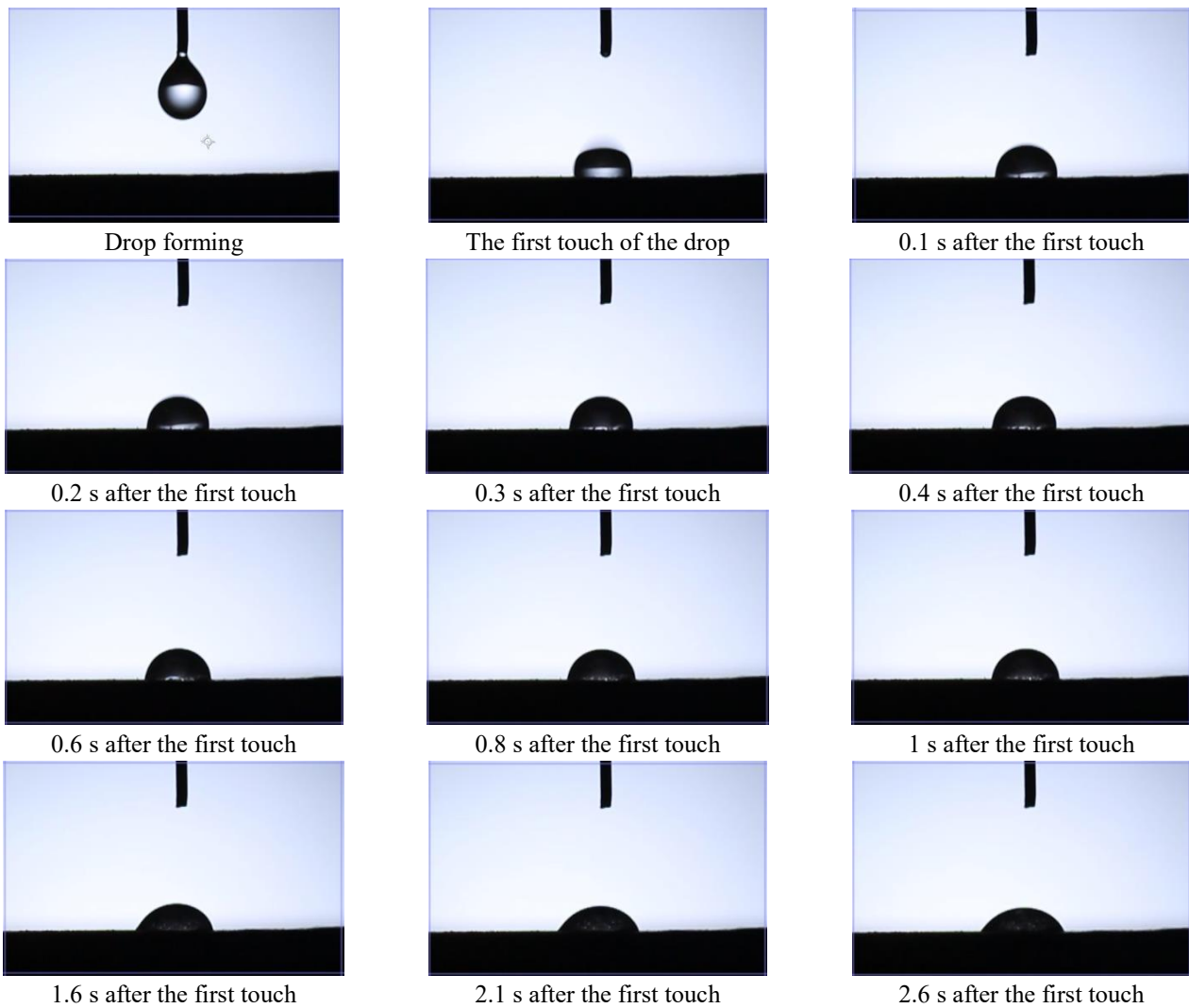


Fig. 8 Snapshots of a falling drop and its stability stages

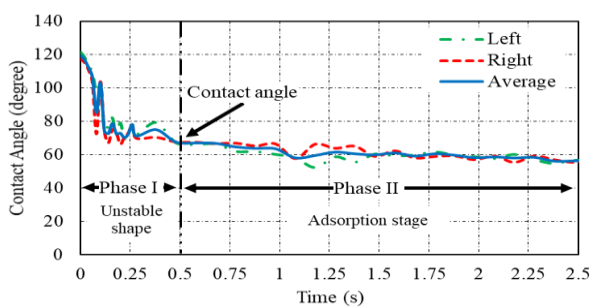


Fig. 9 Stability of a drop during elapsed time

Table 3 Correlation between contact angle and free volumetric swell

Code	Average Contact Angle (Deg.)	Vertical strain (%)	Volumetric strain (%)
A	46.32	1.11	2.44
B	30.20	1.37	3.87
C	52.57	0.50	1.28
D	25.19	4.36	8.31
E	12.16	6.37	12.25
F	60.98	0.27	0.40

