Rheological Properties of Cement Grouts and Bentonite Drilling Muds with and without Saltwater at Two Temperatures Predicted using Vipulanandan Models

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Abstract

Cement grouts are used in multiple applications such as installing pipes and wells, repairing infrastructures, treating and stabilizing soils and rocks and also treating contaminated soils. Drilling muds are used in installing various deep foundations, pipes, tunnels, drilling boreholes and in horizontal direction drillings even along the coastal regions. In this study, cement grouts with water-to-cement ratios of 1.0 and 1.5 were tested with and without 3.5% salt water. Also drilling muds with bentonite clay content of 4% and 6% were tested. Also the tests were performed at 25^{o}C and 75^{o}C. Based on the electrical impedance-frequency response, electrical resistivity was identified as the critical material property to monitor using the Vipulanandan Impedance Model for the cement grouts and the bentonite clay drilling muds. Immediately after mixing the resistivity of cement grouts with water-to cement ratio of 1.0 and 1.5 were 1.42 Ωm and 1.60 Ωm respectively and the salt water and temperature reduced the initial resistivity. The initial resistivity of the drilling muds with 4% and 6% bentonite were 5.5 Ωm and 4.5 Ωm respectively. Rheological tests showed that both fluids were non-Newtonian fluids and were shear thinning. The cement grouts yield stresses were higher than the yield stresses of the drilling muds. Salt water and higher temperature modified the rheological properties of the cement grouts and drilling muds. Vipulanandan rheological model was used to model the behaviors and the maximum shear stress tolerance (new parameter) for the cement grouts were higher than the drilling muds. Also the maximum shear stress tolerance of the drilling mud is an indicator of borehole cleaning (removing mud filtercakes) and also the potential for formation erosion. Vipulanandan rheological model predicted the cement grouts and drilling muds rheological behaviors very well based on the root mean square error (RMSE) and coefficient of variation statistical parameters.

Introduction

Cement grouts are widely employed to stabilize and treat soils and rocks through the injection of a cement-based mixture into the ground (Fan, et al., 2018). This method enhances the soil or rock's strength and load-bearing capacity, rendering it suitable for construction (Shareef, et al., 2023). Additionally, cement grouting effectively addresses contaminated soils by encapsulating and immobilizing contaminants, thereby averting their spread and reducing environmental hazards (Brusseau, 2019). Bentonite-based drilling muds are employed in the drilling of boreholes for wells and in horizontal directional drilling for the installation of pipes and tunnels across diverse infrastructures (Vipulanandan, et al, 2018). The performance of these drilling muds is influenced by several factors, such as changing geological conditions and environmental characteristics at different depths (Vipulanandan, et al., 2014a; Vipulanandan, et al., 2017). From the literature data, the utilization of bentonite in water-based drilling muds ranged from 0.5% to 14% (based on the weight of water), with more than 50% of the studies employing up to 6% bentonite in water-based drilling mud (Vipulanandan, et al., 2014a).

In some of the operations, the drilling using drilling mud is immediately followed by grouting. Hence, it is important to implement effective monitoring and tracking throughout the drilling process using drilling mud and subsequent grouting to minimize the detrimental effects of contamination. A new material characterization method has been developed to identify the critical electrical properties of the grouts and drilling muds so that these can be easily monitored in the field (Vipulanandan, et al., 2014b). Establishing the pumping pressures during the use of grouts and drilling muds is dependent on the rheological properties of these substances. Rheological properties such as viscosity, yield stress, shear thinning behavior, and thixotropy play a crucial role in determining the pumping pressures and overall performance of these materials during drilling operations (Tao, et al., 2020).

Researchers have employed various techniques, including ultrasonic methods, X-ray diffraction, scanning electron microscopy, and calorimetric analysis to monitor and characterize the behavior of cementitious materials (Vipulanandan, et al., 2014b). The electrical resistivity of cement is influenced by various factors, including pore solution composition, water-cement (w/c) ratio, temperature, and moisture content (Polder et al., 2001). Moreover, there is a growing interest in utilizing seawater in grouts in the coastal regions.

