ABSTRACT: Time-dependent measurements of uniaxial compressive strength, and ionic and water transport were conducted to analyze the alteration of shale’s strength, as a function of time, when exposed to aqueous solutions. Results showed that the compressive strength of shale is time-dependent, and it relies highly on water activity and ionic concentration differences between shale and aqueous solutions. Data obtained from this work showed that time-dependent water and ion transport into shale correlated well with compressive strength measurements. It was revealed that initial water extraction by osmosis strengthened shale until ions and their associated water clouds invaded shale causing reduction in its strength. It is quite possible that water flow by diffusion osmosis may have counteracted water flow by chemical osmosis rendering ionic diffusion as the primary regulator on shale strength alteration. Furthermore, it was found that alteration of compressive strength when it interacted with aqueous solutions could be adequately explained within the confines of chemical osmosis, ionic diffusion, and diffusion osmosis. Data suggests that the impact of chemical osmosis on compressive strength is observed earlier than ionic diffusion and diffusion osmosis. Data also showed that potassium ions seem to contribute to the enhancement of the compressive strength of shale.

1. BACKGROUND AND PRIOR WORK
Shale presents a great challenge to drilling engineers and charges the petroleum industry billions of dollars per year. Shale is categorized as partly dewatered, low-permeability sedimentary rock. Although it causes serious drilling issues including, but not limited to, lost circulation, mechanical pipe sticking, bit balling, and excessive torque; wellbore instability is branded as the utmost problematic issue during drilling. The negative communications among shale and mud appear as the main reason for wellbore collapse in shale. Such communications include, among others, mechanical, chemical, physical, hydraulic, thermal, and electrical phenomena. While the causes of such communications are still under investigation, the overall effects of these communications are highly associated with the ionic and water transport into shale. The ionic and water transport may change some of the vital characteristics of shale, such as pore fluid pressure, volumetric expansion behavior, compressive strength, fluid conductivity, and modulus of elasticity. Furthermore, ionic invasion of shale may set in motion shale strength decrease, cement material weakening, shale structure adjustment, pore fluid’s chemistry variations, and eventual failure.

In the absence of hydraulic, thermal, and electrical gradients, chemical osmosis, diffusion osmosis, and ionic diffusion dominate ionic and water flow when shale interacts with aqueous solutions particularly if the water activity (ionic concentration) of shale is different from that of the aqueous solutions. Water and ions flow toward lower chemical activity and ionic concentrations, respectively. Shale is considered to be a nonideal semipermeable membrane that regulates ionic and water flow when interacting with salt solutions.

According to the laws of thermodynamics, chemical osmosis is governed by differences in the chemical potential of aqueous solutions parted by a semipermeable membrane. Direct measurement of chemical potentials of aqueous solutions is not an easy task and still presents challenges to scientists and researchers. However, it is agreed upon that water activity ($a_w$) is used to estimate the chemical potential of aqueous solutions, and it is expressed by the following equation

$$\mu = \mu_0 + RT \ln(a_w)$$  \hspace{1cm} (1)

The water activity ($a_w$) is approximated as follows

$$a_{w,\text{shale}} = \frac{P}{P_0}$$  \hspace{1cm} (2)

Ionic diffusion is a process that describes ionic flow from concentrated solutions to dilute solutions. Fick’s law governs ionic diffusion as
Diffusion osmosis deals with the flow of water together with their corresponding ions, as shown in Figure 1, toward the lower-ionic-concentration region.

\[ J = -D_j \times \left( \frac{C_1 - C_2}{\Delta L} \right) \]  

(3)

Chemical osmosis, diffusion osmosis, and ionic diffusion control ionic and water flow simultaneously when solutions of dissimilar ionic concentrations interact across a semipermeable membrane, as shown in Figure 2, as follows:

- Chemical osmosis promotes water transport in the direction of concentrated solutions.
- Diffusion osmosis causes water flow toward dilute solutions.
- Ionic diffusion transports ions in the direction of dilute solutions.

The mechanical properties of shale, especially compressive strength, could be affected by ionic and water transport. Compressive strength alteration could lead to mechanical instability and collapse of shale especially when the applied stresses exceed its compressive strength. This problem becomes much more problematic for directional drilling in laminated and fractured shale formations and could lead to total loss of drilled hole. A new experimental work was conducted on clay-rich Duvernay samples by to investigate the impact of osmotic pressure while mitigating the effect of capillary pressure. They concluded that the impact of osmotic pressure on fracturing fluid loss is profound and rapid.

Alteration of the compressive strength of shale has generated much interest over the past decades, and several researchers tried to understand the reasons and effects of it on the overall integrity of shale to provide methods and techniques for safe shale drilling. While these studies presented great results and analysis and shed light on the causes and consequences of the alteration of compressive strength of shale on the stability of drilled wellbore, these studies did not monitor the development of shale’s compressive strength alteration (reduction or enhancement) as a function of time. Their recommendations were based on the final state of shale’s compressive strength measurements. I believe that shale’s compressive strength alterations develop over time as water and ions are exchanged between shale and aqueous solutions. Such time-dependent water and ions exchange produces a compressive strength alteration profile that develops over time which may help in designing better solutions for wellbore stability in shale. Zhang et al. argued that variations in shale’s mechanical and physicochemical properties could occur over time. Al-Bazali et al. developed a novel technique for monitoring time-dependent ionic and water transport through shale.