6. Correlation between contact angle and free swelling strains

The results of the contact angle test with the notice to the above points are summarized in Table 3.

As shown in Figs. 11 and 12, there is a good correlation factor for swelling potential to both volumetric and axial strains in the free swelling test.

7. Parametric study

Questions remain to be answered about how different rock properties, such as water content, porosity, and surface roughness of the sample, might affect contact angle measurements. A series of tests were performed to assess the dependency of contact angle in one sample to these parameters.

7.1 Water content

Since the contact angle is dependent on the tendency of

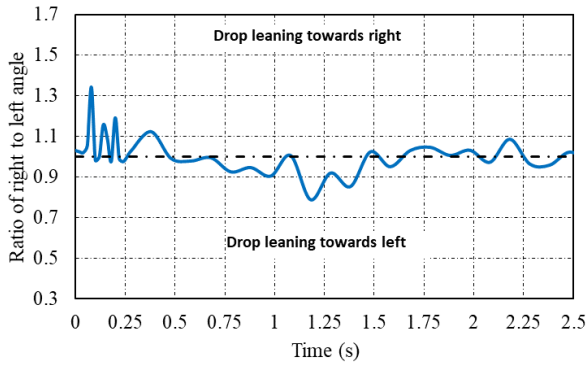


Fig. 10 Oscillation of a drop to the left and right and its final stability

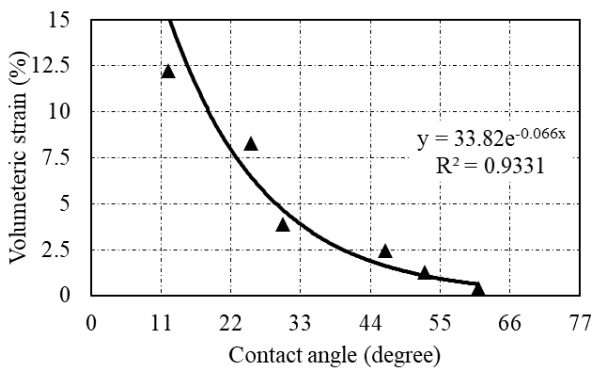


Fig. 11 The relationship between contact angle and Volumetric strain in free swelling test

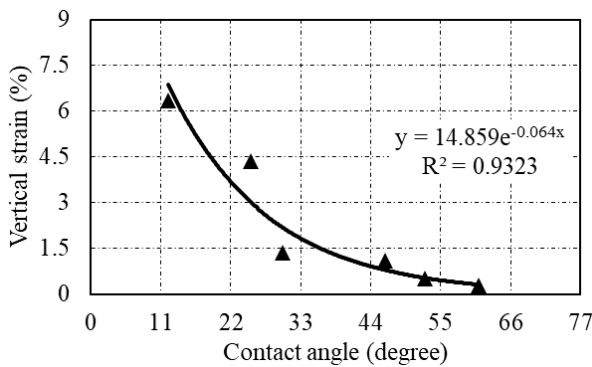


Fig. 12 The relationship between contact angle and vertical strain in the free swelling test

the sample to absorb water molecules, it is expected that a completely dry sample has a higher tendency to absorb water than a sample with higher water content.

To quantify this effect, all samples were first submerged in water for 24 hours, and several contact angle tests were performed on them at different times when the sample was left to dry gradually and naturally at room temperature. Each time the sample's total weight, weight of dry sample plus its contained water, was measured, and its contact angle was also recorded at that water content level. In the end, the sample was oven-dried, and the contact angle of the dry sample was also measured.