Objectives

The overall objective was to quantify the changes in the electrical resistivity and rheological properties of cement grouts and drilling muds under various temperatures. The specific objectives are as follows:

(1) Investigate and compare the rheological properties of cement grout mixtures with water-to-cement ratios of 1 and 1.5, with water based drilling mud with 4% and 6% Bentonite clay contents.
(2) Quantify the effects of 3.5% salt water (sea water) on the rheological properties of the cement grouts.
(3) Investigate the effects of temperatures at 25℃ and 75℃ on the rheological properties of the cement grouts and water based drilling muds.
(4) Modelling the rheological properties of these mixes using the Vipulanandan Rheological Model.

Materials and Methods

Sample Mixture and Specimen Preparation

In this study, Portland cement (PC) Type I was used along with two different water-to-cement ratios (1 and 1.5). Two sets of cement slurries were prepared: one with regular tap water and the other with 3.5% salt water. Bentonite clay was used to make the mud samples with 4% and 6% bentonite clay (by the weight of the water). After mixing, specimens were placed in cylindrical molds that were 50 mm in diameter and 100 mm in height. All molds were wired with two conductive wires (probes) placed 50 mm apart vertically. The testing approach was to measure the electrical properties of freshly mixed grouts and drilling muds immediately after mixing.

Rheological test

The rheology tests were performed using the rotational viscometers. The tests were performed by varying the rotational speed from 1 to 600 rpm, and the resulting shear stresses were measured. Also the samples were heated to the testing temperature in the viscometers. Prior to testing, the viscometers were calibrated using multiple standard solutions.

Electrical Resistivity

In previous studies conducted by Vipulanandan (2021), electrical resistivity was identified as the monitoring parameter to evaluate the performance of modified cement during the curing and hardening process. Two different devices were used to measure the electrical resistivity of the cement slurries and drilling mud. A digital resistivity meter was utilized for fluids, slurries, and semi-solids within the range of 0.01 Ω-m to 400 Ω-m. Additionally, a conductivity meter with a range of 0 to 199.9 μS/cm was used for comparison purposes. During the curing period, electrical resistance was measured using the LCR meter, minimizing contact resistances by using the twoprobe method at a frequency of 300 KHz. Each specimen was calibrated to determine the electrical resistivity (ρ) based on the measured electrical resistance (R), using Equation (1) (Vipulanandan, 2021):

$$\rho = \frac{R}{K+GR} \tag{1}$$

The material parameters K and G will be influenced by the type of solid or fluid material (conductive, semi conductive or insulator), chemical reactions and testing conditions such as temperature, pressure (stress) and contaminations (Vipulanandan 2021).

Rheological modeling

Vipulanandan rheological model (2014)

The drilling mud exhibited a non-linear shear thinning behavior accompanied by yield stress. Based on the test results, the model must satisfy the following conditions in order to accurately represent the observed behavior. Therefore, the conditions are as follows:

$$\tau = \tau_{\circ}, \text{ When } \dot{\gamma} = 0, \tag{2}$$

$$\frac{d\tau}{d\dot{\gamma}} > 0 \tag{3}$$

$$\frac{d^2\tau}{d\dot{\gamma}^2} < 0 \tag{4}$$

$$\text{When } \dot{\gamma} \rightarrow \infty, \text{ then } \tau = \tau^* \tag{5}$$

To meet the conditions specified in Equations (2), (3), (4), and (5), the Vipulanandan rheological model was formulated and developed as follows (Afolabi et al. 2019; Tchameni et al. 2019; Vipulanandan et al. 2014a):

$$\tau = \tau_{\circ} + \left[\frac{\dot{\gamma}}{A+B\dot{\gamma}}\right] \tag{6}$$

where: τ : shear stress (Pa); τ_o: yield stress (Pa); A $(Pa.\ s)^{-1}$ and B $(Pa)^{-1}$: are model parameters; $\dot{\gamma}$: shear strain rate (s^{-1}). This is the only model that also predicts the maximum shear stress (τ_{max}) that the cement grouts and drilling muds can generate or withstand under high shear strain rates:

$$\text{When } \dot{\gamma} \rightarrow \infty, \text{ then } \tau_{max} = \tau_{\circ} + \left[\frac{1}{B}\right]$$

