Modified failure criterion for shales

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ABSTRACT: Most shale rocks which contain an appreciable fraction of reactive clays (e.g. Montmorillonite) will adsorb drilling mud filtrate (water+ions) and cause unstable drilling conditions. When contacted with the mud filtrate, these shales will swell, creating a soft, swollen zone around the wellbore, therefore, the natural mechanical properties or the strength of the swollen shales will decrease causing serious hole problems such as undergauge hole, stuck pipe, overpull on trips, and several other problems. Thus swelling stresses and rock strength reduction must be included in any attempt to effectively model shale mechanical properties after interaction with drilling fluid filtrate. In this study shale swelling stresses were integrated into the prominent Mohr-Coulomb failure criterion and therefore a new form of this criterion has been introduced which combined the natural mechanical properties with swelling stresses to predict the in-situ strength of shales when invaded by the drilling fluid filtrate. The modified failure criterion was verified experimentally.

1 BACKGROUND

1.1 *Introduction*

The swollen zone created around the wellbore during drilling in shale sections will be driven inwardly by high overburden stresses and requires that higher than usual mud weights be used to counteract this inward displacement (Erling et al., 1992). When shale contains high native water content, even before it is exposed to drilling fluid, it is abnormally weak and unable to withstand the differential stress imposed by drilling out the surrounding rock (support).

The mode of failure, when the stress differential created by the relief of lateral stress exceeds the yield strength of the formation, is plastic deformation of the wellbore. If the shale is under abnormally high pore pressure, spalling will be the result (Darley, 1969). Swelling stresses generated due to the interaction between the shale and water based drilling fluids must be taken into account when predicting the effect of swelling on borehole stability and failure criterion (Onaisi et al., 1994).

1.2 *Formulation of the modified failure criterion*

Mohr's strength theory is normally used to represent the strength of rocks subjected to compressive stresses (axial and confining) is given in terms of total stresses by:

$$\tau_f = \tau_o + \sigma \tan\phi \qquad ...(1)$$

In addition the concept of effective stress can be used to modify equation 1 to the following form (Jaeger et al., 1979, and Hayatdavoudi et al, 1986):

$$\sigma^i_{eff} = \sigma^i - P_p \qquad ...(2)$$

$$\tau_f = \tau_o + (\sigma - P_p)\tan\phi \qquad ...(3)$$

Usually, the stress state is represented by Mohr's circle and the angle of obliquity of the resultant stress with x-axis is given by:

$$\beta = {(\tau - \tau_0)}/{\sigma} \qquad ...(4)$$

Failure will occur when (β) increases to the maximum angle of obliquity (ϕ) assuming the rock is fully saturated with water and is not subjected to a positive hydraulic pore pressure. An increase in pore pressure shifts Mohr's to the left and increasing (β) to its maximum value ϕ and failure will occur on the plane represented by τ_f. The dimensional effective stress relation for shale can be defined as follows (Bol et al., 1992):

$$\sigma_{eff}^{i} = \sigma^{i} - P_p \pm \sigma_{hyd}^{i} \quad ...(5)$$

By substituting equation 5 into equation 1 and accounting for moisture adsorption-desorption process, equation 1 can be rewritten as follows:

$$\tau_f = \tau_o + \left(\sigma^{i} - P_p \pm \sigma_{hyd}^{i}\right)\tan\phi \quad ...(6)$$

The swelling (hydration) stress is composed of two major stresses called the osmotic swelling stress and the surface swelling stress, therefore equation 6 can be expanded as follows:

$$\tau_f = \tau_o + \left(\sigma^{i} - P_p \pm (\sigma_{os} + \sigma_{sur})\right)\tan\phi \quad ...(7)$$

Finally the pore pressure term are combined with the swelling terms and defined as the total swelling stress. Therefore equation 7 changes to:

$$\tau_f = \tau_o + (\sigma - \sigma_{ts})\tan\phi \quad ...(8)$$

Equation 8 represents the general form of the modified Mohr-Coulomb failure criterion for shales.