The dependency of contact angle to water content is shown for all the samples in Fig. 13. As it can be seen, with

Table 4 Dependency of contact angle to the porosity

Code	Average Contact Angle (Deg.)	Porosity (%)
A	46.32	13.64
B	30.20	17.44
C	52.57	13.57
D	25.19	18.38
E	12.16	24.12
F	60.98	5.91

increasing water content, the contact angle increases too, which shows rock's tendency to absorb extra water decreases in a wet sample. Also, it was observed that repetitive wetting and drying of a sample does not affect the contact angle measurement so this property seems to be no path-dependent.

The above results show that the dependency of contact angle to the water content follows almost a linear trend.

7.2 Porosity

It is almost impossible to study the effect of porosity change on rocks since each rock has a unique porosity. So only for different samples with their porosities, the relation between contact angle and porosity can be determined (Fig. 14). As expected, a sample with higher porosity has a higher tendency to suck more water. Therefore, for higher porosities, the contact angle decreases (Table 4).

7.3 Surface roughness

The fact that surface roughness affects contact angle measurement has been noticed since this test was devised by Yuan *et al.* (2013). One of the reasons why contact angles in advancing and retreating methods are different is believed to be mainly due to the roughness effect. One of the problems that arise by roughness is that the actual contact angle is different from the apparent contact angle. An exaggeration of roughness effect is depicted in Fig. 15. Therefore, it is important to perform tests on relatively smooth surfaces and keep the same roughness level for all the specimens if one expects to compare or share obtained results with others.

Earlier research showed that tests were performed on a polished surface in the absence of any unified criterion for basic surface roughness (Busseher *et al.* 1983, Vargha-Butler *et al.* 1986). However, in the present study, to simplify this, a saw-cut surface was obtained as the basic surface roughness because everybody has access to that. In this way, the current data and formulation can be used by the others too. In addition, a series of tests on two types of rock were performed where their surfaces were made rough by a series of abrasive papers. By performing contact angle tests on these surfaces, the effect of surface roughness was quantified. Studying the effects of surface roughness helps us understand whether a saw-cut surface is smooth enough to be used as a reference. The abrasive papers used are listed in Table 5.

After applying these papers on two rock samples' surfaces, they became rough. Still, it is notable that the