Results and Discussions

Electrical Resistivity

Preliminary test were performed for 30 minutes to measure the resisitivity and resistance of the cement slurries and drilling muds (all fluids). Test results showed that the parameter G was zero for the tested cement slurries and drilling muds. The parameter K was contant but was senetive to the water-to cement ratio and bentonite clay content. As summarized in Table 1, increasing the water-to-cement ratio from 1 to 1.5 for the cement grout resulted in an increase in the intial electrical resistivity from 1.42 Ω -m to 1.60 Ω -m. Both mixes experienced a reduction in electrical resistivity when 3.5% salt was added, with the values decreasing to 0.52 and 0.16 Ω -m, corresponding to a 63% and 90% reduction, respectively. For the drilling mud the initial electrical resistivity decreased from 5.5 Ω -m to 4.5 Ω -m at 25°C when the bentonite content was increased from 4% to 6%, as summarized in Table 1.

Table 1 The pH and Initial Resisitivity of Grouts and Drilling Muds

Mixtures	pH	Initial Resisitivity (Ωm)
Grout (w/c = 1.0)	11.72	1.42

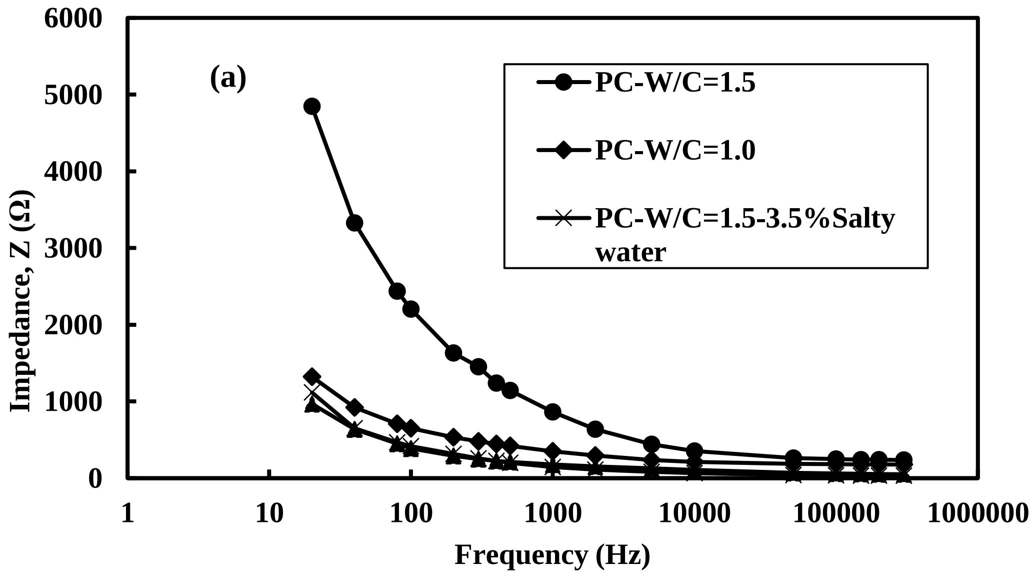
Grout (w/c = 1.5)	11.46	1.60
Grout (w/c = 1.0) with 3.5% salt water	11.45	0.52
Grout (w/c = 1.5) with 3.5% salt water	11.51	0.16
Drilling Mud (4% Bentonite)	6.74	5.5
Drilling Mud (6% Bentonite)	7.66	4.5

pH

As summarized in Table 1, increasing the water-to-cement ratio from 1 to 1.5 in the grout decreased the pH from 11.72 to 11.46. With the addition of 3.5% salt, the grout with a water-to-cement ratio of 1.0 the pH decreased to 11.45. In the grout mix with a water-to-cement ratio of 1.5 the pH increased slightly to 11.51. In the drilling mud the pH increased from 6.74 to 7.66 at 25°C when the bentonite content was raised from 4% to 6%, as summarized in Table 1.

Material Characterization

In Figure 1(a) the impedance-frequency relationship for the cement grouts with and without 3.5% salt at water-to-cement ratio of 1 and 1.5. At extremely high frequencies ($\omega \rightarrow \infty$), the impedance tends towards the bulk resistance of the grout, while at very low frequencies ($\omega \rightarrow 0$), it approaches $R_b + 2R_c$ using the Vipulanandan Impedance Model (Vipulanandan 2021). This indicates that the grout material can be represented by resistance (resistivity). In Figure 1(b) shows similar behavior for the Bentonite clay drilling muds. It is also evident that the 6% drilling mud the electrical impedance at various frequencies decreased compared to the 4% drilling mud and also to the impedance of tap water. Hence, using the electrical impedance-frequency characterization method with the two probes and using the Vipulanandan Impedance Model indicated that resistivity was the critical electrical property for all the cement grouts and drilling clay muds.