1.3 *Use of the Modified Criterion*

The following points show how this model is applied to experimental data:

(i) Swelling stresses are assumed to develop in two orthogonal directions (Chenevert, 1990; and Ching et al., 1990) firstly normal to bedding planes and secondly, parallel to bedding planes as shown in Figure 1:

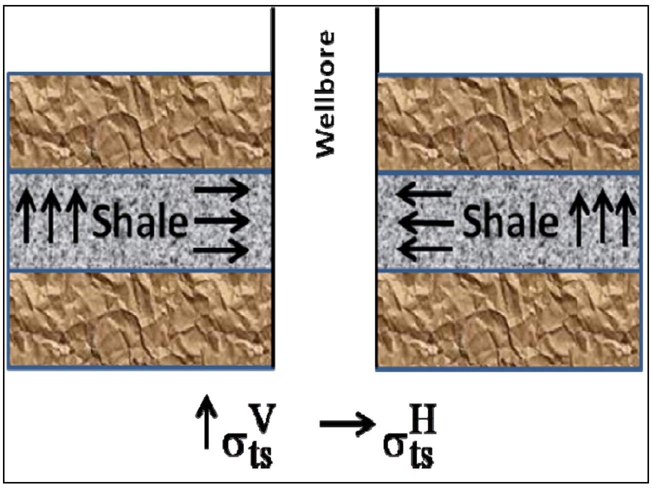

Figure 1. Total swelling directions in shales.

σ_{ts}^{V} = the total swelling stress in the direction normal to bedding planes.

σ_{ts}^{H} = the total swelling stress in the direction parallel to bedding planes.

(ii) Total swelling stresses are related to each other by the anisotropy factor (Chenevert, 1990; and Ching et al., 1990):

$$F_{anis} = \sigma_{ts}^{H} / \sigma_{ts}^{V} \quad ...(9)$$

(iii) Total swelling stresses are integrated into experimental triaxial compressive data as follows:

$$\text{Axial stress at failure} = \sigma_1 - \sigma_{ts}^{V} \quad ...(10)$$

and,

$$\text{Confining stress at failure} = \sigma_3 - \sigma_{ts}^{H} \quad ...(11)$$

(iv) Confining pressures and axial stresses at failure are obtained from triaxial tests conducted on intact shale samples (zero moisture content) under realistic stresses.

(v) Total swelling stresses are obtained from tests conducted on cylindrical shale specimens under realistic stresses.

2 EXPERIMENTAL SET-UP

2.1 *Analysis of the tested shale*

The shale used in this study was moderately hard, grey in color and has an average specific gravity of 2.5. This shale was cored from an underground coal mine (Scotland, U.K.) from a depth between 250 to 270 meters. X-ray diffraction analysis has showed that this shale is composed of: 24% calcite and quartz, 3% Montmorillonite, 13% Illite and 60% Kaolinite.

2.2 *Shale anisotropy factor*

In this technique the shale were cut into cylindrical specimens, and strain gauges were attached diametrically opposed on the samples. The leads were connected and strain gauges coated with water proof material. These strain gauges were arranged to measure swelling strains in both vertical and horizontal directions (normal and parallel to bedding plans). The samples were then placed in desiccator containing saturated salt solutions, and the leads passed through the rubber stopper (bung) on the top of the desiccator, connected to a special designed box containing a set of resistors to complete full bridges. The output voltages from these bridges were connected to a data logger to record the strains at chosen time intervals. The test was terminated when the strains became constant. Plotting the swelling strains at equilibrium normal and parallel to bedding planes at various water activities (relative humidity) yields a straight line. The anisotropy factor equal to the slope of the straight line as shown in Figure 2:

$$\psi = \varepsilon_H / \varepsilon_V \quad ...(12)$$

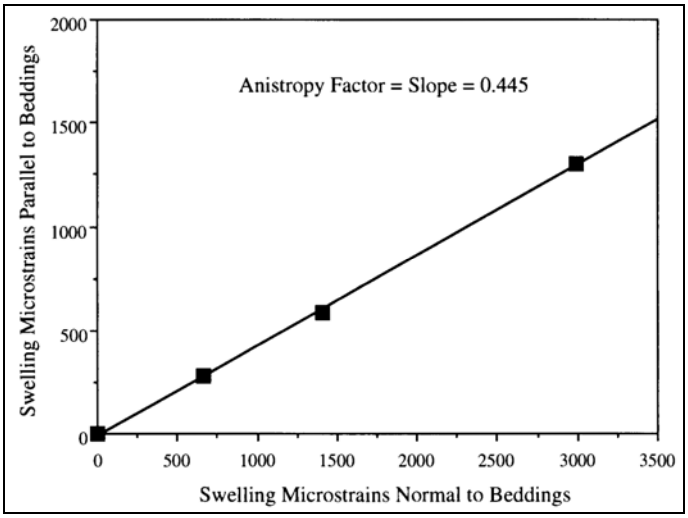

Figure 2. Shale reaction at various relative humidity.

