ANISOTROPY FACTOR FOR SWELLING ROCKS

Musaed N. J. Al-Awad,
Associate Professor, Drilling and Petroleum Related Rock Mechanics
Petroleum Eng. Dept., College of Eng., King Saud University
P.O. Box 800 Riyadh 11421, Saudi Arabia.

ABSTRACT: When contaminated with water, swelling rocks (shales) produces noticeable swelling stresses in vertical and lateral directions. At laboratory, vertical swelling stress can be easily measured using the standard rock mechanics testing facilities. The lateral swelling stress is then estimated. The estimation of the lateral swelling stress mainly depends on the assumed value of the anisotropy factor (the ratio of vertical swelling strains to the lateral swelling strains).

Producing cylindrical core samples (plugs) from swelling rocks are extremely difficult due the sensitivity of these rocks to drilling and coring (cooling) fluids and vibration generated by the coring machine. Thus, a limited number of core samples are available for so many tests. Therefore, there is a need for the development of non-destructive tests to evaluate some of the properties of the swelling rocks required for design and modeling.

This study represents an accurate non-destructive testing technique for the measurement of anisotropy factor using a single core sample. The equipment used in this testing technique is simple, cheap and readily available in any rock evaluation laboratory and the repeatability of these tests is excellent.

1. INTRODUCTION

Shale makes up to 75% of drilled formations and causes over 90% of wellbore instabilities (Santarelli et al., 1992). Shale is often the most difficult of all rocks to maintain a stable wellbore when drilling for oil and gas. Time and money spent overcoming this problem during drilling, together with overall reduced profit margins, has led the oil industry to devote considerable time and efforts to solve the problem of unstable boreholes drilled in shale formations (Kelly, 1968; Singh et al., 1983; Salisbury et al., 1990; Al-Awad et al., 1995; Al-Awad et al., 1996). Increasing demand for wellbore instability analysis during planning stages of a field arises from economic consideration and the escalating use of deviated, extended reach and horizontal wells. Wellbore instability can results in lost circulation where tensile failure has occurred, and sloughing and/or hole closure in the case of compressive failure. In severe cases, the hole instability can lead to stuck pipe and eventually loss of the open hole section. Most borehole instabilities occur when water-based drilling mud is used to drill shale formations. Generally, the causes of wellbore instability are often classified either chemical or mechanical effects (Al-Awad et al., 1996). Often, the instability is a result of a combination of both chemical and mechanical effects. However, only mechanical effects are considered by previous studies dealing with borehole instability modeling, even although wellbore instability has received considerable attention in the literature over the past two decades.

2. MECHANISMS OF SHALE SWELLING

It has been long established that the moisture adsorption (or desorption) of shale rocks can be controlled by the salinity of the drilling fluid (Chenevert, 1970;

Bol et al., 1992). When compacted shale (under constant compaction stress) adsorbs moisture, its total volume increases and swelling strains develop. Developed swelling strains then become an integral part of the effective radial stress acting on the shale formation contributing to borehole failure (instability) (Al-Awad, 1995). The term shale is applied to every thing from clays to lithified materials such as slate. Soft clays are extremely reactive with water while slates are relatively inert (see Table 1). The amount and type of clay, the depth of burial, and the amount and type of pore water in given shale therefore influence the stability of shale. The amount of clay in a given shale depends on the composition of the shale at the time of deposition, and on the changes that may occur in clay after burial. From the viewpoint of wellbore instability, clays may be classified proudly as expandable and non-expandable. Expandable clays belong to a clay group called smectites. Montmorillonite (bentonite) is a high-swelling member of the smectites group. The less-expandable clays most found in shales are illite, chlorite and kaolinite.

