

## Nanoclay Modified Drilling Muds for HPHT Applications

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### Abstract

In this study, the effect temperature on the electrical resistivity and rheological properties of nanoclay modified water based bentonite drilling muds were investigated. Based on the experimental and analytical study the electrical resistivity was identified as the sensing property of the drilling mud so that the changes in the properties can be monitored in real-time during construction. The bentonite contents in the drilling muds were varied up to 8% by the weight of water and temperature was varied from 25°C to 85°C. The nanoclay content was varied between 0 and 0.6% by the weight of the drilling mud to modify the rheological properties and enhance the sensing electrical resistivity of the drilling mud. The results also showed that 0.6% nanoclay decreased the electrical resistivity of the drilling mud from 15% to 36% based on the bentonite content in the drilling mud. The electrical resistivity of the drilling mud with and without nanoclay decreased with the increase in the temperature. The nanoclay modification increased the yield point (YP) and plastic viscosity (PV) by 30% to 61% and 12% to 37% respectively based on the nanoclay content, bentonite content and temperature of the drilling mud. The rheological properties of the drilling muds have been correlated to the electrical resistivity of the drilling mud using nonlinear power and hyperbolic relationships. The model predictions agreed well with the experimental results. Hence the performance of the bentonite drilling muds with and without nanoclay can be characterized based on the electrical resistivity which can be monitored real-time in the field.

### Introduction

The growing concerns about performance, safety and environment pollution have urged the drilling technologists to look for solutions beyond the current methods and technologies for oil and gas extractions from both onshore and offshore reservoirs. Industry needs great discoveries in underlying core science and engineering as the search for hydrocarbon sources has become extreme in terms of going deeper and hence higher pressure and temperature.

Water based drilling fluids, especially water-bentonite suspensions have been used in the oil, gas and geothermal drilling industry for decades. Multi-functional drilling muds are required to transport the rock cuttings to the surface, lubricate and cool the drill bit and apply hydrostatic pressure

in the well bore to ensure well safety. The deeper wells that are being drilled calls for more advanced drilling fluids because of the changes in pressure, temperature and geology with depth. Common viscosifiers used in water based drilling muds are bentonite and /or polymers. The drilling fluid can react with certain types of formation or the pressure can cause the rock to crack, leading to massive loss of fluid into the formation (Riveland 2013). Hence there needs to not only enhance the performance of bentonite based drilling mud but also monitor the performance of the drilling muds during the drilling operations.

Bentonite has been used worldwide as drilling fluid additive (Abdou et al. 2013; Vipulanandan and Mohammed 2014). The main function of the bentonite is to increase the viscosity of the mud and to reduce the fluid loss to the formation. A good quality bentonite should contain mainly montmorillonite (Brigatti et al. 2006). Bentonite often contains other clay minerals such as illite and kaolinite and non-clay components such as quartz and feldspar. Because the sodium based montmorillonite clays have the highest swelling capacity (which is responsible for viscosity build up and formation of low permeability filter cake); the presence of other materials will have an adverse effect on bentonite quality (Abdou et al. 2013). The type of exchangeable ions has a great effect on the swelling capacity of the montmorillonite. If the mineral composition of bentonite is such that its viscosifying power is insufficient, various additives such as nanoclay or polymer can be added (Murray 2006). The application of bentonite in drilling fluids causes many problems, such as porosity and permeability reduction and wettability alteration. Hence, a mud cake with high quality (low permeability and optimum thickness) should be formed. Otherwise, low quality cake causes many problems in drilling operations: for example, it makes stable cake which causes damage to formation. Considering the mentioned problems that occur during drilling operations, this study were carried out on the effect of nanoclay on drilling fluids' rheology. Although many studies on nanoclay have been published, there is no comparative report about its sensibility in drilling muds.