From these tests, it can be seen that the lateral strains are smaller than vertical ones. This difference in magnitude between horizontal and vertical swelling strains is believed to be due to high shale density (2.65 g/cc) and alignment of clay minerals during sedimentation. The shale is considered anisotropic when the anisotropy factor is greater or less than unity.

From this test it was found that for a certain shale type, a unique anisotropy factor was measured regardless of humidity magnitude. This technique can help in determining the anisotropy factor of sensitive shales without critically affecting their mechanical properties.

It is clear from this testing technique that, when shale specimen adsorbed water up to a level above its initial moisture content, swelling strains in both directions normal and parallel to bedding planes are generated. These strains are able to produce or enhance microfractures or/and separate the shale sample through its bedding.

2.3 *Shale Adsorption Isotherm*

Shale Adsorption Isotherm which relates the amount of clay in a shale sample to its moisture content was established for the tested shale. This was performed by placing a sample from the shale under consideration in a range of water activities (relative humidity). This was achieved by placing the shale inside vacuum desiccators containing saturated salt solutions in their shallow base.

Samples inside these desiccators will either gain or lose moisture. The Adsorption Isotherm then established by plotting the gained moisture content at equilibrium versus salt water activity as shown in Figure 3.

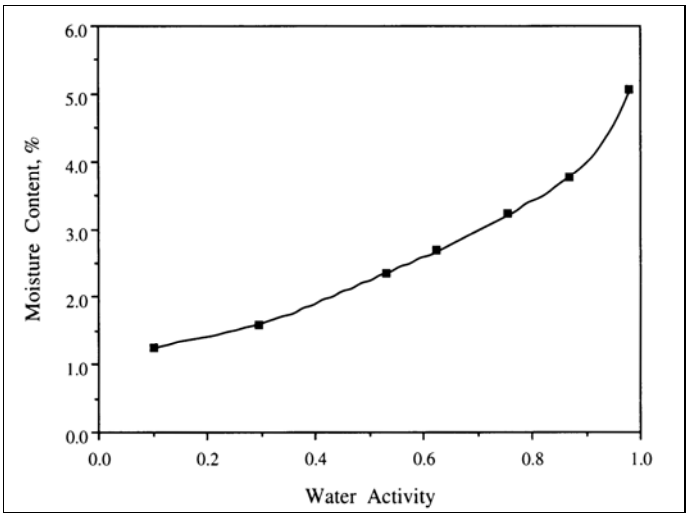

Figure 3. Adsorption isotherm of the tested shale.

2.4 *Swelling strain-moisture content relationship*

When shale moisture content is altered, its dimensions may change due to this alteration. This change in shale dimensions in turn will produce swelling strains in its boundaries. Each cylindrical shale specimen was attached with two strain gauges in order to measure any change in sample dimensions in both directions normal and parallel to bedding planes. The strain gauged samples were then placed in high relative humidity desiccators, and swelling strains in both directions were recorded using a data logging system. When the sample is placed in the desired desiccator, strain gauges leads are connected to the interface box, and then to the data logger, after that, the desiccator is evacuated using vacuum pump. Sample weight is measured at specified time intervals by opening the desiccator and weighing the sample using electronic balance. When there is no change in sample weight, test was terminated. Figure 4 represents the relationship between moisture content and swelling strains for the tested shale obtained by averaging the results of three experimental runs.

2.5 *Measurement of shale swelling strains*

Cylindrical shale specimens of 1.5"x3.25" dimensions were strain gauged with diametrically opposed pairs of bounded 120 active vertical and horizontal electrical resistance strain gauges in 90º rosette.

The specimen was then placed in a triaxial cell and loaded with dedicated loading arrangement and subjected to fluid invasion (9.5% by volume NaCl solution) at 3.45 MPa over an extended period of time until equilibrium was reached i.e. swelling strains were stabilized (see Figure 5) and then the tests were terminated.