This work discusses time-dependent experimental measurements of shale’s compressive strength as it interacts with aqueous solutions. Moreover, this work makes use of a previously developed, by the author, procedure for measuring time-dependent ionic and water flow through shale to better analyze the time-dependent changes in shale’s compressive strength. Incorporating water and ions data with compressive strength measurements should make the analysis of the influence of ionic and water transport through shale more meaningful and practical.
2. SHALE PROPERTIES

Two cylindrical shale cores (A and B) (2.5 inches by 6 feet) were utilized in this investigation. Firm measures were conducted to reduce contamination of shale by air throughout extraction, treatment, storage, and transfer processes. Direct contact of shale with the atmosphere may modify its native water activity and water content. It is important to test shale without altering its native water activity and water content to obtain valid and reliable results. Tables 1 and 2 show mineralogical compositions and petrophysical properties of shales (A and B), respectively.

Table 1. Minerals Make Up of Shale

| minerals make up | shale [A] w/w % | shale [B] w/w % |
|-----------------|-----------------|-----------------|
| quartz          | 15.2            | 15.8            |
| feldspar        | 4.1             | 2.7             |
| calcite         | 1.7             | 0.9             |
| dolomite        | 1.8             | 1.1             |
| pyrite          | 1.4             | 1.2             |
| siderite        | 1.5             | 0.8             |
| clay (total)    | 74.3            | 77.5            |
| chlorite        | 3.5             | n/a             |
| kaolinite       | 6.8             | 9.5             |
| illite          | 7.49            | n/a             |
| smectite        | 22.4            | 20.1            |
| mixed layers    | 34.18           | 29.7            |

Table 2. Shales [A and B] Petrophysical Properties

| shale type (WC) (%) | moisture content (WC) (%) | water activity (aw) | porosity (%) | permeability (nD) | CEC (mL.eq/100 gm) |
|---------------------|---------------------------|---------------------|--------------|-------------------|-------------------|
| [A]                 | 10.09                     | 0.96                | 12.8         | 3.7               | 24.7              |
| [B]                 | 6.5                       | 0.92                | 7.9          | 1.3               | 17.9              |

X-ray crystallography was employed to determine shale’s mineralogical composition by an independent commercial laboratory. The water activity of shale was measured by means of the adsorption isotherm method. Saturated salts were used to accomplish and maintain desired water activity levels, as shown in Table 3. A full description of the methodologies used to estimate porosity, water content, permeability, water activity, and cation exchange capacity (CEC) of shale can be found elsewhere.

3. EXPERIMENTAL METHODOLOGY

In this work, we monitored the time-dependent changes in the unconfined compressive strength as shale interacted with NaCl, CaCl₂, and KCl solutions of various concentrations. Uniaxial compressive strength was measured for different time intervals as follows: 1, 6, 12, 24, 48, 120, 240, 480, and 720 h. This procedure allows us to see the time-dependent impact of chemical osmosis, diffusion osmosis, and ions diffusion on the unconfined compressive strength (mechanical integrity) of shale. Prior studies have measured the uniaxial compressive strength of shale after shale reached equilibrium with the test solution at which the final balance of water and ions exchange has been reached. We believe that it is important to monitor changes in the uniaxial compressive strength of shale as a function of time during shale’s interaction with salt solutions. This allows us to understand and determine which process, chemical osmosis, diffusion osmosis, or ionic diffusion, dominates ionic and water flow as a function of time. Such understanding will pave the way for better drilling fluid design to mitigate wellbore stability problems during drilling.

Time-dependent compressive strength and water and ion uptake measurements were conducted in this work. A triaxial cell was utilized to estimate the unconfined compressive strength of shale, as depicted in Figure 3, and a gravimetric technique was used to measure ionic and water flow.

3.1. Time-Dependent Unconfined Compressive Strength of Shale

In our work, two different shales (A and B) interacted with three salt solutions (NaCl, CaCl₂, and KCl) of three different water activities (aw = 0.90, 0.93, and 0.96) for different time intervals (1, 6, 12, 24, 48, 120, 240, 480, and 720 h). The following describes the time-dependent uniaxial compressive strength experimental procedure when shale A was exposed to NaCl (aw = 0.90) at different time intervals (1, 6, 12, 24, 48, 120, 240, 480, and 720 h). Similar steps were followed when shales A and B were exposed to NaCl, CaCl₂, and KCl of 0.90, 0.93, and 0.96 water activities.