Nanoparticles with noticeable alterations in optical, magnetic and electrical properties are excellent tools for the development of sensors and the formation of imaging contrast (Krishnamoorti 2006). Since the nanoparticles are extremely small in size, nanoparticles are preferred to be used in drilling

mud design as their abrasive forces are negligible with less kinetic energy impact. In addition to many advantages of using nanoparticles in mud design it is safer than conventional mud from the point of environmental view. The nanoparticles are added to mud in small amount, with low concentration of the order of 1%. Nano-based drilling muds could be the fluid of choice in conduction drilling operations in sensitive environments to protect other natural resources (Amanullah et al. 2011). The nanoclay particles can go in between the larger particles and block the flow through them (Riveland 2013). During the past decade the nanomaterial has been used to improve the performance and functionality of a variety of engineering materials used in solar, biomedical, thermoelectric and environmental applications (Liu et al. 2013; Nazzal et al. 2013). Nanoclay is defined as having particle size in the range of 1 to 100 nm. Because montmorillonite clay is hydrophilic, it is not compatible with most polymers and must be chemically modified to make its surface more hydrophobic (Bhat et al. 2012). The use of nanoclay has attracted great interest in the polymer industry during the past decade as polymer modified clay exhibited much better mechanical properties when compared with virgin polymer or conventional micro and macrocomposites (Rehab and Salahuddin 2005; Mohammed and Vipulanandan 2014). Mathematical modeling studied concerning the well and pipeline flow of thixotropic drilling muds and crude oils. Drilling muds (oil-based muds, water-based muds) exhibit complex rheological behavior (Bingham or Herschel–Bulkley model). The limitations of the mathematical modeling studies concerning thixotropic drilling mud and crude oil flows have two main causes. Despite recent advancements in tools such as quality HTHP/LT (high-temperature/high-pressure/low temperature) viscometers, a unified rheological model valid for a wide range of pressures, temperatures, and flow regimes which could account for complex rheological effects such as thixotropic and yield stress still does not exist (Livescu 2012).

In this study, enhancing the sensing and rheological properties of bentonite drilling mud modified with nanoclay at different temperatures were tested and quantified with the electrical resistivity of the drilling mud.

## Objectives

The overall objective was to quantify the effect of temperature on the electrical resistivity and rheological properties of bentonite drilling mud modified with nanoclay. The specific objectives are as follows:

- (i) Evaluate the effect of nanoclay on the electrical resistivity (nondestructive and sensing properties) and rheological properties of the bentonite drilling muds at different temperatures.
- (ii) Investigate the relationship between electrical resistivity of the drilling mud and the rheological properties of the bentonite drilling mud so that it can be used as a real – time monitoring parameter.

## Materials and Methods

### Electrical Resistivity

In this study, two different resistivity devices were used to measure the electrical resistivity of drilling mud. A digital resistivity meter was used to measure the resistivity of fluids, slurries, and semi-solids with resistivities in the range of  $0.01 \Omega\text{-m}$  to  $400 \Omega\text{-m}$ . Also a conductivity meter with conductivity (inverse of resistivity) in the range of 0 to  $199.9 \mu\text{S/cm}$  was also used to compare the results. The electrical resistivity of the modified drilling mud with nanoclay was measured using the resistivity meter and conductivity meter at various temperatures. Both of the devices were calibrated using standard sodium chloride (NaCl) solution.

### Rheological Properties

The rheological properties yield point (YP), plastic viscosity (PV), apparent viscosity (AV), gel strength 10 sec (Gel 10'') and gel strength 10 min (Gel 10') of the drilling mud were measured. The bentonite content in drilling mud was varied up to 8% by the weight of water. Bentonite drilling mud modified with varying amount of nanoclay up to 0.6% by total weight of drilling mud were tested in the temperature range of  $25^{\circ}\text{C}$  to  $85^{\circ}\text{C}$  using a viscometer with the speed range of 0.3 to 600 rpm.

### HTHP Filtrate Measurement

Measuring the HTHP fluid loss of a drilling mud involves heating the fluid in a controlled environment to a temperature that is expected in the well. When test temperature was reached, long term filtrate volume was determined at a temperature differential to simulate downhole conditions. The equipment designed for this purpose includes a heating jacket (with a bimetallic thermostat) a cell to contain the fluid, a means to pressurize the cell and a means of collecting filtrate. Gauging the effect of temperature on the fluid filtrate volume is the main purpose of the HTHP test and accurate temperature measurements are required. Thermocouple device was used to monitor the fluid temperature the fluid in the cell. Test results indicated the fluid temperature met the targeted test temperature within the API recommended one hour heat up period for the 500 mL HTHP cell. The filtrate volume was measured according to API specification 13A. Long term fluid loss was modeled using Eqn. (1).

$$FL = \frac{t}{F + H * t}$$

(1)

where:

FL: fluid loss (mL).

t : time (min).

