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A NEW INDIRECT METHOD FOR EVALUATION OF THE SWELLING POTENTIAL OF ARGILLACEOUS ROCKS

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ABSTRACT: One of the most important characteristics of argillaceous rocks is their swelling potential. This can be determined either by direct or indirect methods. Conventional tests are performed in which one of the properties/indices of rock is associated with the swelling potential. Since the direct tests are usually costly and time consuming, this article is focused on introducing a new method for evaluation of the swelling potential of argillaceous rocks. This is a quicker and less expensive test. The present study shows that there is a good correlation between “Contact Angle” of a drop of water on a flat rock surface with its swelling potential. Since the swelling potential is associated with molecular structure and surface tension of molecules, it is expected that contact angle (which is also influenced by this surface tension) be correlated with swelling potential.

In the present study, free swelling, contact angle, plastic and liquid limit tests are conducted on rock samples and their correlations are determined. The results showed that although there is an exponential relationship between plasticity index and swelling strain, using this parameter as an indirect method for swelling evaluation, has some limitations. On the other hand, due to the ability of contact angle to distinguish rocks with different swelling potentials, using this parameter has been proven to be an appropriate criterion for assessment of swelling potential.

INTRODUCTION

The swelling phenomenon, according to the definition of ISRM (1983), is a combination of physico-chemical reactions in rocks with involvement of water and stress relief. Swelling occurs in soils or rocks with clay, anhydrite or pyrite/marcasite minerals, Barla (2008).

Swelling of rocks causes major problems for rock engineering projects both during construction and over in the operational life. In Belchen tunnel in Switzerland, marl, anhydrite and opalinus clay were excavated which presented problems like heaving of invert and cracking of drainage pipes soon after excavation. A 17 m high cavity was formed at the roof of the Sallsjo tailrace tunnel in Sweden about a year after commissioning of the tunnel. This was due to the presence of a 3 m wide shear zone containing montmorilonite clay. Singh and Goel (2006) reported that over 31 years of service in Bozberg tunnel in Switzerland, invert heaves of 27 and 33 cm were observed in anhydrite and opalinus shales respectively. Similarly, due to increased swelling pressure behind the concrete lining of Masjed–Soleiman underground power house cavern (PHC) in Iran, cracks were generated in the concrete lining at the contacts with mudrock layers as reported by Doostmohammadi (2008). Due to problems of swelling rocks that can cause, the evaluation of this parameter has a significant role in engineering projects, which cross such formations.

Evaluation of the swelling potential of rocks can be done either by direct or indirect methods. Conventional tests such as free swelling described by ISRM (1983) are classified as direct methods in which the rock sample is exposed to water and the resulting swell is measured directly in the surface of rock. Most of the direct methods for swelling tests are time consuming and costly. Such laboratory tests may take from a few days to even a few years as performed at Karlsruhe University, Mutschler (2003). However for indirect methods, which are usually very fast relationships are provided, which

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correlate this potential to one of the properties/indexes of the rock. The duration of long test for swelling measurement is usually not acceptable by many projects especially at the early stages of their feasibility study. In these circumstances, a quick and accurate enough test can be very useful for swell evaluation.

Various indirect methods for assessing swelling capacity of expansive soils have been proposed so far as explained by Asgari and Fakher (1994). Indirect methods use one or more soil parameters (such as percentage of clay–size fraction (< 2µm), activity, density, plasticity index, liquid limit or water content of soil specimen) and relate it to swelling potential.

This paper aims to establish a new indirect method for evaluation of swelling potential in rocks. This is based on the concept of surface tension of a rock sample and its wettability property. Wettability is defined as the preference of a solid to attract a liquid or gas (known as the wetting phase) rather than another as described by Vijapurapu (2002). In other words, wettability is defined as the ability of one fluid to spread or adhere to a rock surface in the presence of other immiscible fluids. The "contact angle" test is a quick test which can be utilized for this purpose. To make a comparison between the correlation of this new method and older ones foo the swelling potential, a series of plasticity index tests were also performed.