- NaCl solution of 0.90 water activity is prepared by adding sodium chloride to water at the right proportion, as shown in Figure 4. Using Figure 4, we can also prepare NaCl solutions of 0.93 and 0.96 water activities. Similar graphs exist, in the literature, for KCl and CaCl₂ solutions.
- Cut 10 cylindrical samples of shale A of 0.75” radius and 3’ length and put them in a can of mineral oil to avoid air contact with the samples. Number shale samples from 1 to 10 for record tracking purposes.
- Prepare the triaxial cell for running a uniaxial compressive strength test. Details can be found in AL-Bazali.
- Take sample 1 and clean it by removing the oil from its surface using standard hexane solvent. Put it in the triaxial cell and measure its compressive strength. This is the native “unaltered” compressive strength of shale A and should serve as a benchmark for all compressive strength measurements as shale interacts with NaCl, KCl, and CaCl₂ solutions of 0.90, 0.93, and 0.96 water activities for different times. The native compressive strength of shale A was measured at 5.98 MPa. Since sample 1 did not interact with the NaCl solution, we may assign its time interval to zero hour (time = 0 h) for reference purposes.
- Prepare 9 containers (beakers) and pour NaCl solution of 0.90 water activity into them.
- Take shale A samples 2, 3, 4, 5, 6, 7, 8, 9, and 10, clean them using hexane solvent and put them in the containers (beakers), and monitor the time. After 1 h, remove sample 2 from the container and measure its uniaxial compressive strength. Record the result.
- Measure and record the uniaxial compressive strength of shale samples 3−10 at different time periods as follows; sample 3 (6 h), sample 4 (12 h), sample 5 (24 h),
Repeat the above procedure for shale A interaction with NaCl solutions of 0.93 and 0.96 water activities, CaCl\(_2\) solutions having 0.90, 0.93, and 0.96 water activities, and KCl solutions having 0.90, 0.93, and 0.96 water activities.

Repeat the above procedure for shale B interaction with NaCl solutions of 0.90, 0.93, and 0.96 water activities, CaCl\(_2\) solutions of 0.90, 0.93, and 0.96 water activities, and KCl solutions of 0.90, 0.93, and 0.96 water activities. Record all results for shales A and B.

### 3.2. Water and Ion Transport

Water and ions exchanged as shale communicates with aqueous solutions of different concentrations were measured gravimetrically. This technique involves monitoring the shale’s weight alterations under different scenarios. Equations 4 and 5 were employed to estimate the quantity of gained or lost water and ions as shale interacts with different aqueous solutions of different concentrations.

#### Table 4. Measurements of Unconfined Compressive Strength (MPa) of Shale A (\(a_w = 0.96\))

| time (h) | NaCl \((a_w = 0.90)\) | NaCl \((a_w = 0.93)\) | NaCl \((a_w = 0.96)\) | CaCl\(_2\) \((a_w = 0.90)\) | CaCl\(_2\) \((a_w = 0.93)\) | CaCl\(_2\) \((a_w = 0.96)\) | KCl \((a_w = 0.90)\) | KCl \((a_w = 0.93)\) | KCl \((a_w = 0.96)\) |
|---------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0       | 5.98           | 5.98           | 5.98           | 5.98           | 5.98           | 5.98           | 5.98           | 5.98           | 5.98           |
| 1       | 6.61           | 6.08           | 4.87           | 6.51           | 6.81           | 5.73           | 6.19           | 6.21           | 6.16           |
| 6       | 7.45           | 6.23           | 4.61           | 7.29           | 7.59           | 5.19           | 7.23           | 6.99           | 6.27           |
| 12      | 7.79           | 6.85           | 4.29           | 7.61           | 8.013          | 4.52           | 7.79           | 7.51           | 6.81           |
| 24      | 6.07           | 6.74           | 3.98           | 7.17           | 8.66           | 3.91           | 8.27           | 7.93           | 7.05           |
| 48      | 5.54           | 5.34           | 3.81           | 6.35           | 7.18           | 3.56           | 9.1            | 8.31           | 7.18           |
| 120     | 4.82           | 4.88           | 3.83           | 5.16           | 6.66           | 3.44           | 9.56           | 8.73           | 7.49           |
| 240     | 3.63           | 4.51           | 3.78           | 4.82           | 5.19           | 3.49           | 9.45           | 8.91           | 7.51           |
| 480     | crumbled       | 4.47           | 3.8            | 3.39           | 4.72           | 3.63           | 9.61           | 9.14           | 7.43           |
| 720     | crumbled       | 4.52           | 3.76           | crumbled       | 4.29           | 3.5            | 9.8            | 8.89           | 7.48           |

Figure 3. Diagram of the triaxial cell utilized for unconfined compressive strength test.

Figure 4. Water activity versus concentration for NaCl solutions.
Table 5. Measurements of Unconfined Compressive Strength (MPa) of Shale B \((a_w = 0.92)\)