F and H: model parameters.

Model parameters, coefficient of determination ( $R^2$ ) and root mean square error (RMSE) are summarized in Table 2.

## Modeling

### (i) Bingham Plastic Model

The Bingham plastic model was the first two-parameter model that gained widespread acceptance in the drilling industry and is represented as follows.

$$\tau = YP + PV * \dot{\gamma}$$

(2)

where:

$\tau$  : shear stress (Pa).

YP: yield point (Pa).

PV: plastic viscosity (cP).

$\dot{\gamma}$  : shear strain rate ( $s^{-1}$ ).

### (ii) Nonlinear Model Parameters (NLM)

The electrical resistivity ( $\rho$ ) of drilling mud using bentonite (B), nanoclay (NC) was influenced by the composition of the drilling muds and temperature (T ( $^{\circ}C$ )). It is being proposed to relate the model parameters to the independent variables (bentonite content and nanoclay content) using a nonlinear power relationship as proposed by Vipulanandan and Mohammed (2014).

Hence the effects of bentonite and nanoclay on the electrical resistivity of the drilling muds were separated as follows:

$$\rho = k * (B)^a * (T)^b + q * (B)^c * (T)^d * (NC)^e \quad (3a)$$

Based on 63 data from the current study and using nonlinear optimization following relationship was obtained:

$$\rho = 29.8 * (B)^{0.64} * (T)^{-0.23} - 60.3 * (B)^{-2.9} * (T)^{-0.2} * (NC)^{0.5} \quad (3b)$$

For ( $25^{\circ}C \leq T \leq 85^{\circ}C$ )

The NLM parameters were obtained from multiple regression analyses using the least square method. The relation between experimental and predicted data of the electrical resistivity ( $\rho$ ) of drilling mud using Eqn. (3b) shown in Fig. 1 and the coefficient of determination for the 63 data was 0.89.

### (iii) Correlation between Rheological Properties and Electrical Resistivity

Changes in rheological properties with temperature for the bentonite drilling mud modified with nanoclay can be related to the electrical resistivity as follows:

$$YP \text{ or } PV \text{ or } AV \text{ or } Gel_{10} \text{ or } Gel_{10}'' = h * (\rho)^m + p * (\rho)^q \quad (4)$$

where:

YP: yield stress (Pa).

PV: plastic viscosity (cP).

AV: apparent Viscosity (cP).

$Gel_{10}''$ : Gel strength at 10 s (Ib/100ft<sup>2</sup>).

$Gel_{10}'$ : Gel strength at 10 min (Ib/100ft<sup>2</sup>).

$\rho$ : electrical resistivity of drilling mud using Eqn. (3).

h, m, p and q are model parameters and are summarized in Table 1.

### (iv) Hyperbolic Resistivity Model

Usluogullari and Vipulanandan (2012) used the hyperbolic relationship to represent the variation of compressive strength with curing time for cemented sand.

Mohammed and Vipulanandan (2014) used the hyperbolic relationship to predicate the relation between compressive and tensile strength of sulfate contaminated CL soils with and without polymer treatment. Vipulanandan and Mohammed (2014) used hyperbolic relationship to predicate the maximum shear stress limit for the bentonite drilling mud modified with acrylamide polymer.

Based on the inspection of the test data following relationship is proposed:

$$Y = A - \frac{\rho}{C + D * \rho}$$

(5)

where:

Y: rheological properties of modified drilling mud with nanoclay at different temperature ranging between  $25^{\circ}C$  to  $85^{\circ}C$ .

$\rho$ : electrical resistivity of modified drilling mud (Eqn. 3).

A, C and D: model parameters are summarized in Table 1 (units are based on the predicting rheological property).

### Comparison of Model Predictions

In order to determine the accuracy of the model predictions with the experimental data, both coefficient of determination ( $R^2$ ) and the root mean square error (RMSE) in curve fitting as defined in Eqns. (6) and (7) were quantified as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{N}}$$

(6)

$$R^2 = \left( \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 * \sum_i (y_i - \bar{y})^2}} \right)^2$$

(7)

where  $y_i$  = experimental test value;  $x_i$  = predicted value by the model;  $\bar{y}$  = mean of the experimental test values;  $\bar{x}$  = mean of the predicted values and N is the number of data points.