SWELLING MECHANISM

Swelling is caused by one or a combination of three mechanisms as explained by Einstein (1996): mechanical, osmotic and intra-crystalline. Mechanical swelling is caused by dissipation of excess pore pressure. Osmotic swelling is related to the double layer effect, i.e. the large difference in concentration between ions held electrostatically close to the clay particle surfaces and the ions in the pore water further away. Osmotic swelling is controlled by the interaction of repulsive forces related to the double layer effect and externally applied stresses. Klein (2001) described the intra-crystalline swelling which is caused by hydration of the exchangeable cations. The cations hydrate upon contact with water and arrange themselves in a plane halfway between the clay layers. This results in a widening of the space between the clay layers and the overall effect depends on the number of water layers between the clay layers.

Occurrence of each mechanism depends on the rock forming minerals. For example, osmotic swelling occurs in clay bearing rocks while interacrystalline swelling occurs in smectite and mixed layer clays in anhydrite and in pyrite and marcasite.

The main groups of crystalline materials that make up clays are kaolinite, illite and montmorillonite. These are often called swelling or expansive clays. One feature of these minerals is having high specific surface (surface area per unit mass). The specific surface of kaolinite ranges from 10 to 20 m^2 /gr while for illite it ranges from 65 to 100 m^2 per gr. Montmorilonite can have a specific surface as high as 1000 m^2 /gr. Large surface area in this group cause significant role of surface forces in the behavior of clays.

The surface charges on clay minerals are negative (anions). These negative surface charges attract cations and positively charged side of water molecules from surrounding water source. Consequently, a thin film or layer of water, called absorbed water, is bonded to the mineral surface. The thin film or layer of water is known as diffuse double layer (Figure 1). The largest concentration of cations occurs at the mineral surface and decreases exponentially with distance away from the surface.

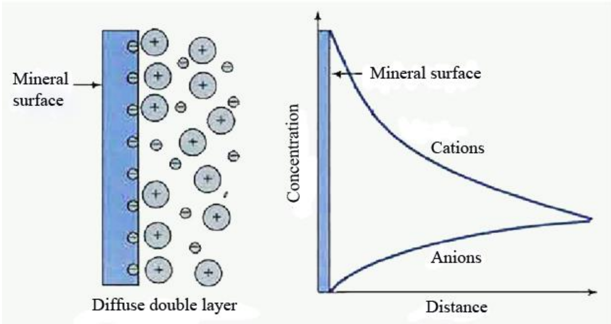

Figure 1: Diffuse double layer

The swelling of purely argillaceous rocks (i.e. rocks not containing anhydrite) is for all practical purposes sufficiently well understood. Under tunneling conditions, the swelling of argillaceous rocks is of an osmotic nature. This means that the cation concentration is lower in the pore water than close to the surface of the clay particles. This is because the latter (due to their negative electrostatic charge) attracts the cations (Figure 2). To compensate for the difference in concentration, pore water enters into the space between the clay particles (osmosis) and forces them apart. This can be prevented by applying a counter pressure, which theoretically decreases rapidly nonlinearly with the distance between the clay particles.

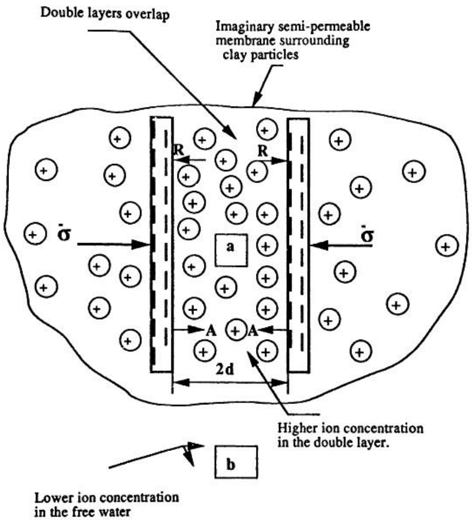

Figure 2: Double layers around clay particles

Gouy double layer theory is a theoretical method for calculation of swelling pressure using mineralogical parameters. Some of the parameters considered in this method are specific surface area of clay fraction, cation – exchange capacity (CEC), ion concentration that is far from the clay surface and electrical potential that is midway between the clay surface, Keith (2008). Therefore, according to this method, mineralogical investigation is required to assess the swelling pressure.