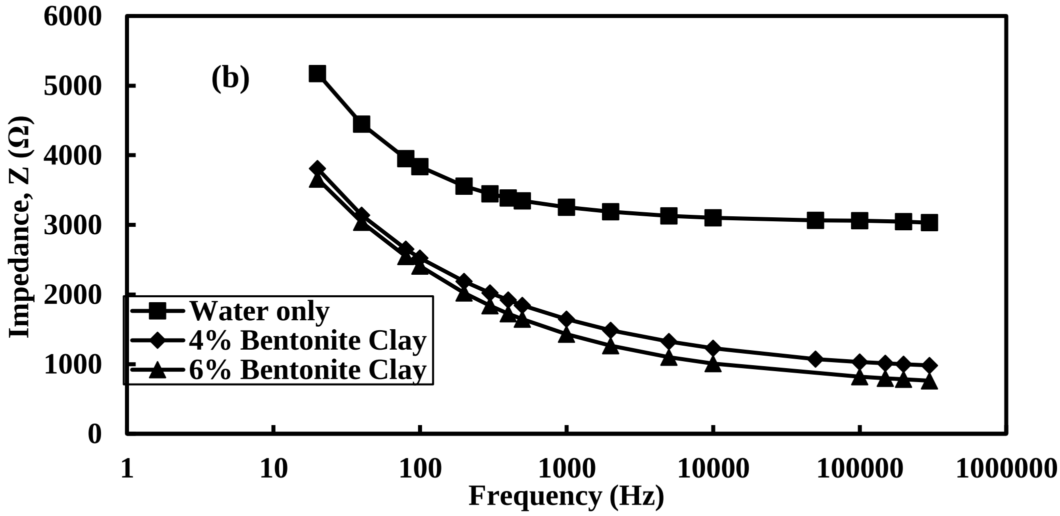


Figure 1. Impedance-Frequency Responses at 25°C (a) Cement grouts and (b) Bentonite Clay drilling muds.

Rheological Properties

(a). Cement Grouts

Effect of Temperatures and 3.5% Salt Water (Sea Water)

(i). Grout (water-to-cement ratio = 1.0)

The Vipulanandan Rheological model was used to predict the shear thinning behavior of cement grouts with a water-to-cement ratio of 1.0 at temperatures of 25°C and 75°C as shown in Figure 2a. The model achieved a coefficient of determination (R^2) of 1.00, indicating a perfect fit. The root means square of error (RMSE) ranged from 0.41 Pa to 0.21 Pa, as summarized in Table 2. The yield stresses (τ_o) of the cement grout at 25°C and 75°C were 6.4 Pa and 4.4 Pa, respectively, showing a reduction of 31%. The model parameter A for the cement grouts at 25°C and 75°C were 4.5 and 11.4, respectively, representing a 153% increase with temperature increase (Table 2). The model parameter B for the cement grouts at 25°C and 75°C were 0.02 and 0.03, respectively, indicating a 50% increase as the temperature increased (Tabl 2).

(ii). Grout (water-to-cement ratio = 1.0) and 3.5% Salty water

The Vipulanandan Rheological model was used to predict the shear thinning behavior of cement grouts with a water-to-cement ratio of 1.0 and 3.5% salty water at temperatures of 25°C and 75°C as shown in Figure 2b. The model achieved a coefficient of determination (R^2) of 1.00, indicating a perfect fit. The root means square of error (RMSE) ranged from 0.58 Pa to 0.41 Pa, as summarized in Table 2. The yield stresses (τ_o) of the cement grout at 25°C and 75°C were 5.74 Pa and 3.9 Pa, respectively, showing a reduction of 32%. The model parameter A for the cement grouts at 25°C and 75°C were 4.17 and 11.2, respectively, representing a 168% increase with temperature. The model parameter B for the cement grouts at 25°C and 75°C were 0.02 and 0.03, respectively, indicating a 50% increase as the temperature increased (Table 2).