| time (h) | NaCl \((a_w = 0.90)\) | NaCl \((a_w = 0.93)\) | NaCl \((a_w = 0.96)\) | CaCl\(_2\) \((a_w = 0.90)\) | CaCl\(_2\) \((a_w = 0.93)\) | CaCl\(_2\) \((a_w = 0.96)\) | KCl \((a_w = 0.90)\) | KCl \((a_w = 0.93)\) | KCl \((a_w = 0.96)\) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0        | 4.8            | 4.8            | 4.8            | 4.8            | 4.8            | 4.8            | 4.8            | 4.8            | 4.8            |
| 1        | 4.88           | 4.6            | 3.87           | 5.1            | 4.79           | 4.2            | 5.4            | 5.23           | 4.56           |
| 6        | 5.02           | 4.39           | 3.45           | 5.35           | 4.51           | 3.78           | 5.91           | 5.88           | 4.28           |
| 12       | 5.16           | 4.1            | 2.97           | 4.88           | 3.69           | 3.29           | 6.35           | 6.18           | 4.61           |
| 24       | 5.09           | 3.82           | 2.71           | 4.19           | 3.17           | 2.87           | 6.79           | 6.91           | 4.69           |
| 48       | 4.85           | 3.51           | 2.49           | 3.61           | 2.88           | 2.41           | 7.31           | 6.85           | 4.81           |
| 120      | 4.37           | 3.09           | 2.1            | 2.92           | 2.59           | 1.77           | 7.66           | 7.15           | 4.87           |
| 240      | 4.05           | 2.87           | 1.88           | 2.61           | 2.14           | 1.84           | 7.54           | 7.37           | 4.79           |
| 480      | 3.99           | 2.91           | crumbled       | 2.34           | 1.92           | 1.61           | 7.71           | 7.29           | 4.96           |
| 720      | 4.09           | 2.85           | crumbled       | 2.21           | 1.83           | crumbled       | 7.9            | 7.41           | 5.1            |

Figure 5. Unconfined compressive strength of shale A when exposed to various salt solutions.

Figure 6. Unconfined compressive strength of shale B when exposed to various salt solutions.

\[
W_w \% = \left( \frac{W_w - W_{\text{da}} - W_{\text{ps}} + W_{\text{pd}}}{W_{\text{pa}}} \right) \times 100\% \tag{4}
\]

\[
W_p \% = \left( \frac{W_{\text{da}} - W_{\text{pd}}}{W_{\text{pa}}} \right) \times 100\% \tag{5}
\]
This test measures water and ions exchanged when shales (A and B) interacted with three different salt solutions (NaCl, CaCl$_2$, and KCl) of three different water activities ($a_w = 0.90, 0.93,$ and 0.96) for different time intervals (1, 6, 12, 24, 48, 120, 240, 480, and 720 h). Results from this test will be combined with time-dependent compressive strength test to better understand the behavior of mechanical properties of shale as it interacts with aqueous solutions. It is vital to remark that $W_w\%$ calculated by eq 4 is the net effect of water exchanged between shale and aqueous solutions. This net water includes water exchanged by chemical osmosis and diffusion osmosis.

4. RESULTS AND DISCUSSION

Tables 4 and 5 and Figures 5 and 6 show the impact of NaCl, CaCl$_2$, and KCl solutions of 0.90, 0.93, and 0.96 water activities on the unconfined compressive strength of shales A and B, respectively. Similar observations and trends were seen and shared when shales A and B interacted with NaCl, CaCl$_2$, and KCl solutions. Therefore, it is adequate to only analyze the interaction of shale A with NaCl, CaCl$_2$, and KCl solutions. While the following discusses and analyzes only experimental results of shale A, such discussion and analysis apply to shale B.

Two observations can distinctly be seen in Table 4 and Figure 5. First, the behavior of shale A’s compressive strength depends highly on the water activity gradient that exists between shale A and the solution. Second, the response of shale A compressive strength is ion-specific where KCl solution has a different effect on shale A compressive strength, at all concentrations, compared to NaCl and CaCl$_2$ solutions.

4.1. Interaction of Shale A with NaCl and CaCl$_2$ Solutions. When shale A ($a_w = 0.96$) communicated with NaCl and CaCl$_2$ of 0.90 water activities, we noted that its compressive strength increased in the first 12 h and it decreased thereafter. Also, we observed that shale A sample immersed in NaCl solutions for 480 and 720 h crumbled and failed. A similar observation was made when shale A was immersed in CaCl$_2$ solution for 720 h. A similar trend was seen when shale A communicated with NaCl and CaCl$_2$ solutions of 0.93 water activities but no shale failure was observed. The trend is completely different when shale A communicated with NaCl and CaCl$_2$ solutions of 0.96 water activities where the compressive strength of shale A decreased for all time intervals (1–720 h). These observations can be explained within the confines of three mechanisms: chemical osmosis, ionic diffusion, and diffusion osmosis.

When shale A communicated with NaCl and CaCl$_2$ of 0.90 and 0.93 water activities, a chemical potential variance was established in the direction of the test solutions (NaCl and CaCl$_2$) since the water activity of shale A is greater than the water activity of the solution (NaCl and CaCl$_2$). This chemical potential gradient promoted water flow out of shale and into the solutions which may have caused an early increase in shale A compressive strength since a reduction of water content in the shale’s pore structure enhances its strength and mechanical stability. The strength improvement for shale A lasted about 12 h, after which shale strength deteriorated. This could be due to ionic diffusion and diffusion osmosis due to the forced ionic concentration difference in the direction of shale since the concentration of NaCl and CaCl$_2$ is higher in the test solution than in the shale. Therefore, Na$^+$, Ca$^{2+}$, and Cl$^-$ ions flowed into shale A. The flow of ions into shale A may have changed its mechanical properties and contributed to the reduction of its compressive strength. Also, diffusion osmosis took place in the direction of ionic diffusion since water clouds cannot be separated from their respective ions. The flow of water by diffusion osmosis may have negated the beneficial impact of chemical osmosis which drew water out of shale A. The adverse impact of both ionic diffusion and diffusion osmosis may have taken over the beneficial impact of chemical osmosis after 12 h shown in Table 4 and Figure 5. It is fair to argue that chemical osmosis effects on the compressive strength of shale A are observed earlier than ionic diffusion and diffusion osmosis effects. This is due to the fact that chemical osmosis...
occurs faster than ionic diffusion and diffusion osmosis since the mobility of water molecules is higher than the mobility of ions.