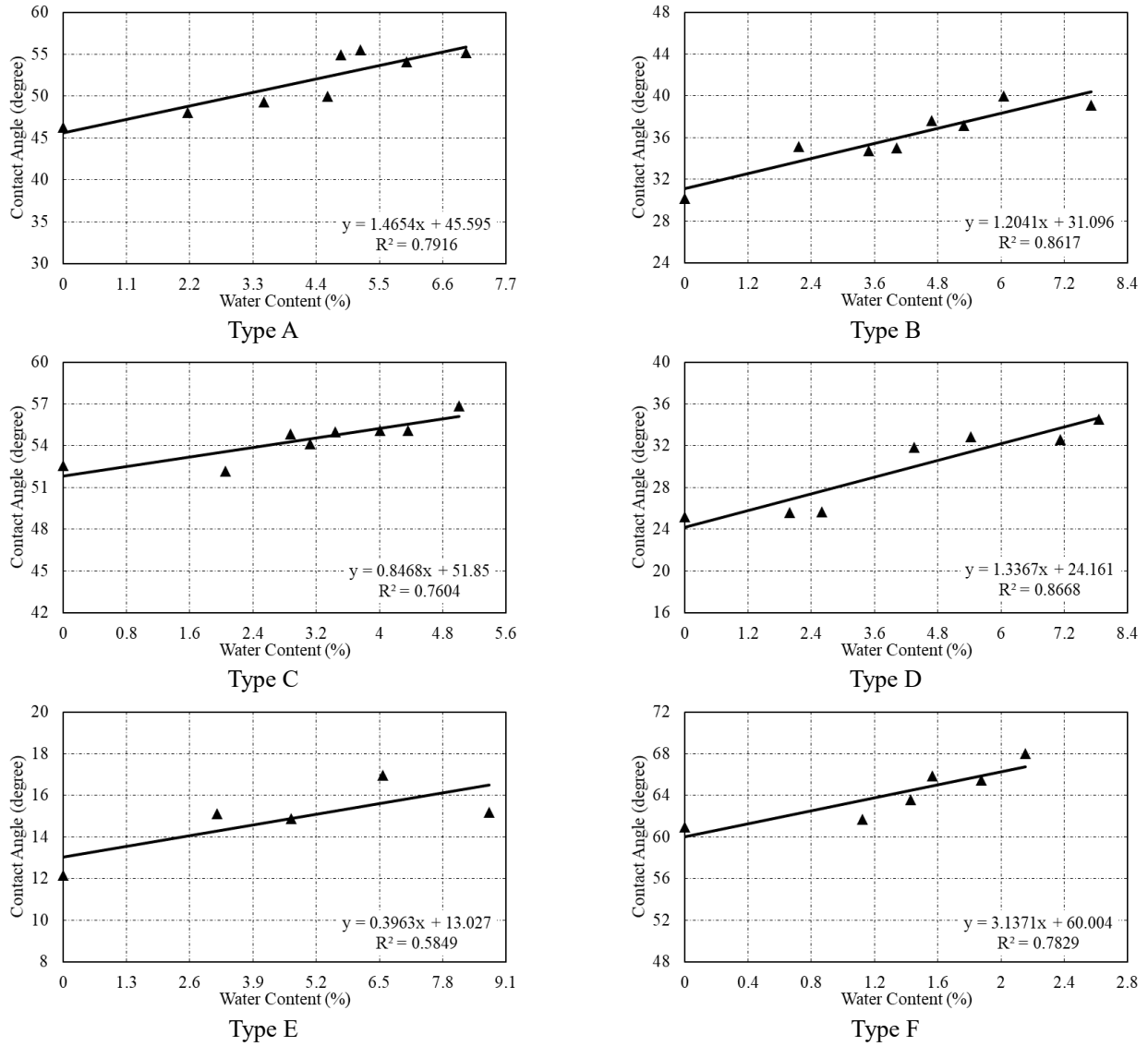


Fig. 13 The relationship between water content and contact angle for samples

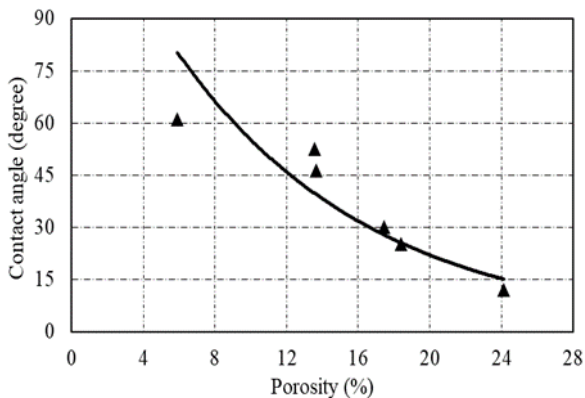


Fig. 14 The relationship between porosity and contact angle

actual roughness will be softer than the original roughness of the papers because the clay particles quickly fill the gap between abrasive particles and reduce the effective

roughness of the sample. To quantify the actual roughness, a laser scanner was used to quantify the actual roughness of these prepared surfaces. The accuracy of the roughness measurement is in order of 10 microns (Fig. 16). Fig. 17 shows a comparison between the grit roughness and the actual roughness of the roughened specimens.

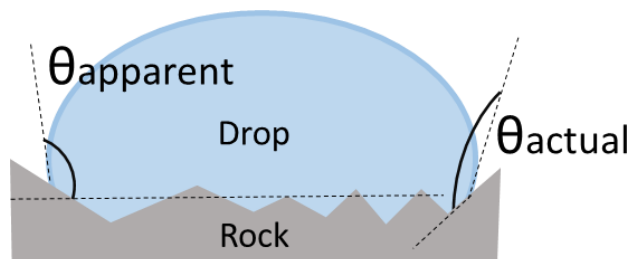


Fig. 15 Difference between apparent and actual contact angles for a rough surface

Table 5 Characteristics of the abrasive papers

Abrasive paper	Standard P	The average diameter of particles (Microns)
Very hard	P 60	250
Hard	P 100	160
Relatively hard	P 120	125
Soft	P 1500	12
Very soft	P 2000	9