Clays swell by three mechanisms (Grim, 1968): (i) Crystalline swelling (surface hydration or ionic hydration), (ii) Osmotic hydration, and (iii) Dissolution mechanism. Surface hydration is brought about by hydration of bonding water molecules to oxygen atoms on the surface of the clay's silicate layers, and ionic hydration caused by formation of hydration shells around exchangeable cations, which compensate for charge deficiencies due to lattice substitutions in the clay crystal. The second mechanism of swelling, osmotic hydration, is initiated in certain types of clays after they have undergone complete crystalline swelling and have been exposed to free water or moisture. Osmotic swelling is caused by establishing a higher concentration of hydrated, exchangeable cations near the surface of opposing clay plates (which have been separated by crystalline swelling), closer to the centre of negative charge, then in the central region between them. The clay surface behaves as two plates coated with like charges and tend to repel one another. In the third mechanism not only smectite-like clays or expandable clays are responsible for shale swelling when exposed to water, but also non-smectite shales. These clays swell and disperse when exposed to polar solvents such as water (dipolar), and this is believed to be due to a dissolution mechanism which manifests itself as hydration of the contact points between the quartz particles. The shale-water interaction replaces the shale-shale hydration bonds, as a result the latter hydrogen bonds that stabilize the shale ate the contact points no longer exist and the shale is observed to destabilize or undergo dissolution.

3. SHALE ANISOTROPY MEASUREMENT

Shale anisotropy factor is essential in most analysis dealing with borehole instability or shale swelling problems. Anisotropy factor of swelling shales is the ratio between swelling strains parallel to bedding planes at equilibrium (ε_H) and swelling strains normal to bedding planes at equilibrium (ε_V). In other words, it is the slope of the straight line relates the swelling strains in the directions normal and parallel to beddings planes measured at various water activities (relative humidities).

In this study, three different shales with different properties were used. The properties of these shales are shown in Table 2. Vertical and lateral swelling strains were measured for strain gauged shale specimens conditioned at various humidities. Shales were cut into cylindrical specimens, and strain gauges were attached diametrically opposed on the samples as shown in Figure. 1. The leads were connected and strain gauges coated with waterproof material. The strain gauges were arranged to measure swelling strains in both vertical and lateral directions (normal and parallel to bedding planes). The samples were then placed in desiccators containing different saturated salt solutions (see Table 3), and the leads passed through the rubber stopper on the top of the desiccator, connected to a strain conditioning interface and data logger and a personal computer. The output strains were recorded continuously with time and temperature. The test is terminated when strains become constant (within approximately 2 to 7 days) and the tested samples are left to dry to room temperature for any further tests or placed in a lower humidity desiccators to measure shrinkage strains caused by moisture desorption. Figures 2, 3 and 4 show the swelling strains normal and parallel to bedding planes for the three shale samples measured at three different levels of humidity (29.5%, 75.5% and 96%). It can be noticed that swelling strains normal to bedding planes are greater than those parallel to bedding planes. This was due to separation of the layers composing the tested shale be water molecules. Swelling strains increases when the relative humidity increases. Maximum swelling strains can be recorded when the shale specimen is fully saturated with water which. Plotting swelling strains at equilibrium at various humidities (water activities) yield a straight line. The slope of the straight line fitting the data points is the anisotropy factor. Figure 5 shows cross-plots between swelling strains generated normal and parallel to bedding planes at equilibrium for the three tested shale samples. The anisotropy factors of the tested shales were 0.44, 0.13 and 0.67 for samples "A", "B" and "C" respectively. It is clear that these shales are anisotropic because their anisotropy factors were less than unity. It is also interesting to note that moisture adsorption-desorption process is reversible and can be used as a double check of the data obtained by adsorption method by simply allowing the samples to dry out in lower humidity desiccators (see Figure 6).

4. CONCLUSIONS:

- Water adsorption tendency of shales provides the net effect of all clays and ions present in the shale as related to the degree of hydration.

- Adsorption-desorption is a reversible process and hence each one can be derived from the other.

- Shale anisotropy factor can be easily determined using a non-destructive and cheap test using a single shale specimen.
- Anisotropy factor is mainly dependent on the type of swelling clays composing the shale under consideration.
- Shale samples used in the anisotropy determination test are mechanically undisturbed and can be used in further investigations.