### Results and Discussions Electrical Resistivity

Increasing the bentonite content (B) and nanoclay content (NC) in the drilling mud nonlinearly decreased the electrical resistivity. Increasing the bentonite content from 0 to 1% reduced the electrical resistivity of drilling mud from  $19.5 \Omega$ -m to  $10.4 \Omega$ -m, a 46% reduction. The electrical resistivity decreased from  $7.5 \Omega$ -m to  $3.3 \Omega$ -m when bentonite content was increased from 2% to 8% at  $25^{\circ}C$  as shown in Fig. 2. Increasing bentonite content from 2% to 8% (by weight of water) reduced the electrical resistivity by about 56% as shown in Fig. 2. Hence the electrical resistivity is a good tool for quality control for the drilling mud. This is a clear indication of the sensitivity of electrical resistivity to the bentonite and nanoclay contents and was represented as follows:

$$\rho = 19.5 - \frac{B(\%)}{0.06 + 0.056 * (B\%)} \quad R^2 = 0.99, \quad \text{No. of data} = 10$$

(8)

$$\rho = 19.5 - \frac{NC(\%)}{0.013 + 0.08 * (NC\%)} \quad R^2=0.99, \text{ No. of data}=9$$

(9)

With increasing the temperature from 25°C to 85°C the electrical resistivity of drilling mud with 6% of bentonite decreased by 24%. Additional of 0.6% of nanoclay to drilling mud with 6% of bentonite the electrical resistivity ( $\rho$ ) decreased by 28% at room temperature. With increasing of bentonite, nanoclay and temperature the electrical resistivities of drilling mud nonlinearly decreased as shown in Fig. 2. Another nonlinear relationship (Eqn. (10)) was used to predict the electrical resistivity ( $\rho$ ) with increasing the nanoclay and temperature of drilling mud (Fig. 2). Model parameters were correlated with bentonite and nanoclay content as shown in Eqns. 11 and 12.

$$\rho = \beta(T)^{-\alpha} \quad (10)$$

$$\beta = 28.6 * (B)^{-0.72} - 0.00015 * (B)^{-5.7} * (NC)^{-8.7}$$

No. of Data=11,  $R^2=0.94$  (11)

$$\alpha = 2.7E - 5 * (B)^{4.14} + 0.64 * (B)^{-0.65} * (NC)^{0.4}$$

No. of Data=11,  $R^2=0.86$  (12)

where:

$\rho$ : electrical resistivity of modified drilling mud at different temperatures ( $25^\circ\text{C} \leq T \leq 85^\circ\text{C}$ ).

$\beta$  and  $\alpha$  are model parameters.

## Rheological Properties

Rheology of the drilling mud formulated with different percentages of bentonite (B) up to 8%, and varying the amount of nanoclay (NC) up to 0.6% at different temperatures were studied. Yield point (YP), plastic viscosity (PV), apparent viscosities (AV), and gel strengths (Gel) were measured according to API specifications. YP and PV were determined based on Bingham plastic model. Rheology properties of the drilling muds are summarized as follows:

### (a) Yield Point (YP)

Additional of bentonite and nanoclay increased the yield point (YP) of the drilling mud. YP of drilling mud increased from 2 Pa to 31 Pa when the bentonite content changed from 2% to 8% at 25°C. Additional of 0.2% of nanoclay to drilling mud with 2% and 8% bentonite increased the yield point (YP) by 10% and 21% respectively at room temperature. The YP of drilling mud with 2% and 8% bentonite content modified with 0.2% nanoclay decreased by 80 % and 48% respectively with increasing the temperature from 25°C to 85°C as shown in Fig. 3. Additional of 0.6% of nanoclay the yield point (YP) increased from 13% to 62% based on the bentonite content in the drilling mud at a temperature of 25°C as shown in Fig.3. The electrical resistivity of drilling mud decreased while the yield point (YP)

increased as shown in Fig. 8 (a). The relationships between yield point and electrical resistivity for drilling mud based bentonite modified with nanoclay at temperature varied from 25°C to 85°C was modeled using the NLM (Eqn. (4)) and hyperbolic relationship (Eqn. (5)). The coefficient of determination ( $R^2$ ) for the NLM and hyperbolic models were 0.83 and 0.82 respectively. The root mean squares of error (RMSE) for the NLM and hyperbolic models were 3.63 Pa and 3.57 Pa respectively as summarized in Table 1.