PLASTICITY INDEX AND SWELLING

For a long time, swelling was known to be a close function of the plasticity index. The plasticity index is the range of water content where the soil exhibits plastic behavior, Budhu (2008). This parameter is the difference between the liquid limit and the plastic limit of a soil. Both liquid and plastic limits have been developed by Attherberg, a Swedish scientist, to describe the consistency of fine-grained soils with varying moisture content. The moisture content at the point of transition from semisolid to a plastic state is the plastic limit, and from plastic to liquid state is the liquid limit. The plastic limit is determined by rolling a thread of a fine portion of a soil sample on a flat non-porous surface, while the Casagrande cup is used to determine the liquid limit.

Since both swelling potential and plasticity index are functions of the amount of water absorbed by clay, plasticity index has widely been used for indirect evaluation of swelling potential in expansive soils as well as in weak rocks. Figure 3 shows a sample of such relationships.

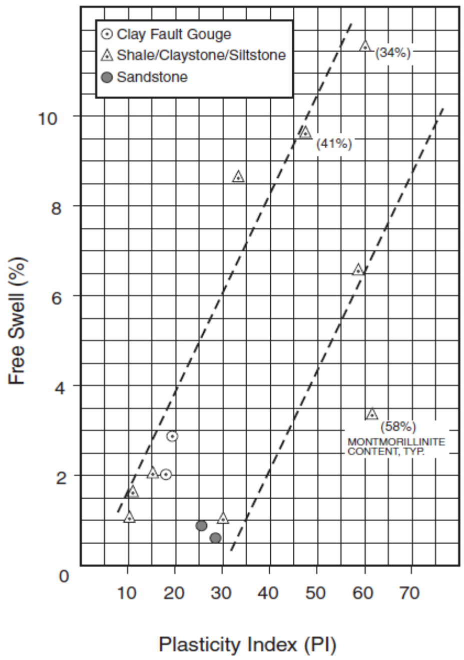

Figure 3: Relationship between free swell and plasticity index for various rocks (Klein, 2001)

WETTABILITY AND SWELLING

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. Many different methods have been proposed for measuring the wettability of a system. Contact angle is one of the quantitative methods for measuring wettability. Contact angle describes the shape of a liquid drop on a solid surface. The shape of the drop reveals information about the chemical bonding nature of the surface. This bonding determines its wettability and adhesion, Vijapurapu (2002).

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 optimally satisfy the bonding forces with nearby neighbors. Consider the idealized solid as shown in Figure 4.

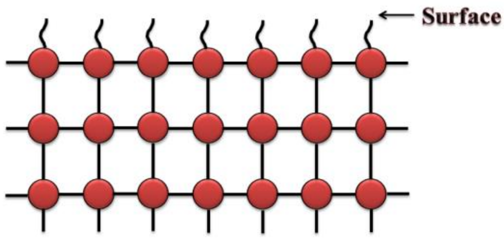

Figure 4: Schematic of an idealized solid surface (Vijapurapu, 2002)

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. But 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 wetting and adhesion. Hence, the contact angle is used to estimate the nature and strength of these bonds.

As mentioned before, swelling potential is dependent on the type of the clay minerals and the related parameters of the clay’s surface that can be associated with the nature and the chemical bond of the surface. Therefore, the idea of using contact angle for developing a new indirect swelling evaluation method was established based on the relationship between contact angle and the nature and strength of the surface chemical bond. On the other hand, ease of the sample preparation, visible results and the high speed of the contact angle measurement test are other reasons for the choice of contact angle.

EXPERIMENTAL STUDIES

For the present laboratory tests, marl and mudstone samples were obtained from a water diversion tunnel of the Nargesi Dam site located in the Mishan Formation and the Bakhtiari Formation in Iran.

In order to identify the relationship between swelling strain and contact angle, both free swelling and contact angle tests were conducted on five types of samples. These five types included three types of marls (A, B and C) and two types of mudstones (E and F). For the free swelling tests, the method suggested by ISRM (1983) has been used and for the contact angle test, the device shown in Figure 5 was utilized. As mentioned before, the contact angle is the angle between a tangent drawn on the drop’s surface at the resting point and a tangent to the supporting surface. Using a computerized image processing program, the contact angle is measured from a photo taken with a high resolution camera of the drop at the time of it contacting the resting surface.