5. REFERENCES

Bol. G. M., 1992, "Borehole Instability in Shales.", SPE paper no. 24975, European Petroleum Conference.", Cannes, France, Nov. 16-18.

Chenevert M. E., 1970, "Shale Alteration by Water Adsorption.", Journal of Petroleum Technology, Sept., pp. 1141-1148.

Grim, R. E., 1968, "Clay Mineralogy.", McGraw Hill Co., New York.

Kelly Jr., 1968, "A New Look at Troublesome Shales.", Oil and Gas J., pp 94-112.

Musaed N. J. Al-Awad and B.G.D. Smart, 1995, “Physico-Chemical Modelling of Shale-Drilling Fluid Interaction Under Simulated Downhole Stresses.”, Al-Azhar Engineering Fourth International Conference, Cairo, Egypt, pp. 173-189, December 16-19.

Musaed N. J. Al-Awad and B.G.D. Smart, 1996, “Characterization of Shale- Drilling Fluid Interaction Mechanisms Related to Wellbore Instability.”, Journal of King Saud University, Volume 8, Engineering Sciences No. (2), pp. 187-215.

Santarelli F. J., Chenevert, M. E. and Osisanya, S. O., 1992, "On the Stability of Shales and Its Consequences in Terms of Swelling and Wellbore Stability.", Paper no. 23886 on the IADC/SPE Drilling Conference, New Orleans, Louisiana, Feb. 18-21.

Salisbury D. P. and Deem C. K.; 1990, "Tests Show How Oil Muds Increases Shale Stability.", World Oil, pp. 57-65, October.

Singh M. M., and Cummings R. A., 1983, "Predicting Moisture-Induced Deterioration of Shales.", International Congress on Rock Mechanics, Melbourne, Australia.

Table. 1 Shale classification based on clay type.

Shale class	Characteristics	Clay content
1	Very soft rock, highly rich in easily dispersible clays to colloidal state.	High concentration of montmorillonite and low concentration of illite.
2	Soft rock, relatively medium rich in clays which are easy to disperse in colloidal state.	Medium concentration of montmorillonite and low concentration of illite.
3	Medium soft rock, highly rich in moderately dispersible clays and has strong ability to swell.	High concentration of illite and chlorite.
4	Medium hard rock, little colloidal dispersion and little swelling tendency.	Medium concentration of illite and chlorite.
5	Hard rock, no colloidal dispersion and little swelling.	High concentration of kaolinite, medium concentration of chlorite and chlorite.

Table. 2 Mineralogical analysis of the tested shales.

Components	Percentage by weight		
	Shale #A	Shale #B	Shale #C
Smectite	---	---	71
Illite	70	13	9
Chlorite	---	1	---
Kaolinite	---	58	13
Mixed-layers	---	---	2
Quartz and Calcite	30	27	7
Organic matter	--	1	---

Table. 3 Relative humidity of saturated salt solutions.

Shale used	Relative humidity, %	Shale used	Relative humidity, %
P_2O_5	0	$ZnCl_2$	10
$CaCl_2$	29.5	$Ca(NO3)_2$	50.5
NH_4NO_3	62.5	NaCl	75.5
KNa-Tartarate	87	$Na_2C_4H_4O_6.2H_2O$	92
KH_2PO_4	96	$K_2Cr_2O_7$	98