When shale A interacted with NaCl and CaCl$_2$ solutions of 0.96 water activities, we noted that the compressive strength of shale A decreased for all time intervals (1–720 h). This can be easily attributed to the absence of chemical potential difference since the water activity of shale A equals the water activity of NaCl and CaCl$_2$ solutions. Therefore, water movement out of shale did not occur due to chemical osmosis and consequently the strength of shale was not enhanced. Concurrently, ionic diffusion and diffusion osmosis may have forced hydrated ions to flow into shale due to the existence of an ionic concentration gradient in the direction of shale A. The flow of ions and their associated water clouds may have affected the mechanical stability and compressive strength of shale A leading to shale's compressive strength reduction as pointed out in Table 4 and Figure 5. A similar argument can be made for shale B interactions with NaCl and CaCl$_2$ solutions of 0.90, 0.93, and 0.96 water activities as shown in Table 5 and Figure 6.

### 4.2. Interaction of Shale A with KCl Solutions

When shale A interacted with KCl solutions of 0.90, 0.93, and 0.96 water activities, we noted that the compressive strength of shale A increased for all time intervals (1–720 h), as shown in Figure 5. Besides the beneficial impact of chemical osmosis on the shale’s compressive strength enhancement, potassium ions are thought to improve the strength of shale unlike sodium and calcium ions. The enhancing mechanism for potassium ion is still not clear but it is claimed that, due to its size, potassium ion fits exactly into the clay lattice structure and thus greatly reduces clay swelling and expansion.

The presence of potassium ions in sufficient concentrations may decrease the thickness of the diffuse double layer, which lessens the expansive tendency of clay. AL-Bazali notes “if sufficient shrinkage occurs to the diffuse double-layer thickness of interacting clay particles, van der Waals forces become more dominant over electrostatic repulsive forces which causes clay particles to attract each other and thereby provide more stability and strength enhancement and prevent clay swelling”. A similar argument can be made for shale B interactions with KCl solutions of 0.90, 0.93, and 0.96 water activities, as shown in Figure 6.

### 4.3. Time-Dependent Water and Ion Uptake

The objective of this test is to confirm time-dependent water and ion transport into shale and correlate it with compressive strength data shown in Figures 5 and 6. Figure 7 shows time-dependent water and ion transport when exposing shale A to NaCl solutions of 0.90, 0.93, and 0.96 water activities.

![Figure 8](https://pubs.acs.org/doi/10.1021/acsomega.2c02831)

**Figure 8.** Time-dependent uniaxial compressive strength of shale A as a function of time-dependent water and ion transport when exposing shale A to NaCl solution ($a_w = 0.90$).
NaCl solution \((a_w = 0.90)\). As seen in Figure 8, changes in uniaxial compressive strength of shale A correlate well with water and ion uptake where compressive strength increased when water is extracted out of shale and decreased when ions and their associated water moved into shale. Water extraction, up to 2.2% by weight, out of shale A took place for 6 h after which the amount of extracted water decreased steadily reaching a value of almost 0% by weight after 720 h. Concurrently, the number of ions that flowed into shale A increased steadily over time reaching a value of 4.1% by weight after 720 h.

It is quite obvious, from Figure 8, that during shale A interaction with NaCl solution \((a_w = 0.90)\), chemical osmosis occurs prior to ionic diffusion and diffusion osmosis. Figure 8 shows the net movement of water which includes both osmotic water (chemical osmosis) and associated water (diffusion osmosis). It is valid to accept that net water exchanged when shale A \((a_w = 0.96)\) interacted with NaCl solution \((a_w = 0.96)\) was mainly due to diffusion osmosis since their chemical potentials are equal. On the contrary, water uptake by shale A when it interacted with NaCl solution of 0.90 water activity, shown in Figure 8, was due to the combined effect of both chemical and diffusion osmosis. It is practically acceptable to claim that subtracting net water exchanged when shale A \((a_w = 0.96)\) interacted with NaCl solution \((a_w = 0.96)\) from net water exchanged as shale A \((a_w = 0.96)\) interacted with NaCl solution \((a_w = 0.96)\) yields osmotic water transported into shale A by chemical osmosis as shale A interacted with NaCl \((a_w = 0.90)\), as explained in Figure 9. Separating water exchanged by chemical osmosis from water exchanged by diffusion osmosis has been well documented in many studies.\(^4\)\(^6\)\(^13\)\(^6\)

One can conclude from Figure 9 that chemical osmosis dominated water uptake into shale A for 36 h while diffusion osmosis took over after that. Both processes operated simultaneously with one dominating the other as time elapsed.