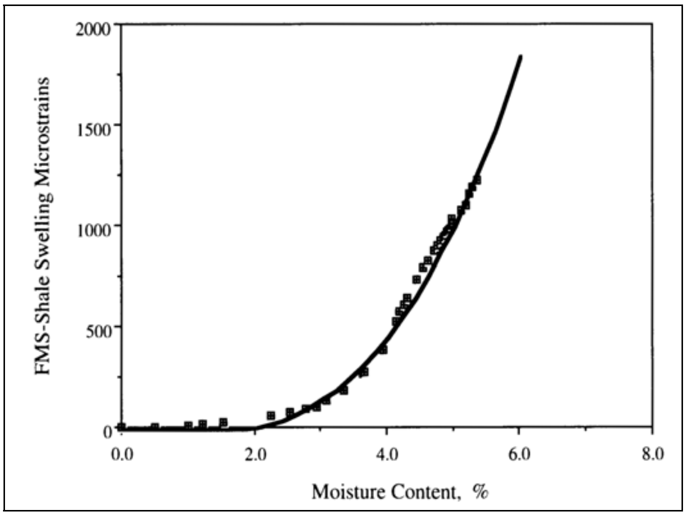

Figure 4. Shale reaction at various moisture contents.

The measured swelling strains generated due to shale-fluid interaction were converted to swelling stresses using the following technique:

(i) For any specific period of time the recorded swelling strains normal to beddings can be read from Figure 5 which represents experimental time-strain relationship.

(ii) The computed swelling strain in step (i) is used to obtain the corresponding moisture content from Figure 4.

(iii) Moisture content read in step (ii) is used to compute the corresponding water activity from Figure 3 i.e. the Adsorption Isotherm.

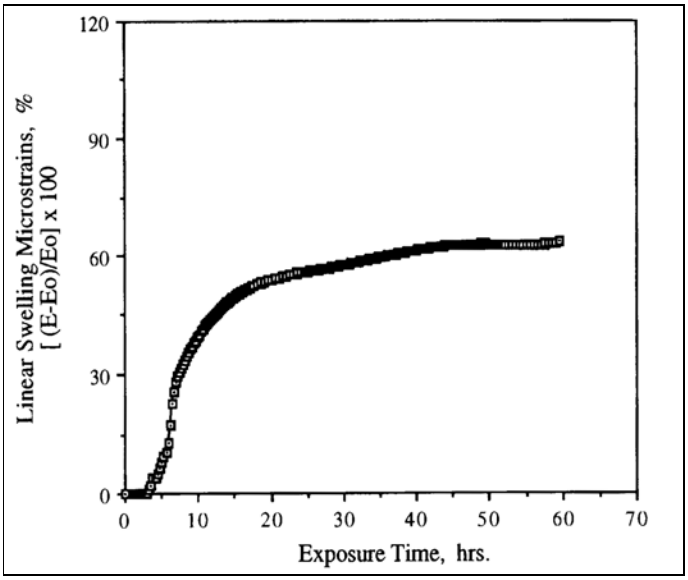

Figure 5. Shale swelling at 9.5% NaCl solution.

(iv) The Resulted water activity obtained in step (iii) is substituted in the adsorptive pressure law (Schmitt et al., 1994; and Chenevert, 1969) to obtain the experimental swelling stresses as follows:

$$P = \left[\frac{RT}{\overline{V}}\right] \ln a_w \quad ...(13)$$

Table 1 shows the conversion process of the experimental swelling strains to swelling stresses as explained previously.

Table 1. Conversion of swelling strains to stresses.

Exposure Time, hr.	Swelling Strains x 10-6	Moisture Content % by Weight	Shale Water Activity	Experimental Swelling Pressure MPa	Shale Adsorptive Pore Pressure MPa	Net Swelling Pressure MPa
1	338	3.677	0.852	-22.33	-22.64	0.31
7	422	3.902	0.883	-17.28	-22.64	5.36
52	472	4.023	0.898	-15.1	-22.64	7.54

3 FAILURE CRITERION MEASUREMNT

1.5"x3.25" shale cylindrical specimens were placed in a Hoek-type triaxial cell rated to 70 MPa providing radial confinement by means of hydraulic oil acting on a synthetic membrane jacketing the specimen, this confining pressure being developed by means of servo-controlled hydraulic intensifier.

Axial load was provided by a stiff testing. Ten specimens were used to establish Mohr circles required to obtain the locus of the failure envelope. All of these ten shale specimens have zero moisture content i.e. zero pore pressure.

In the other hand failure criterion for hydrated shales were determined by placing shale specimens inside a specially designed triaxial cell and the conditions shown in Table 2 were applied. When swelling strains were stabilized the axial load were increased until failure was recorded.

Table 2. Shale swelling testing conditions.