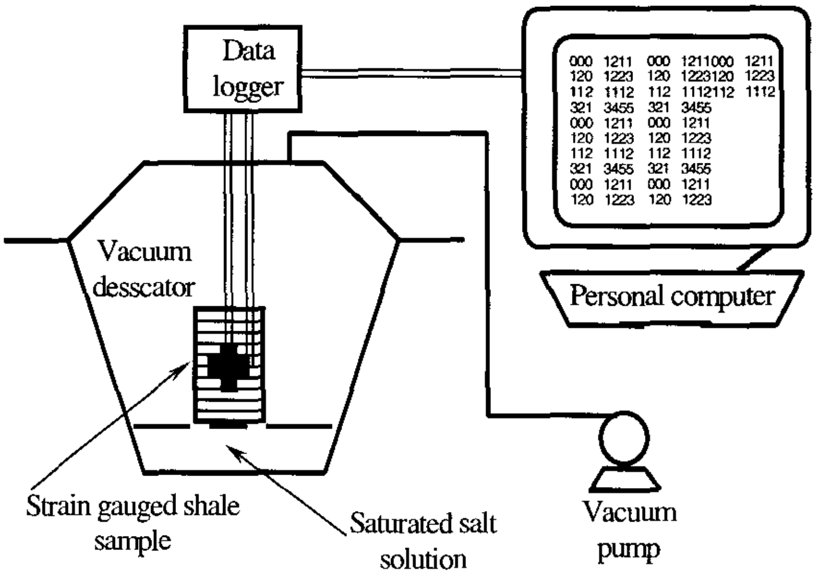
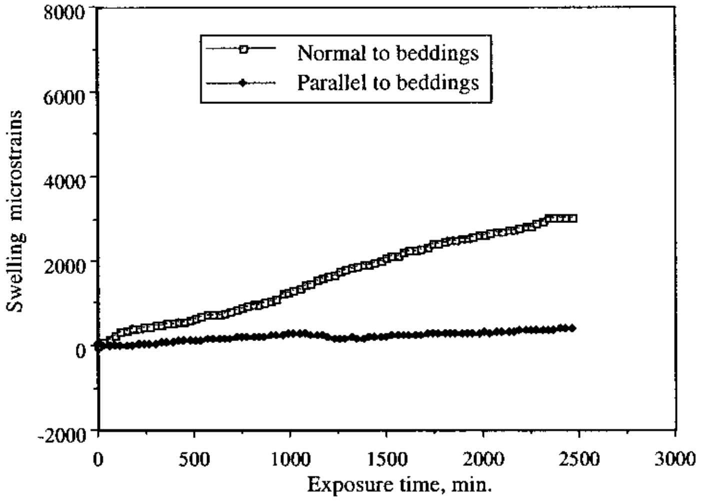
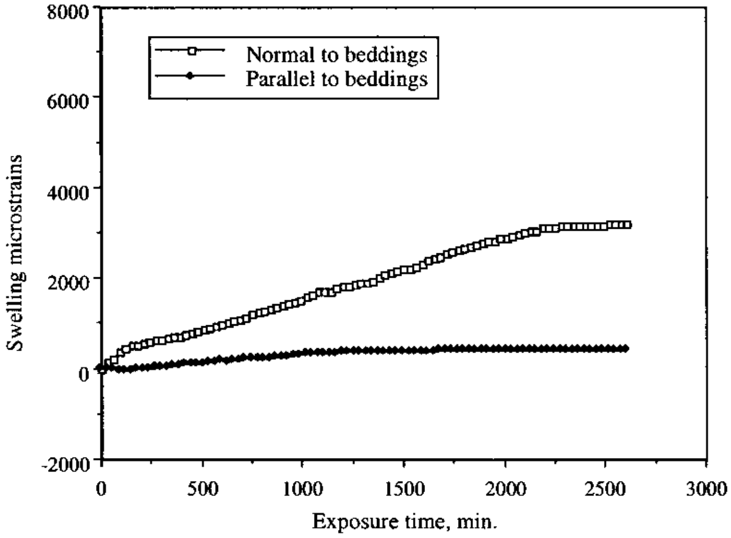


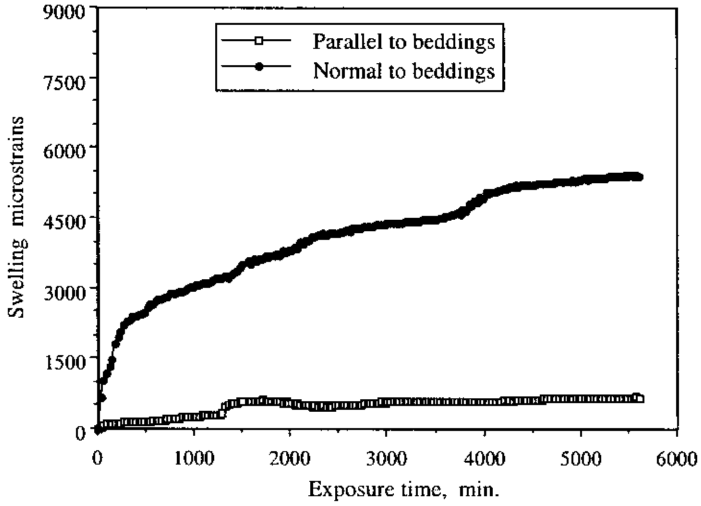
Figure. 1 Swelling experimental set-up.