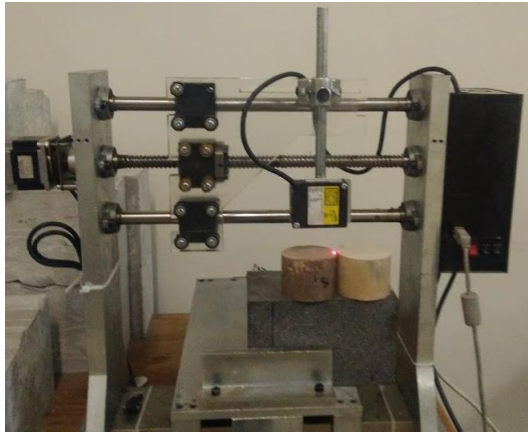


Fig. 16 Laser scanner for recording surface roughness

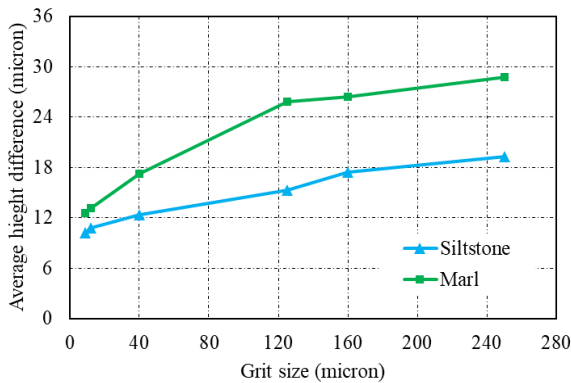


Fig. 17 Comparison between grit and actual surface roughness

Table 6 The roughness of the surfaces recorded by the laser scanner

Code	Roughness Amplitude (microns)
A	10.108
B	9.876
C	10.010
D	9.806
E	9.637
F	10.936

According to the above figure, when the roughness of the surface decreases, it tends to reach a limiting number (around 10 microns) regardless of the sample type. This number is almost the roughness an individual gets when cutting the samples with a saw blade. Table 6 shows the actual roughness of 6 samples obtained from their saw-cut surfaces

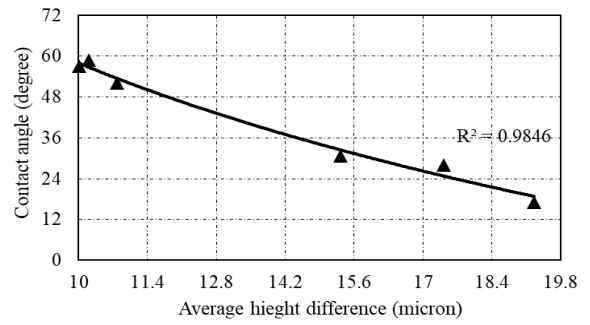


Fig. 18 The relationship between average height difference and contact angle for samples A

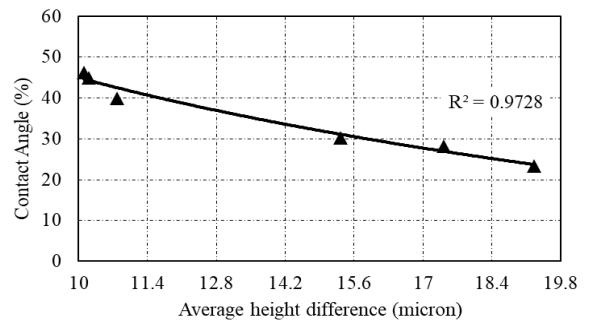


Fig. 19 The relationship between average height difference and contact angle for samples C

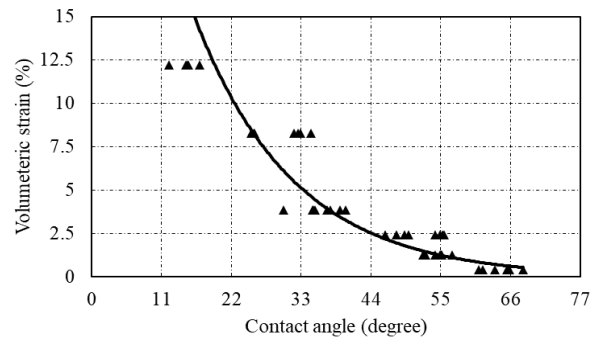


Fig. 20 Correlation between contact angle and volumetric strain

Figs. 18 and 19 depict how different roughness can affect contact angle measurement for rock types A and C. As it is shown, the smoother the surface, the higher the measured contact angle. It means that rougher surfaces return lower contact angles. In other words, if the roughness of a surface is too high, a contact angle test might return lower values than usual, which results in the overestimation of the swelling potential. Therefore, working on a saw-cut surface is safe enough to avoid any roughness effect on actual contact angle measurement.

All the tested samples are shown in Fig. 20, which indicates a good correlation between contact angle and swelling strain. However, no formulation is provided to leave room for additional tests to increase the data bank for this new approach.