Similar arguments can be made for shale A interactions with NaCl \((a_w = 0.93 \text{ and } 0.96)\). Also, the previous technique can be extended to analyze shale A interactions with CaCl\(_2\) and KCl solutions and shale B interactions with NaCl, CaCl\(_2\), and KCl solutions.

### 4.4. Effect of Water Activity Gradient on Shale’s Unconfined Compressive Strength

Water activity gradient is the primary driver for water flow by chemical osmosis, otherwise known as “osmotic flow”. The direction of water flow occurs from a solution of high water activity to a solution of lower water activity. As the water activity gradient increases, water flow toward the lower-water-activity solution also increases until equilibrium is reached and the water activities in both regions equalize, at which water flow ceases.\(^1\)

It can be inferred from Table 4 and Figure 5 that the compressive strength of shale A increased more appreciably during early times (1–12 h) when interacting with NaCl, CaCl\(_2\), and KCl solutions of 0.90 water activity than when interacting with the same solutions of 0.93 and 0.96 water activities. This is in line with expectations since the water activity of shale A is 0.96 which results in a larger water activity difference with test solutions of 0.90 water activities than with solutions of 0.93 and 0.96 water activities. This translates into a larger chemical potential difference and thus more water flow out of shale A, all of which resulted in a higher compressive strength of shale A. It is important to mention that the effect of chemical osmosis is compromised by ionic diffusion and diffusion osmosis at later times, as seen in Table 4 and Figure 5.

### 5. LIMITATIONS AND FUTURE WORK

While this work sheds light on the macro picture regarding the influence of time-dependent chemical osmosis, ionic diffusion, and diffusion osmosis on the mechanical stability of shale, it ignored processes that take place at the micro level, which could improve our knowledge of the mechanical performance of shale as it interacts with salt solutions and help us design better drilling fluids solutions to mitigate wellbore stability problems. One of these processes relates to changes in diffuse...
double-layer thickness of shale as a result of water and ions invasion into the electrical double layer of shale. Another phenomenon that should be studied relates to the mechanical behavior of the different minerals that make up the shale’s grains. Namely, grain-scale mechanism and cracking preferences need to be explored in future studies. The mechanical behavior of these individual minerals may have a profound effect on the overall mechanical integrity of shale rocks.\textsuperscript{37,38}

Future work will investigate diffuse double-layer thickness changes to analyze the total impact of salt solutions of various concentrations on shale’s compressive strength.

6. RECOMMENDATIONS

The findings of this study presented guidelines for better wellbore stability control and drilling mud design. Data proposed that the effect of chemical osmosis on compressive strength is observed earlier than ionic diffusion and diffusion osmosis. This finding could effectively be used to help mitigate wellbore stability problems especially when drilling troublesome shale. Namely, drilling mud engineers should focus on osmotically removing water from shale when drilling short sections of sensitive shale (150–300 m in thickness). This can be done by utilizing concentrated salt solutions in the formulation of drilling muds so that the water activity of the drilling mud is much lower than that of the targeted shale. In addition, drilling mud engineers must avoid using concentrated salt solutions when drilling long sections of sensitive shale (>300 m) because the detrimental impact of both diffusion osmosis and ionic diffusion may negate the positive effect of chemical osmosis. Data also exhibited that potassium ion seems to outperform sodium and calcium ions in the enhancement of the compressive strength of shale.

7. CONCLUSIONS

- Compressive strength (mechanical stability) of shale is time-dependent.
- Behavior of the compressive strengths of shales A and B depends highly on the established water activity gradient between shale and salt solutions.
- The response of the compressive strengths of shales A and B is ion-specific where KCl solution seems to have different effects on the compressive strength of shales A and B at all concentrations compared to other salt solutions.
- In the presence of a water activity gradient, chemical osmosis is responsible for water exchange between shale and aqueous solutions.
- Ionic flow into shale could affect the mechanical stability of shale and contribute to the reduction of its compressive strength.
- Water flow by diffusion osmosis could negate the advantageous effect of chemical osmosis.
- Chemical osmosis effects are observed earlier than both ionic diffusion and diffusion osmosis effects. This is due to the fact that chemical osmosis occurs faster since the mobility of water molecules is higher than the mobility of hydrated ions.
- Unlike sodium and calcium ions, potassium ions seem to contribute to the enhancement of the compressive strength of shale.
- Water flows toward lower-water-activity solutions until equilibrium is reached and the water activities on both solutions equalize, at which water flow ceases.

![Image](https://pubs.acs.org/10.1021/acsomega.2c02831)

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Notes
The authors declare no competing financial interest.
Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.
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Biography
Talal AL-Bazali is currently an Associate Professor of Petroleum Engineering at Kuwait University. Dr. Talal AL-Bazali teaching and research interests include drilling engineering, drilling fluids chemistry and rock mechanics. Dr. AL-Bazali holds a B.S. degree from University of Tulsa, M.S. and Ph.D. degrees from the University of Texas at Austin, all in Petroleum Engineering.