(a) Relative humidity = 29.5% .

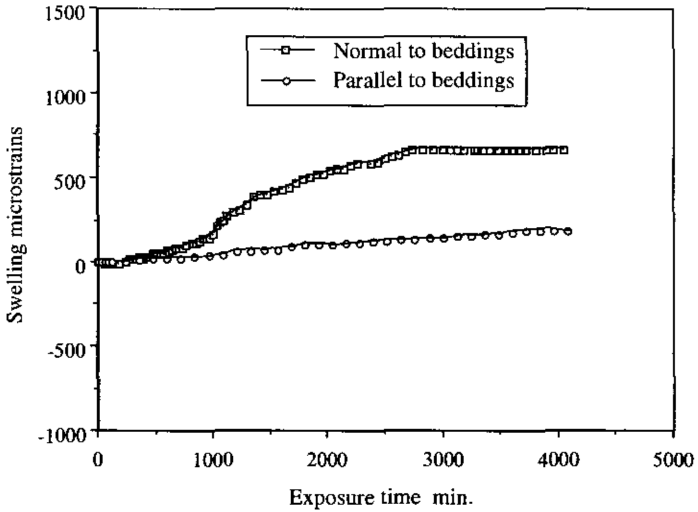


(b) Relative humidity = 75.5 % .

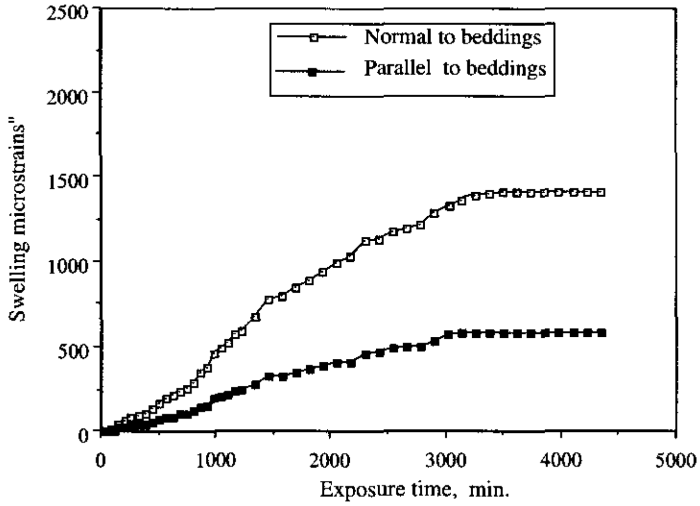


(c) Relative humidity = 96 % .

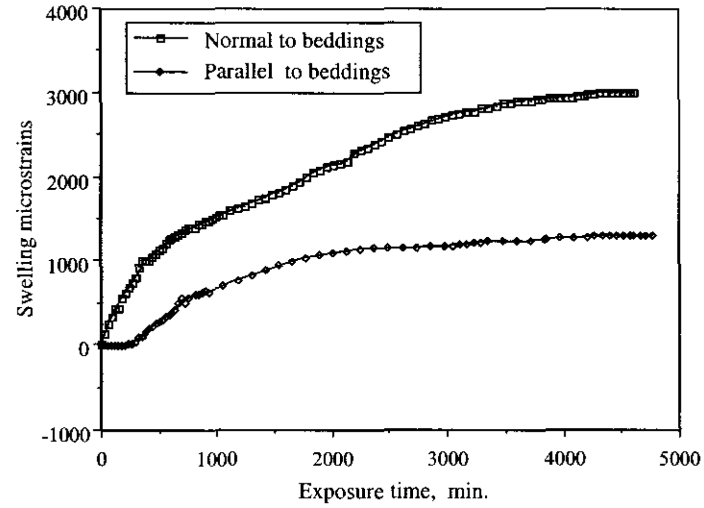
Figure. 2 Swelling microstrains for shale sample "A"



(a) Relative humidity = 29.5% .