8. Conclusions

The present paper is an effort to propose a simple and fast method to evaluate the swelling potential of clay-bearing rocks. The proposed method requires minimal sample preparation and avoids cumbersome and time-consuming sample preparation processes, as are common in the classical methods.

The main idea of this method is based on assessing the swelling potential from the sample's surface rather than from its bulk. The swelling behavior of a sample is more than anything related to the clay particles, their charges, and interactions with water. These properties are certainly reflected on the sample's surface as surface tension. Therefore, the swelling behavior of clays is very much reflected on its surface, and this can be utilized to overcome many problems that we encounter in saturating a low permeability clay-bearing rock.

Goniometric contact angle tests performed on six rock samples showed a close correlation with the volumetric strain of the free swelling test. The higher the swelling potential is, the lower would be the contact angle. The setup for this test is very simple, and many tests can be done in a very short time. Sample preparation is limited to just making a saw-cut flat surface and oven drying the sample. Since the sample is not completely submerged in this test, the disintegration of the sample is not an issue. In addition, small samples could be used since the test scale is as small as a water drop.

It was shown that contact angle could be dependent on surface roughness, sample porosity, and water content. To eliminate these effects, it is always suggested to use a dry sample and perform the test on a simple saw cut surface for a specific clay-bearing rock. No additional surface treatment such as polishing is required. The correlation presented in this paper is valid for samples prepared with the above two assumptions. It is hoped that with further use of this method and the accumulation of more data, a more accurate correlation becomes available in the future.

It is worth noting that the samples used in this study were all clay-bearing materials; therefore, no chemical swelling has been involved (such as Gypsum or Pyrite), and the mechanism of swell mainly consisted of mechanical or osmotic ones. Also, the level of swelling recorded in those rocks can be categorized as moderate, so more samples should be tested with perhaps higher swelling potential or very low swelling to add to the range of these tests and check the validity of this method for the upper and lower ends of swelling too.

Acknowledgments

The authors would like to thank Mr. H.Y. Samani for his early collaboration in starting this research. Also, using Rock Mechanics facilities at the School of Mining at the University of Tehran is mostly appreciated.

References

Abdallah, W., Buckley, J.S., Carnegie, A., Edwards, J., Herold, B.