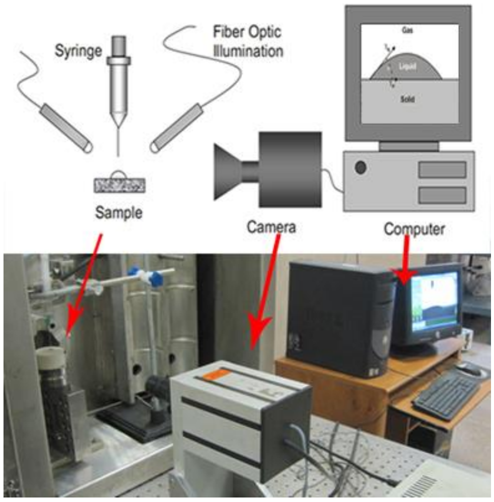

Figure 5: Contact angle apparatus
(Institute of Petroleum Engineering, University of Tehran, Iran)

In addition to the contact angle tests, plastic limit and liquid limit tests were performed (according to ASTM under designation D-4318) to determine the relationship between plasticity index and swelling potential.

TEST RESULTS AND DISCUSSION

The results of pictures taken from the shape of the liquid drop on the rock samples surface and their contact angles are shown in Figure 6. The results of contact angle and their associated free swelling tests are summarized in Table 1. According to this, it can be concluded that surface energy of mudstone samples is more than the marl samples because the contact angle of mudstone samples is less than for the marl samples.

Table 1: Results of free swelling and contact angle tests

Sample	Contact angle (degree)	Maximum Swelling Strain (%)
A	21.32	1.86
B	27.80	0.8
C	30.08	0.02
D	10.63	16
E	17.96	6

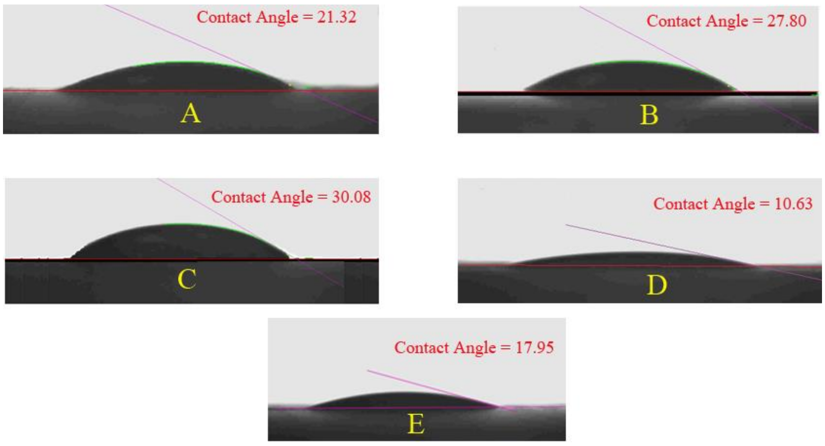

Figure 6: Shape of a liquid drop on a rock samples surface and them contact angles

The obtained results are drawn in Figure 7 which shows that swelling strain decreases with increasing contact angle. The dependency of these two parameters together is very strong (correlation coefficient 99%) represented by the following equation.

$$\varepsilon_s = -0.0002a^3 + 0.0631a^2 - 3.1277a + 42.4 \quad (1)$$

Where ε_s is the swelling strain and the contact angle.

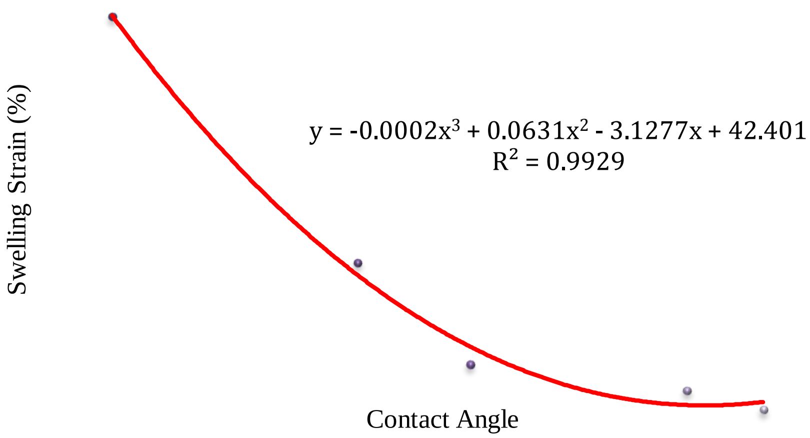

Figure 7: Relationship between swelling strain and contact angle

Plastic and liquid limits of rock samples obtained from related tests are given in Table 2. All samples based on Burmister qualitative classification of plasticity index (1949) are classified in medium plasticity category, Das (2002). The relationship between plasticity index and swelling strain is shown in Figure 8. This dependency is in the shape of the following exponential function in which swelling strain increases with increasing plasticity index.