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NOMENCLATURE LIST

\( \mu_a \), chemical potential of the particular component at temperature \( T \) and pressure \( P \) (Joule/kg)

\( \mu_i^a \), chemical potential of the particular component at standard condition (Joule/kg)

\( R \), ideal gas constant (8.314 J K\(^{-1}\)mol\(^{-1}\))

\( T \), temperature (K)

\( a_w \), water activity

\( P \), aqueous vapor pressure of the atmosphere above the shale (Pa = kg·m\(^{-1}\)·s\(^{-2}\))

\( P_o \), aqueous vapor pressure of the atmosphere above pure water (Pa = kg·m\(^{-1}\)·s\(^{-2}\))

\( J \), mass flux of \( i \)th ion (kg·m\(^{-2}\)·s\(^{-1}\))

\( D_i \), diffusion coefficient of the \( i \)th ion (m\(^2\)/s)

\( C_{ip} \), concentration of \( i \)th ion in shale’s pore fluid (mol/m\(^3\))

\( C_{is} \), concentration of \( i \)th ion in salt solution (mol/m\(^3\))

\( \Delta L \), shale’s length (m)

\( W_{iwa} \), weight of preserved sample in air (gram)

\( W_{iwp} \), weight of preserved sample after drying (gram)

\( W_{ipa} \), altered weight of sample after immersion in salt solutions (gram)

\( W_{iwp} \), dry weight of altered sample (gram)

\( W_{iwa} \), relative weight of water gained or lost from shale

\( W_{iwp} \), relative weight of ions gained or lost from shale

REFERENCES

(1) Mao, L.; Lin, H.; Cai, M.; Zhang, J. Wellbore stability analysis of horizontal wells for shale gas with consideration of hydration. J. Energy Resour. Technol. 2022, 144, No. 113003.
(2) Chenevert, M. E. Shale alteration by water adsorption. J. Pet. Technol. 1970, 22, 1141–1148.

(3) Mody, F. K.; Hale, A. H. Borehole-stability model to couple the mechanics and chemistry of drilling-fluid/shale interactions. J. Pet. Technol. 1993, 45, 1093–1101.

(4) Al-Bazali, T. M.; Al-Mudhihi, S.; Chenevert, M. E. An experimental investigation of the impact of diffusion osmosis and chemical osmosis on the stability of shales. Pet. Sci. Technol. 2011, 29, 312–323.

(5) Tariq, Z.; Mahmoud, M.; Alade, O.; Abdulraheem, A.; Mustafa, A.; Mokheimer, E.; Al-Nakhli, A. 2021). Productivity Enhancement in Multilayered Unconventional Rocks Using Thermochemicals. J. Energy Resour. Technol. 2021, 143, No. 033001.

(6) Ewy, R. T.; Stankovic, R. J. Shale Swelling, Osmosis, and Acoustic Changes Measured Under Simulated Downhole Condition. SPE Drill. Compl. 2010, 25, 177–186.

(7) Santarelli, F. J.; Carminati, S. Do shales swell? A critical review of available evidence. In SPE/IADC Drilling Conference, OnePetro, 1995, February.

(8) Al-Bazali, T.; Zhang, J.; Chenevert, M. E.; Sharma, M. M. Experimental and numerical study on the impact of strain rate on failure characteristics of shales. J. Pet. Sci. Eng. 2008, 60, 194–204.

(9) Al-Bazali, T. M.; Zhang, J.; Chenevert, M. E.; Sharma, M. M. An experimental investigation on the impact of diffusion osmosis, chemical osmosis, and capillary suction on shale alteration. J. Porous Media 2008, 11, 719–731.

(10) Al-Bazali, T. M.; Zhang, J.; Wolfe, C.; Chenevert, M. E.; Sharma, M. M. Wellbore instability of directional wells in laminated and naturally fractured shales. J. Porous Media 2009, 12, 119–130.

(11) Pan, B.; Clarkson, C. R.; Younis, A.; Song, C.; Debuhr, C.; Ghanizadeh, A.; Birss, V. I. Fracturing Fluid Loss in Unconventional Reservoirs: Evaluating the Impact of Osmotic Pressure and Sulfacetant and Methods to Upscale Results. In Unconventional Resources Technology Conference, 26–28 July 2021, Unconventional Resources Technology Conference (URTeC), 2021, December; pp 2084–2099.

(12) Lashkaripour, G. R.; Jalloiean, R. The effect of water content on the mechanical behaviour of fine-grained sedimentary rocks. In ISRM International Symposium, OnePetro, 2000, November.

(13) Steiger, R. P. Advanced triaxial swelling tests on preserved shale cores. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Pergamon, 1993, December; Vol. 30, No. 7, pp 681–685.

(14) Koncagül, E. C.; Santi, P. M. Predicting the unconfined compressive strength of the Breathitt shale using shale durability, Shore hardness and rock structural properties. Int. J. Rock Mech. Min. Sci. 1999, 36, 139–153.

(13) Al-Bazali, T.; Zhang, J.; Chenevert, M. E.; Sharma, M. M. Maintaining the stability of deviated and horizontal wells: Effects of mechanical, chemical and thermal phenomena on well design. Geomech. Geoproc. Int. J. 2008, 3, 167–178.