Table 2. Vipulanandan Rheological model parameter for cement grouts.

Mix (Grouts)	Temperature (˚C)	Vipulanandan Rheological Model					
		τ_o (Pa)	A	B	τ_{max} (Pa)	RMSE (Pa)	R^2
W/C=1.0	25	6.44	4.53	0.02	64.92	0.41	1.00
W/C=1.0-3.5% Salt	25	5.74	4.17	0.02	61.44	0.58	1.00
W/C=1.5	25	5.19	4.06	0.02	62.59	0.31	1.00
W/C=1.5-3.5% Salt	25	2.40	3.04	0.02	57.31	0.80	1.00
W/C=1.0	75	4.50	11.45	0.03	42.36	0.21	1.00
W/C=1.0-3.5% Salt	75	3.90	11.22	0.03	41.22	0.41	1.00
W/C=1.5	75	4.50	11.73	0.03	42.39	0.36	1.00
W/C=1.5-3.5% Salt	75	2.00	8.54	0.03	36.56	0.34	1.00

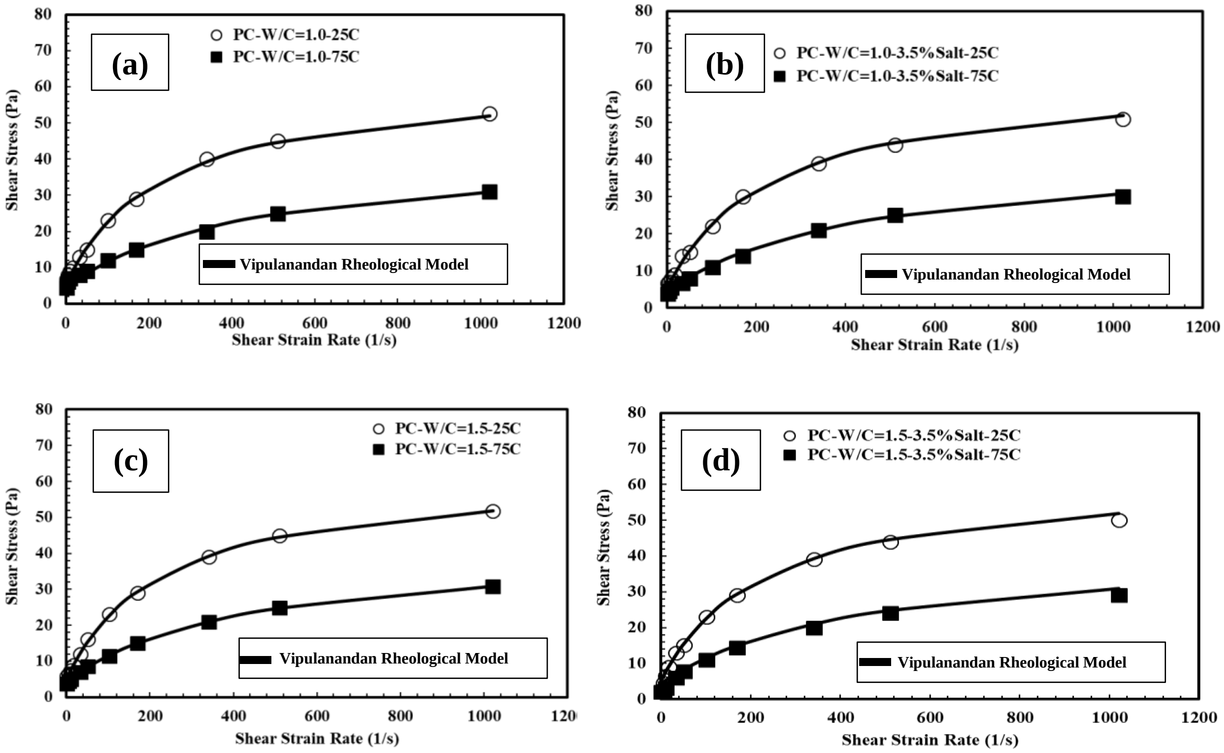


Figure 2 Measured and Predicted shear stress-shear strain rate relationship for Cement grouts at 25C and 75C (a) w/c =1.0, (b) w/c=1.0 with 3.5%Salt, (c) w/c=1.5 and (d) w/c=1.5 with 3.5%salt.