- and Fordham, E. (2007), "Fundamentals of wettability", Schlumberger Wettability Workshop.
- Adam, N.K. and Jessop, G. (1924), "CCL.-Angles of contact and polarity of solid surfaces", *J. Chemical Soc.*, **127**, 1-5.
- Alonso, E.E., Berdugo, I.R. and Ramon, A. (2013), "Extreme expansive phenomena in anhydritic-gypsiferous claystone: The case of Lilla tunnel", *Géotechnique*, **63**(7), 584-612. <https://doi.org/10.1680/geot.12.P.143>.
- Alonso, E.E., Sauter, S. and Ramon, A. (2015), "Pile groups under deep expansion: a case history", *Canadian Geotech. J.*, **52**(8), 1111-1121. <https://doi.org/10.1139/cgj-2014-0407>.
- Amott, E. (1959), "Observations relating to the wettability of porous rock", *Soc. Petroleum Eng.*, **216**, 156-162. <https://doi.org/10.2118/1167-G>.
- Asghari-Kalajahi, E., Barzegari, G. and Jalali-Milani, Sh. (2019), "Assessment of the swelling potential of Baghmishkeh marls in Tabriz, Iran", *Geomech. Eng.*, **18**(3), 267-275. <https://doi.org/10.12989/gae.2019.18.3.267>.
- ASTM D7334-08 (2013), *Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement*, ASTM International; Pennsylvania, US. <https://doi.org/10.1520/D7334-08R13>.
- AlZubaidi, R.M., AlRwai, K.H. and AlFalahi, A.J. (2013), "Using cement dust to reduce swelling of expansive soil", *Geomech. Eng.*, **5**(6), 565-574. <http://dx.doi.org/10.12989/gae.2013.5.6.565>.
- Angin, Z. and Ikizler, S.B. (2018), "Assessment of swelling pressure of stabilized bentonite", *Geomech. Eng.*, **15**(6), 1219-1225. <https://doi.org/10.12989/gae.2018.15.6.1219>.
- Barla, G., Pazzagli, G., Rabagliati, U. and Travalini, S. (1986), "The San Donato Tunnel (Florence)", *Proceeding of International Congress on Large Underground Openings*, Firenze, Italy.
- Berdugo, I.R., Alonso, E., Romero, E. and Gens, A. (2009a), "tunneling and swelling in triassic sulphate-bearing Rocks: Part I. Case studies from Baden-Württemberg", *Epsilon*, **12**, 13-37.
- Berdugo, I.R., Alonso, E., Romero, E. and Gens, A. (2009b), "Tunneling and swelling in triassic sulphate-bearing rocks: part II: case studies from Jura Mountains", *Epsilon*, **12**, 39-53.
- Busseher, H.J. Van Pelt, A.W.J., De Jong, H.P. and Arends, J. (1983), "Effect of spreading pressure on surface free energy determinations by means of contact angle measurements" *Journal of Colloid Interface Science*, **95**, 23-27. [https://doi.org/10.1016/0021-9797\(83\)90067-X](https://doi.org/10.1016/0021-9797(83)90067-X).
- Butscher, C., Mutschler, T. and Blum, P. (2016), "Swelling of clay-sulfate rocks: a review of processes and controls", *Rock Mech. Rock. Eng.*, **49**(4), 1533-1549. <https://doi.org/10.1007/s00603-015-0827-6>.
- Butscher, C., Breuer, S. and Blum, P. (2018), "Swelling laws for clay-sulfate rocks revisited", *Bull. Eng. Geol. Environ.*, **77**(1), 399-408. <https://doi.org/10.1007/s10064-016-0986-z>.
- Einstein, H.H. (1996), "Tunnelling in difficult ground-Swelling behaviour and identification of swelling rocks", *Rock Mech. Rock. Eng.*, **29**(3), 113-124. <https://doi.org/10.1007/BF01032649>.
- Einstein, H.H. (1979), "Tunneling in swelling rocks", *Underground Space*, **4**(1), 51-61.
- Ghadernejad, S. (2018), "Study on the swelling of clayey rocks by contact angle method", Master Thesis, University of Tehran, Tehran, Iran.
- Grob, H. (1976), "Swelling and heave in Swiss tunnels", *Bull. Int. Assoc. Eng. Geology*, **13**, 55-60. <https://doi.org/10.1007/BF02634728>.
- Grob, H. (1979), "Swelling in belchen tunnel", *Proceeding of Underground Construction*, Lucerne, Switzerland, July.
- ISRM (1979), "Suggested methods for determining water content, porosity, density, absorption and related properties and swelling