(16) Luo, Y. Rock mechanics and wellbore stability of deep shale during drilling and completion processes. J. Pet. Sci. Eng. 2021, No. 108882.

(17) Simpson, J. P.; Dearing, H. L. Diffusion Osmosis: An unrecognized cause of shale instability. In IADC/SPE Drilling Conference, OnePetro, 2000, February.

(18) Al-Bazali, T. M. Insight on the inhibitive property of potassium ion on the stability of shale: a diffuse double-layer thickness (κ−1) perspective. J. Pet. Explor. Prod. Technol. 2021, 11, 2709–2723.

(19) Huang, L.; Guo, Y.; Li, X. Mechanical response to dynamic compressive load applied to shale after thermal treatment. J. Nat. Gas Sci. Eng. 2022, 102, No. 104565.

(20) Lomba, R. F.; Chenevert, M. E.; Sharma, M. M. The ion-selective membrane behavior of native shales. J. Pet. Sci. Eng. 2000, 25, 9–23.

(21) Al-Bazali, T. A novel experimental technique to monitor the time-dependent water and ions uptake when shale interacts with aqueous solutions. Rock Mech. Rock Eng. 2013, 46, 1145–1156.

(22) Chenevert, M. E.; Amanullah, M. Shale preservation and testing techniques for borehole-stability studies. SPE Drill. Compl. 2001, 16, 146–149.

(23) Al-Bazali, T. Maintenance of the stability of deviated and horizontal wells: Effects of Thermal-Mechanical-Drilling fluids to minimize drilling and completion problems associated with hydratable clays. J. Pet. Technol. 1982, 34, 1661–1670.

(24) Aslannezhad, M.; Kalantari, A.; Keshavarz, A. Borehole stability in shale formations: Effects of Thermal-Mechanical- Parameters on well design. J. Nat. Gas Sci. Eng. 2021, 88, No. 103852.

(25) McBride, M. B. A critique of diffuse double layer models applied to colloid and surface chemistry. Clay Minerals 1997, 45, 598–608.

(26) Al-Bazali, T. M. The consequences of using concentrated salt solutions for mitigating wellbore instability in shales. J. Pet. Sci. Eng. 2011, 110, 94–101.

(27) Shi, X.; Wang, L.; Guo, J.; Su, Q.; Zhao, X. Effects of inhibitor KCl on shale expansibility and mechanical properties. Petroleum 2019, 5, 407–412.

(28) Liu, H.; Cui, S.; Meng, Y.; Li, Z.; Yu, X.; Sun, H.; Zhou, Y.; Luo, Y. Rock mechanics and wellbore stability of deep shale during drilling and completion processes. J. Pet. Sci. Eng. 2021, 205, No. 108882.

(29) Cano, A. C.; Van Stappen, J. F.; Wolterbeek, T. K.; Hangx, S. J. Uniaxial compaction of sand using 4D X-ray tomography: The effect of deviated wells. J. Geophys. Eng. 2020, 23.

(30) Aslannezhad, M.; Kalantari, A.; Keshavarz, A. Borehole stability in shale formations: Effects of Thermal-Mechanical-Chemical parameters on well design. J. Nat. Gas Sci. Eng. 2021, 88, No. 103852.

(31) Mirowski, M. B. A critique of diffuse double layer models applied to colloid and surface chemistry. Clay Minerals 1997, 45, 598–608.

(32) Al-Bazali, T. M. The consequences of using concentrated salt solutions for mitigating wellbore instability in shales. J. Pet. Sci. Eng. 2011, 110, 94–101.

(33) Shi, X.; Wang, L.; Guo, J.; Su, Q.; Zhao, X. Effects of inhibitor KCl on shale expansibility and mechanical properties. Petroleum 2019, 5, 407–412.

(34) Liu, H.; Cui, S.; Meng, Y.; Li, Z.; Yu, X.; Sun, H.; Zhou, Y.; Luo, Y. Rock mechanics and wellbore stability of deep shale during drilling and completion processes. J. Pet. Sci. Eng. 2021, 205, No. 108882.

(35) Simpson, J. P.; Dearing, H. L. Diffusion Osmosis: An unrecognized cause of shale instability. In IADC/SPE Drilling Conference, OnePetro, 2000, February.

(36) Zhang, J.; Chenevert, M. E.; Al-Bazali, T.; Sharma, M. M. A New Granivimetric – Swelling Test for Evaluating Water and Ion Uptake of Shales. SPE 89831 Presented at the SPE Annual Technical Conference and Exhibition held in Houston, Texas, USA, 26–29 September, 2004.

(37) Schuck, B.; Desbois, G.; Urai, J. L. Grain-scale deformation mechanisms and evolution of porosity in experimentally deformed Boom Clay. J. Struct. Geol. 2020, 130, No. 103894.

(38) Cano, A. C.; Van Stappen, J. F.; Wolterbeek, T. K.; Hangx, S. J. Uniaxial compaction of sand using 4D X-ray tomography: The effect of mineralogy on grain-scale compaction mechanisms. Mater. Today Commun. 2021, 26, No. 101881.