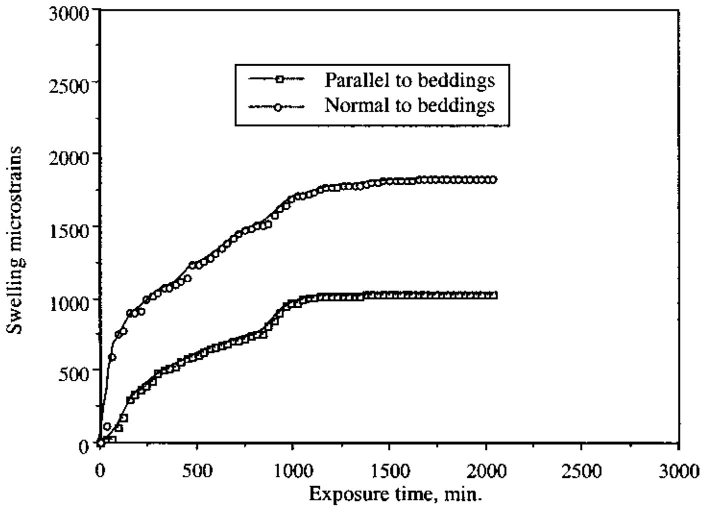


(b) Relative humidity = 75.5% .

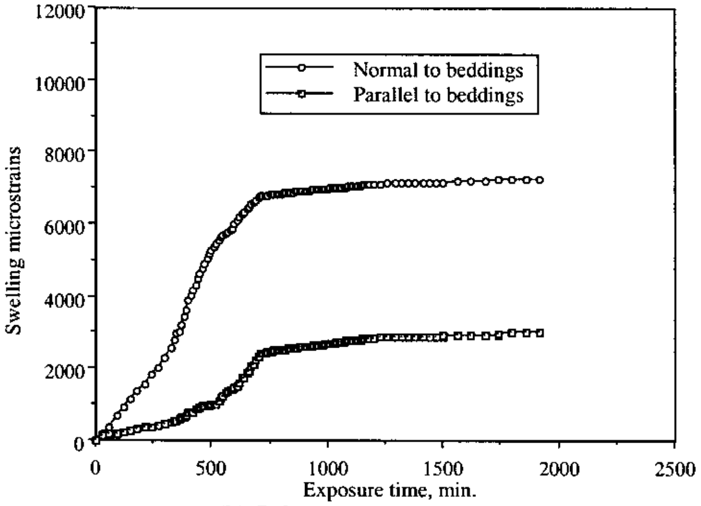


(c) Relative humidity = 96% .

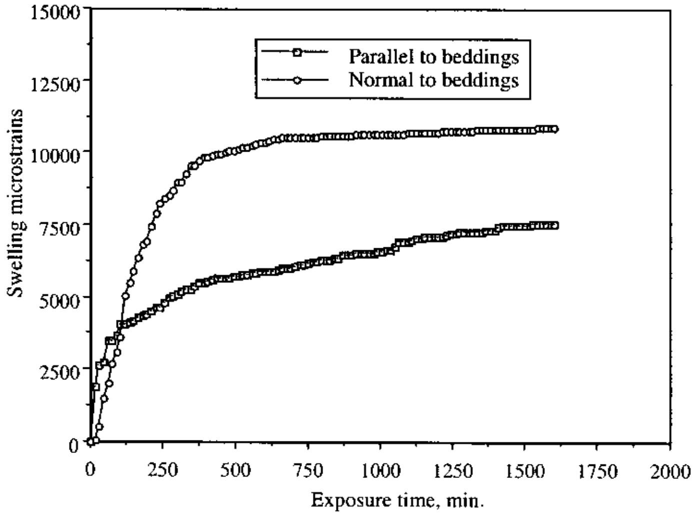
Figure. 3 Swelling microstrains for shale sample "B"



(a) Relative humidity = 29.5 % .