- and slake durability index properties”, *Int. J. Rock Mech. Min. Sci.*, **16**, 141-156.
- ISRM (1989), “Suggested methods for laboratory testing of argillaceous swelling rocks”, *Int. J. Rock Mech. Min. Sci.*, **26**, 415-426. [https://doi.org/10.1016/0148-9062\(89\)90937-6](https://doi.org/10.1016/0148-9062(89)90937-6).
- ISRM (1999), “Suggested methods for laboratory testing of swelling rocks”, *Int. J. Rock Mech. Min. Sci.*, **36**(3), 291-306. [https://doi.org/10.1016/S0148-9062\(99\)00005-4](https://doi.org/10.1016/S0148-9062(99)00005-4).
- Johnson, R.E. and Dettre, R.H. (1964), *Advances in Chemistry Series*, American Chemical Society, Washington, US.
- Klein, S. (2001), “An approach to the classification of weak rock for tunnel projects”, *Proceeding of Rapid Excavation and Tunneling Conference*, Colorado, U.S.A.
- Kong, L.W., Zeng, Z.X., Bai, W. and Wang, M. (2018), “Engineering geological properties of weathered swelling mudstones and their effects on the landslides occurrence in the Yanji section of the Jilin-Hunchun high-speed railway”, *Bull. Eng. Geology Environ.*, **77**, 1491-1503. <https://doi.org/10.1007/s10064-017-1096-2>.
- Kovári, K., Amstad, Ch. and Anagnostou, G. (1988), “Design/Construction methods - Tunneling in swelling rocks”, *Proceeding of the 29th US Symposium of Key Questions in Rock Mechanics*, Minnesota, USA, June.
- Olsen, R.S., Palmstrom, G., Palmstrom, A. and Strømme, B. (1989), “Tunnel collapses in swelling clay zone”, *Tunnels Tunnelling Int.*, **21**(11), 49-58.
- Mao, D., Nilsen, B., Feng, S., Zhao, H. and Lu, M. (2015), “A case study of tunnel instability in weakness Zone containing swelling clay”, *Proceeding of Shotcrete for Underground Support XII*, Singapore, October.
- McPhee, C., Reed, J. and Zubizarreta, I. (2015), “Best practice in coring and core analysis”, *Core Anal. Best Practice Guide*, Elsevier Public., **64**, 313-347. <https://doi.org/10.1016/B978-0-444-63533-4.00001-9>.
- Mehranpour, M.H., Rassouli, F.S. and Moosavi, M. (2012), “Impression Relaxation Test, a new relaxation method to determine the time dependent characteristics of salt rock”, *46th US Rock Mechanics/Geomechanics Symposium*, Illinois, U.S.A., June.
- Moosavi, M. and Samani, H. (2017), “A new indirect method for evaluation of the swelling potential of argillaceous rocks”, *Proceedings of the 17th Coal Operators’ Conference*, Wollongong, Australia, February.
- Moosavi, M., Yazdanpanah, M.J. and Doostmohammadi, R. (2006), “Modelling the cyclic swelling pressure of mudrock using artificial neural network”, *J. Eng. Geology*, **87**, 178-194. <https://doi.org/10.1016/j.enggeo.2006.07.001>.
- Neumann, A.W. and Good, R.J. (1979), “Techniques of Measuring Contact Angles”, *In: Good, R. Surface and Colloid Science: Experimental Methods*. Stromberg (Plenum Publishing, New York), **11**, 31-91. <https://doi.org/10.1007/978-1-4615-7969-4>.
- Phelps, D.J. and Brandt, J.R. (1989), “Performance of tunnels in swelling rock at Dickson Dam, Alberta”, *Proceeding of 7th Canadian Tunnelling conference*, Vancouver, Canada, February.
- Pimentel, E. (2015), “Existing methods for swelling tests-a critical review”, *Energy Procedia*, **76**, 96-105. <https://doi.org/10.1016/j.egypro.2015.07.857>.
- Ramon, A. and Alonso, E.E. (2018), “Heave of a building induced by swelling of an anhydritic riassic claystone”, *Rock Mech. Rock Eng.*, **51**, 2881-2894. <https://doi.org/10.1007/s00603-018-1503-4>.
- Rassouli, F.S., Mehranpour, M.H. and Moosavi, M. (2012), “Study of punch tip effect on creep of materials in impression creep test”, *46th US Rock Mechanics/Geomechanics Symposium*, Illinois, USA, June.
- Steiner, W. and Metzger, R. (1988), *Experience from Tunnels in Swelling Rock*, Report to Swiss Federal Railways for the Wisenberg-Tunnel Project.
- Steiner, W., Rossi, P.P. and Devin, P. (1989), “Flat jack measurements in the lining of the Hauenstein tunnel as a design base for the New Wisenberg tunnel”, *Proceeding of International Congress on Progress and Innovation in Tunneling*, Toronto, Canada, September.
- Steiner, W. (1993), “Swelling rock in tunnels: Rock characterization, effect of horizontal stresses and construction procedures”, *Int. J. Rock Mech. Mining Sci. Geomec. Abstract*, **30**, 361-380. [https://doi.org/10.1016/0148-9062\(93\)91720-4](https://doi.org/10.1016/0148-9062(93)91720-4).
- Taggart, A.F., Taylor, T.C. and Ince, C.R. (1930), “Experiments with flotation reagents”, *Amer. Institute Mining Metallurgic. Eng.*, **87**, 285-366.
- Vargha-Butler, E.I., Kashi, M., Hamza, H.A. and Neumann, A.W. (1986), “Direct contact angle measurements on polished sections of coal”, *J. Coal Preparat.*, **3**, 53-75. <https://doi.org/10.1080/07349348608905274>.
- Vijapurapu, C. (2002), *The Effects of Rock and Fluids Characteristics on Reservoir Wettability*, Master Thesis, Andhra University, Visakhapatnam, India.
- Yongxin, Q., Xiaolan, X., Mengxion, Sh. and Zhilan, W. (1988), “Engineering classification of the argillaceous rocks and rapid prediction of their swelling potential”, *Proceeding of the International Symposium on Engineering in Complex Rock Formations*, Beijing, China, November.
- Yuan, Y. and Lee, T.R. (2013), “Contact angle and wettability properties”, *Surface Sci. Techniq., Springer Series Surface Sci.*, **51**, 3-33. https://doi.org/10.1007/978-3-642-34243-1_1.

CC