(iii). Grout (water-to-cement ratio = 1.5)

The Vipulanandan Rheological model was used to predict the shear thinning behavior of cement grouts with a water-to-cement ratio of 1.5 at temperatures of 25°C and 75°C as shown in Figure 2c. The model achieved a coefficient of determination (R^2) of 1.00, indicating a perfect fit. The root means square of error (RMSE) ranged from 0.31 Pa to 0.36 Pa, as summarized in Table 2. The yield stresses (τ_o) of the cement grout at 25°C and 75°C were 5.2 Pa and 4.5 Pa, respectively, showing a reduction of 13.5%. The model parameter A for the cement grouts at 25°C and 75°C were 4.1 and 11.7, respectively, representing a 185% increase with temperature increase. The model parameter B for the cement grouts at 25°C and 75°C were 0.02 and 0.03, respectively, indicating a 50% increase as the temperature increased (Table 2).

(iv). Grout (water-to-cement ratio = 1.5) and 3.5% Salty water

The Vipulanandan Rheological model was used to simulate the shear thinning behavior of cement grouts with a water-to-cement ratio of 1.5 and 3.5% salty water at temperatures of 25°C and 75°C as shown in Figure 2d. The model achieved a coefficient of determination (R^2) of 1.00, indicating a perfect fit. The root means square of error (RMSE) ranged from 0.8 Pa to 0.34 Pa, as summarized in Table 2. The yield stresses (τ_o) of the cement grout at 25°C and 75°C were 2.4 Pa and 2.0 Pa, respectively, showing a reduction of 16.7%. The model parameter A for the cement grouts at 25°C and 75°C were 3.04 and 8.54, respectively, representing a 181% increase with temperature increase. The model parameter B for the cement grouts at 25°C and 75°C were 0.02 and 0.03, respectively, indicating a 50% increase as the temperature rose.

(b). Drilling Muds
Effect of Temperatures

(i). 4% Bentonite Clay (Ben)

The Vipulanandan Rheological model was used to predict the shear thinning behavior of 4% Bentonite drilling mud at temperatures of 25°C and 75°C as shown in Figure 3a. The model coefficient of determination (R^2) was 1.00, indicating very good predictions. The root mean square of error (RMSE) ranged from 0.05 Pa to 0.06 Pa, as summarized in Table 3. The yield stresses (τ_o) of the drilling mud at 25°C and 75°C were 1.4 Pa and 4.08 Pa, respectively, showing an increase of 191%. The model parameter A for the drilling mud at 25°C and 75°C were 69.7 and 72.5, respectively, representing a 4% increase with temperature increase. The model parameter B for the drilling mud at 25°C and 75°C were 0.06 and 0.07, respectively, indicating a 16.5% increase as the temperature increased (Table 3).

(ii). 6% Bentonite Clay (Ben)

The Vipulanandan Rheological model was used to simulate the shear thinning behavior of 6% Bentonite drilling mud at temperatures of 25°C and 75°C as shown in Figure 3b. The model coefficient of determination (R^2) was 1.00, indicating very good predictions. The root mean square of error (RMSE) ranged from 0.13 Pa to 0.15 Pa, as summarized in Table 3. The yield stresses (τ_o) of the drilling mud at 25°C and 75°C were 2.8 Pa and 11.9 Pa, respectively, showing an increase of 325%. The model parameter A for the drilling mud at 25°C and 75°C were 31.4 and 44.9, respectively, representing a 43% increase with temperature increase. The model parameter B for the drilling mud at 25°C and 75°C was 0.03 for both temperatures.

Table 3 Vipulanandan Rheological model parameter for drilling mud.