Drilling Fluid Type	=	9.5% by volume NaCl Solution.
Drilling Fluid Water Activity	=	0.95
Shale Type	=	FMS-Shale.
Shale Water Activity	=	0.85
Test Fluid Injection Pressure	=	3.45 MPa.
Confining Pressure at all Swelling Tests	=	6.895 MPa.
Axial Load at all Swelling Tests	=	7.85 kN.
Dimensions of Shale Specimens	=	1.5" X 3.25"

Failure data obtained from triaxial tests for both natural intact (moisture content = 0 i.e. zero pore pressure) and hydrated shale specimens (a_W = 0.85) are shown in Table 3.

Table 3. Triaxial compression test results.

Case no.	Confining Pressure σ_3, MPa	Axial Stress at Failure σ_1, MPa	Remarks
1	6.895	30.67	Natural Sample with Moisture Content = 0
2	6.895	28.96	After 1 hour Exposure to 9.5 % by volume NaCl Solution
3	6.895	26.36	After 7 hours Exposure to 9.5 % by volume NaCl Solution
4	6.895	23.62	After 52 hours Exposure to 9.5 % by volume NaCl Solution

4 RESULTS AND DISCUSSION

Table 4 shows how the triaxial data of intact shale samples is combined with swelling data to predict the change in shale mechanical properties while Figures 6 and 7 represent a comparison between natural intact and reacted (hydrated) shale failure criterion with those obtained using the modified Mohr-Coulomb failure criterion. Although more tests are required to assess this model, it is provided reasonable predictions of shale strength reduction. It is clear that shale strength decreases as the total swelling stress increases.

It was found that, shale apparent cohesion decreases as the swelling stresses increases due to the increase in the amount of invasion fluid which is weakened the bonds between clay particles and lubricate the existing microfractures as well as the natural bedding planes. Additionally, the angle of internal friction was found to be independent of swelling stresses magnitude.

Table 4. Triaxial compression test results.

Measured triaxial failure data for FMS-shale at its natural intact conditions		Calculated triaxial failure data for FMS-shale when exposed to 9.5% by volume NaCl solution Initial moisture content = 3.67 Initial water activity = 0.85	
Initial moisture content = 0 Initial water activity = 0 No swelling test F_{anis} = 0.45 σ_{ts}^V =Experimentally determined $\sigma_{ts}^H = F_{anis} * \sigma_{ts}^V$		Final moisture content = 4.023 Final water activity = 0.893 Swelling test duration = 52 hours F_{anis} = 0.45 σ_{ts}^V = Experimentally determined $\sigma_{ts}^H = F_{anis} * \sigma_{ts}^V$	
σ_{ts}^H = 0 MPa	σ_{ts}^V = 0 MPa	σ_{ts}^H = 3.26 MPa	σ_{ts}^V = 7.54 MPa
σ_1 MPa	σ_3 MPa	$\bar{\sigma}_3 = [\sigma_3 - \sigma_{ts}^H]$ MPa	$\bar{\sigma}_1 = [\sigma_1 - \sigma_{ts}^V]$ MPa
2.00	17.53	−1.26	9.95
3.00	22.00	−0.26	14.41
4.00	25.00	0.74	17.41
5.00	26.30	1.74	18.71
6.00	27.41	2.74	26.72
7.00	30.70	3.74	23.11
8.00	32.44	4.74	24.86
9.00	34.20	5.74	26.62
10.00	36.00	6.74	28.41
11.00	39.50	7.74	31.91

These results are in complete agreement with (Hayatdavoudi et al., 1986). Therefore equation 8; which represents the proposed modified failure criterion for shales; can be written in the following form:

$$\tau_f = \tau_o^* + \sigma \tan\phi \qquad ...(12)$$

$$\tau_f^* = \begin{bmatrix} \tau_o \quad \text{When} \quad \sigma_{ts=0} \Rightarrow \Delta MC=0 \quad \text{or} \\ (\tau_o + \sigma_{ts} \tan\phi) \quad \text{When} \quad \sigma_{ts>0} \Rightarrow \Delta MC>0 \end{bmatrix}$$