$$\varepsilon_s = 0.0223 e^{0.3477 PI} \tag{2}$$

Table 2: Test results of liquid and plastic limits

Sample	Liquid limit	Plastic Limit	Plasticity index
A	32	19	13
B	30	20	10
C	34	29	15
D	38	20	17
E	37	20	17

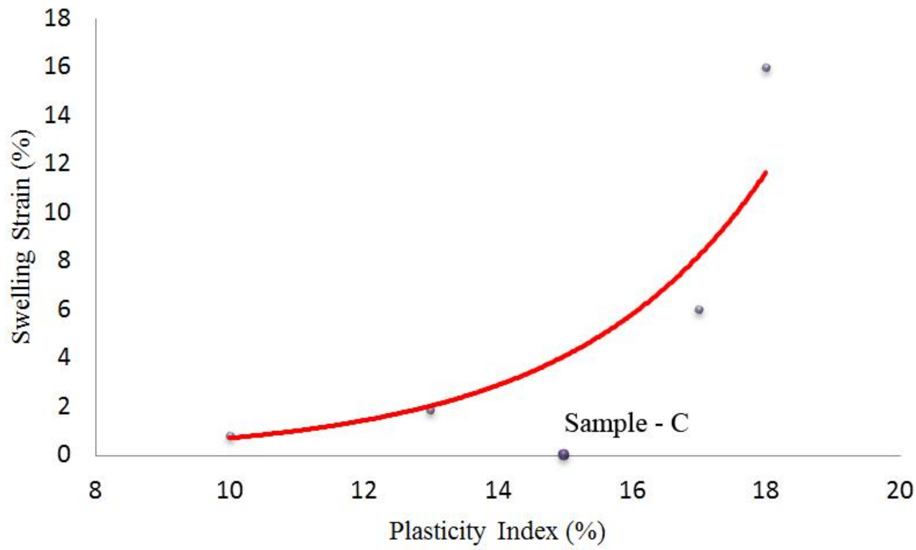

Figure 8: Exponential relationship between swelling strain and contact angle

In the above equation, ε_s is the swelling strain and PI is the plasticity index. As shown in Figure 8, sample C does not follow the general trend of the curve. This means that there are some clays that behave plastically but do not show any swelling behavior. In fact all of the clays behave plastically (with different extents) but only some of them swell. Therefore plastic index is not a good criterion to be used for evaluating swelling behavior. On the other hand, contact angle is very sensitive to the clay minerals therefore sample C in Figure 8 is very well in line with the general trend of the swelling graph.

CONCLUSION

This paper has described a new approach to indirectly evaluate the swelling potential of rocks. Contact angle, free swelling, plastic and liquid limit tests were performed and relationships were proposed to show the dependency of swelling strain to the plasticity index and contact angle.

The results show that there is a nonlinear inverse relationship between swelling strain and contact angle. This relationship is described by a third order algebraic function (equation 1). On the other hand, an exponential relationship between swelling strain and plasticity index has been observed.

According to the inability of the plasticity index to make a distinction between clay mineral types, using the plasticity index as an indirect method for evaluating rock swelling is under question.

Unlike plasticity index, contact angle was proved to be an appropriate parameter for indirect evaluation of swelling potential of rocks. This is due to the fact that the contact angle is very well dependent on the mineral type and is influenced by their surface energy, the parameter which also is influential in swelling behavior. The conclusion was derived from the fact that the contact angle can distinguish between rocks with different swelling potential, because there is a relationship between the nature and strength of rock surface chemical bond and contact angle. Relatively easier sample preparation and faster tests and also visible results are other advantages of this test which makes it a superior swelling index measuring method in comparison with other swelling tests.

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