Mix	**Temperature (˚C)**	**Vipulanandan Rheological model**					
		τ_o (Pa)	**A**	**B**	**τ_{max} (Pa)**	**RMSE (Pa)**	**R^2**
4%Ben	25.00	1.40	69.73	0.06	17.74	0.05	1.00
6%Ben	25.00	2.80	31.44	0.03	40.99	0.15	1.00
4%Ben	75.00	4.08	72.49	0.07	18.40	0.06	1.00
6%Ben	75.00	11.90	44.93	0.03	47.70	0.13	1.00

(c). Yield shear stress

At 25°C, the yield stress (τ_0) for the cement grout with water-to-cement ratios of 1.0 and 1.5 were 6.44 Pa and 5.19 Pa, respectively, as summarized in Table 4. When the temperature increased to 75°C, the yield stress for both the mixtures decreased to 4.5 Pa. With 3.5% salt water the yield stress decreased to 5.74 Pa and 2.40 Pa for the mixtures with water-to-cement ratios of 1.0 and 1.5, respectively at 25°C. Similarly at 75°C, with 3.5% salt water the yield stress decreased to 3.90 Pa and 2.00 Pa for the mixtures with water-to-cement ratios of 1.0 and 1.5, respectively.

For the drilling mud, at a temperature of 25°C, the yield stress (τ_0) for the mud containing 4% and 6% bentonite were 1.40 Pa and 2.80 Pa, respectively, as summarized in Table 4. Increasing the temperature from 25°C to 75°C raised the yield stress for the mud with 4% and 6% bentonite to 4.08 Pa and 11.90 Pa, respectively.