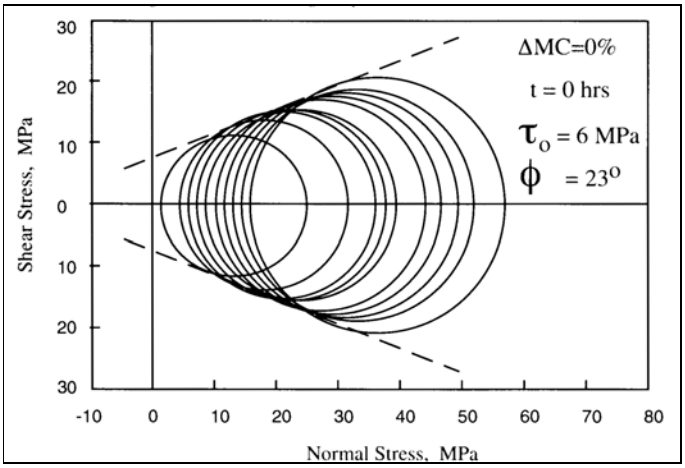

Figure 6. Natural intact shale failure criterion.

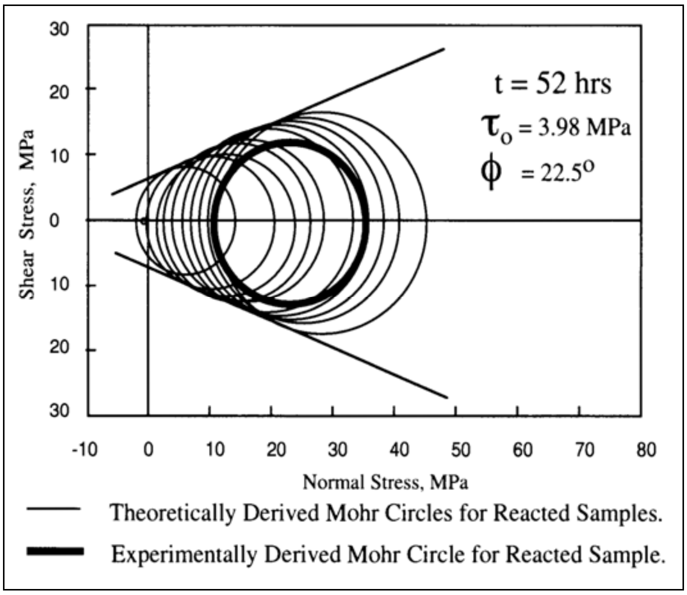

Figure 7. Shale failure criterion at 9.5% NaCl.

5 CONCLUSIONS

Based on the previous discussion, the following conclusions can be withdrawn:

(i) Mohr-Coulomb failure criterion was modified to account for the swelling stresses generated due to shale-fluid interaction.

(ii) Swelling strains were measured experimentally under realistic stresses and were found to be function of moisture front advance i.e. function of exposure time.

(iii) Shale apparent cohesion was decreased when the swelling stresses were increased; while the angle of internal friction was found to be independent of swelling stresses magnitude.

(iv) The modified criterion represents a new effective method which can be applied to predict the reduction in shale strength due to the incompatibility with drilling fluid; hence borehole instability can be avoided.

(v) Shale strength was reduced when mud filtrate front was advanced away from the wetted end of test sample. This process was perfectly described by the modified failure criterion.

6 NOMENCLATURE

a_w	=	Water activity.
F_{anis}	=	Shale anisotropy factor.
P	=	Hydration Stress.
Pp	=	Pore fluid pressure.
R	=	Gas constant.
T	=	Absolute temperature.
$\overline{V}$	=	Pure water partial molar volume.
β	=	Angle of obliquity, degrees.
ϕ	=	Angle of internal friction.
ΔMC	=	Net gain in moisture.
τ_f	=	Shear stress at failure.
τ_o	=	Apparent cohesion of rock.
σ	=	Normal stress.
σ^i_{eff}	=	Effective stress at i-direction.
σ^i	=	Total Stress at i-direction.
σ^i_{hyd}	=	Hydration stress at i-direction.
σ_{ts}	=	Total swelling stress.
σ^V_{ts}	=	Total swelling stress normal to bedding planes.
σ^H_{ts}	=	Total swelling stress parallel to bedding planes.
σ_{os}	=	Osmotic swelling stress.
σ_{sur}	=	Surface swelling stress.
ψ	=	Anisotropy coefficient.
ε_H	=	Swelling strains parallel to bedding planes.
ε_H	=	Swelling strains normal to bedding planes.

7 KEYWORDS

Shale, Reactive clays, mud filtrate, Swelling stresses, Mechanical properties, In-situ strength, Anisotropy factor, Mohr-Coulomb failure criterion, Drilling fluid, Adsorption isotherm, Moisture content, Water activity.

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