(b) Relative humidity = 75.5 % .



(c) Relative humidity = 96 % .

Figure. 4 Swelling microstrains for shale sample "C"

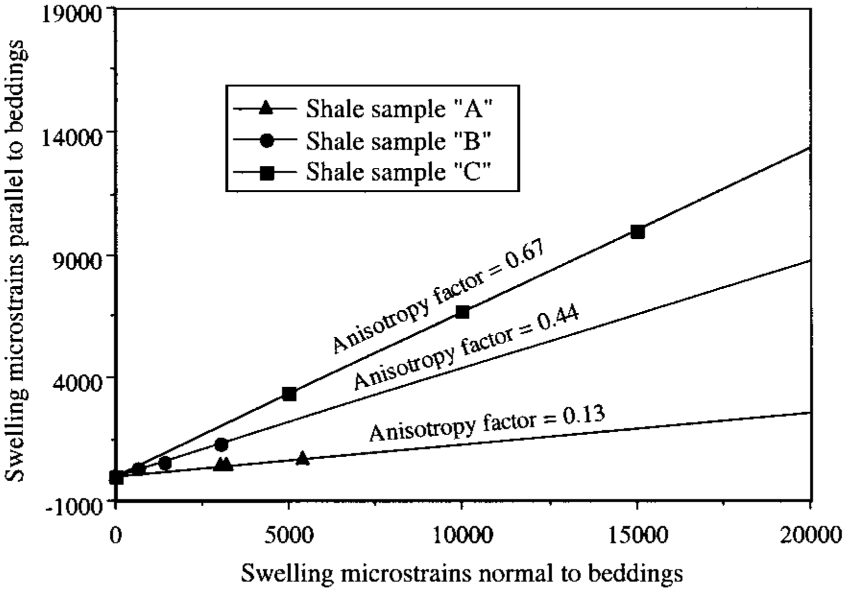


Figure. 5 Swelling microstrains for three shales exposed to variable humidity.

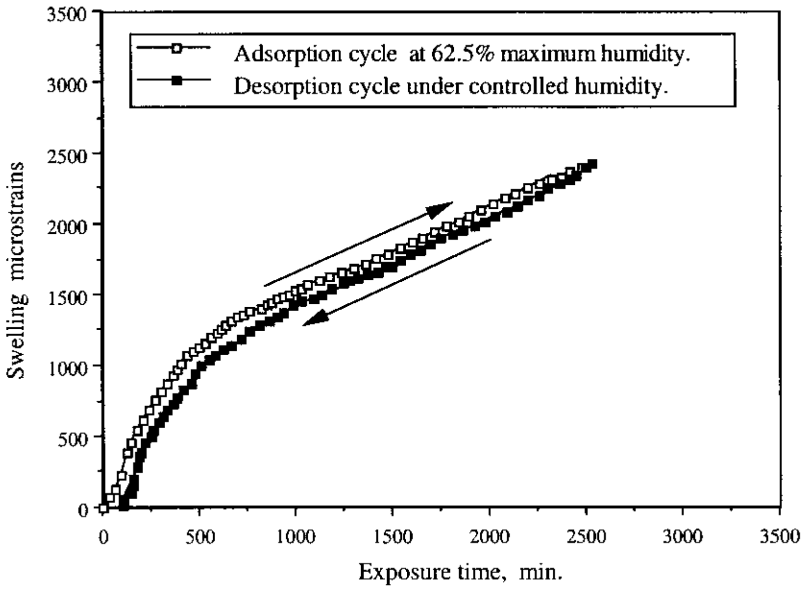


Figure. 6 Moisture adsorption-deorption phenomena for shale sample "B".