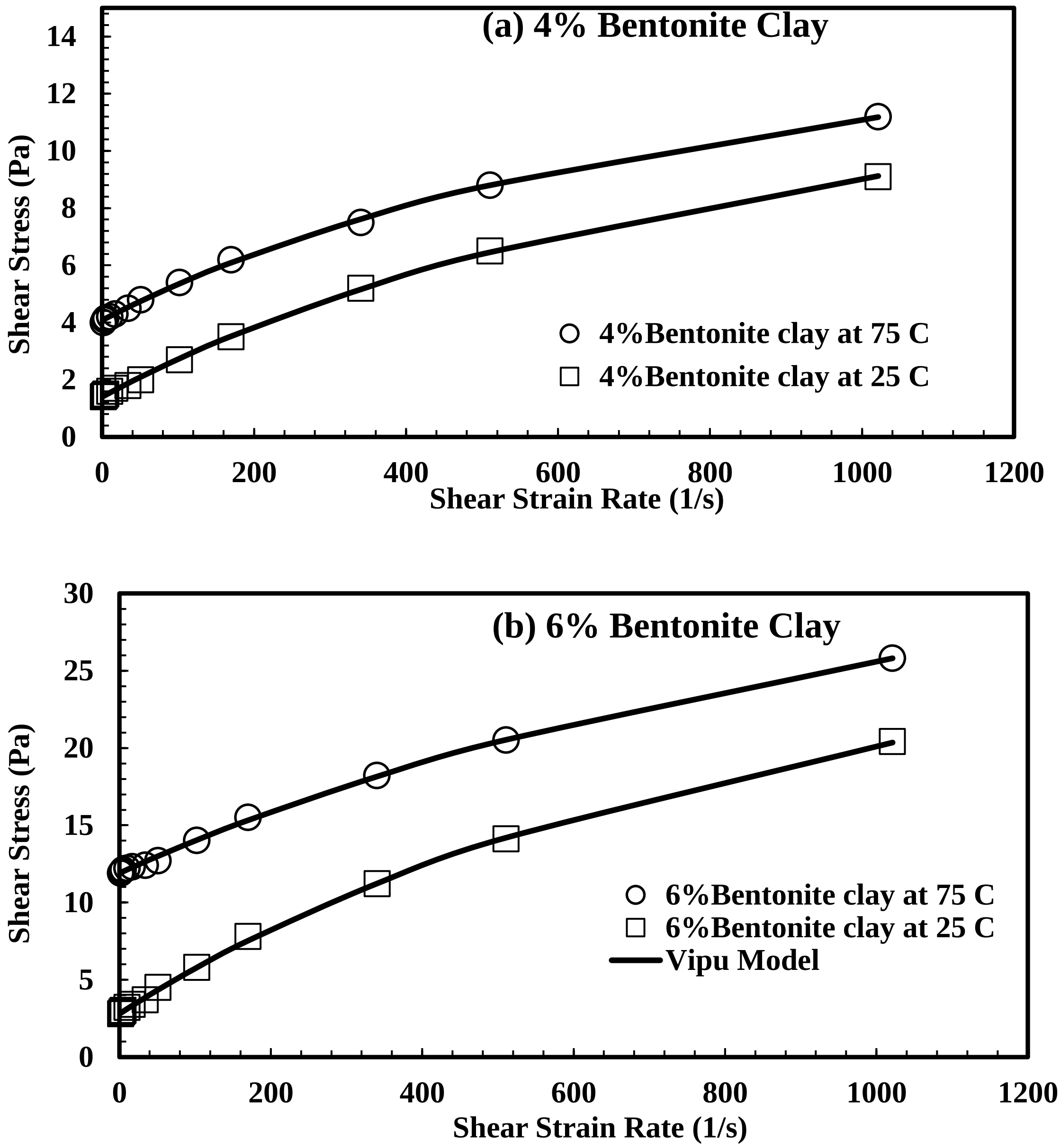


Figure 3. Predicted and measured shear stress-shear strain rate relationship for Bentonite Drilling mud (a) 4% BentoniteClay and (b) 6% BentoniteClay.

(d). Maximum shear stress

At 25°C, the maximum stress (τ_{max}) for the cement grout with water-to-cement ratios of 1.0 and 1.5 was 64.92 Pa and 62.59 Pa respectively, as summarized in Table 4. When the temperature increased to 75°C, the maximum stress for both mixtures decreased to about 42.4 Pa. With 3.5% salt water it further reduced in maximum stress to 61.44 Pa and 57.31 Pa for the mixtures with water-to-cement ratios of 1.0 and 1.5 respectively at 25°C. Similarly at 75°C with 3.5% salt water the maximum stress decreased to 41.22 Pa and 36.56 Pa for the mixtures with water-to-cement ratios of 1.0 and 1.5 respectively.

Regarding the drilling mud, at a temperature of 25°C, the maximum stress (τ_{max}) for the mud containing 4% and 6% bentonite were 17.7 Pa and 41 Pa, respectively, as summarized in Table 4. Increasing the temperature from 25°C to 75°C raised the maximum stress for the mud with 4% and 6% bentonite to 18.40 Pa and 47.70 Pa, respectively (Table 4).

Table 4 The Yield Stress and Maximum Shear Stress for the Grouts and Drilling Muds

Mixtures	Temperature (°C)	Yield stress (Pa)	Maxium Shear Stress (Pa)
Grout (w/c = 1.0)	25	6.44	64.92
	75	4.50	42.36
Grout (w/c = 1.5)	25	5.19	62.59
	75	4.50	42.39
Grout (w/c = 1.0) with 3.5% salt water	25	5.74	61.44
	75	3.90	41.22
Grout (w/c = 1.5) with 3.5% salt water	25	2.40	57.31
	75	2.00	36.56
Drilling Mud (4% Bentonite)	25	1.40	17.74
	75	4.08	18.40
Drilling Mud (6% Bentonite)	25	2.80	40.99
	75	11.90	47.70

Conclusions

Based on this study on the testing and modeling the cement grouts and drilling bentonite caly drilling muds following conclusions are advanced:

1. For the cement grouts and drilling muds the critical electrical property was resisitivy based on the impedance-frequency responses.. The drilling muds with 4% and 6% Bentonite clay exhibits greater impedance values compared to cement grouts with a water-to-cement ratio of 1.0 and 1.5. The initial resisitivity was sensitive to the type of matrial and the compositions.
2. For the cement grouts increasing the water-to-cement ratio from 1.0 to 1.5 decreased yield stress and maximum shear stress.
3. For the cement grouts with 3.5% salty water (representing sea water) there was notable reduction in the yield stress and maximum shear stress.
4. Inceasing the temperature from 25^{o}C to 75^{o}C resulted in a reduction of the maximum shear stress of the cement grout mixes with water-to-cement ratios of 1.0 and 1.5.
5. The maximum shear stress for the drilling mud containing 4% Bentonite clay was much lower compared to the grouts with a water-to-cement ratio of 1.0 and 1.5.

6. The 6% Bentonite clay drilling mud had higher yield stress and maximum shear stress compared to the 4% drilling mud.
7. Increasing the temperature from $25^{o}C$ to $75^{o}C$ increased in the yield stress and maximum shear stress of the drilling muds containing 4% and 6% Bentonite clay.

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