### (b) Plastic Viscosity (PV)

The PV for the drilling muds with 2%, 4%, 6% and 8% of bentonite content were 6.7 cP, 13.6 cP, 28 cP and 47.6 cP respectively. When the bentonite of drilling mud with 2% and 8% bentonite was modified using 0.6% nanoclay (by total weight of drilling mud) at room temperature PV was increased by 37% and 27% respectively as shown in Fig. 4. Increasing the temperature from 25°C to 85°C for drilling mud with 8% of bentonite modified with 0.6% of nanoclay decreased the PV from 65 cP to 47 cP. The relationships between plastic viscosity and electrical resistivity for the drilling mud based bentonite modified with nanoclay at temperature varied from 25°C to 85°C was modeled using the NLM (Eqn.(4)) and hyperbolic relationship (Eqn. (5)) and the coefficients of determination ( $R^2$ ) for the NLM and hyperbolic models were 0.83 and 0.78 respectively. The root mean squares of error (RMSE) were 6.64 cP and 4.23 cP for the NLM and hyperbolic relationships respectively as summarized in Table 1.

### (c) Apparent Viscosity (AV)

The apparent viscosity of control drilling mud with 2%, 4%, 6% and 8% of bentonite at room temperature were 7.7 cP, 19.7 cP, 41.2 cP and 63.1 cP respectively. Bentonite drilling mud with 0.6% nanoclay (by total weight of drilling mud) at room temperature increased AV from 18% to 42% based on the amount of bentonite in the drilling mud. Increasing the temperature from 25°C to 85°C for drilling mud with 8% of bentonite modified with 0.6% of nanoclay decreased the AV from 88.2 to 62.7 cP as shown in Fig. 5 (b). The relationships between apparent viscosity and electrical resistivity for drilling mud based bentonite modified with nanoclay at temperature varied from 25°C to 85°C was modeled using the NLM (Eqn. (4)) and hyperbolic relationship (Eqn. (5)). The coefficients of determination ( $R^2$ ) for the NLM and hyperbolic models were 0.84 and 0.82 respectively. The root mean squares of error (RMSE) were 9.83 cP and 9.34 cP for the NLM and hyperbolic relationships respectively as summarized in Table 1.

### (d) Gel Strength (Gel)

#### (i) Gel Strength 10 sec (Gel10")

The Gel10" of drilling mud at room temperature varied from 10 to 37 lb/100ft<sup>2</sup> based on the bentonite content in the drilling mud. Addition of 0.6% of nanoclay to the drilling mud increased the Gel10" by 11% to 41% based on the bentonite content. Increasing the temperature to 85°C reduced the

Gel10" of the 8% bentonite drilling mud modified with 0.6% of nanoclay by 35% as shown in Fig. 6 (b). The relationship between Gel10" and electrical resistivity for drilling mud based bentonite modified with nanoclay in the temperature range of 25°C to 85°C was modeled using the NLM (Eqn. (4)) and hyperbolic model (Eqn. (5)). The coefficient of determination ( $R^2$ ) was 0.84 and 0.85 respectively. The root mean squares of error (RMSE) were 4.32 lb/100ft<sup>2</sup> and 4.17 lb/100ft<sup>2</sup> for the NLM and hyperbolic relationships respectively as summarized in Table 1.

### (ii) Gel Strength 10 min (Gel10')

The Gel10' of drilling mud with 2% up to 8% of bentonite without nanoclay at room temperature varied from 16 lb/100ft<sup>2</sup> to 42 lb/100ft<sup>2</sup>. Adding 0.6% of nanoclay to the 8% bentonite drilling mud at room temperature increased the Gel10' by 25%. Increasing the temperature to 85°C reduced the Gel10' of the drilling mud and with 8% of the drilling mud the reduction was 28% as shown in Fig. 7 (b). The relationships between Gel10' and electrical resistivity for drilling mud based bentonite modified with nanoclay in the temperature range of 25°C to 85°C was modeled using the NLM (Eqn. (4)) and hyperbolic relationship (Eqn. (5)). The coefficient of determination ( $R^2$ ) were 0.83 and 0.84 for the NLM and hyperbolic relationships respectively. The root mean squares of error (RMSE) for the NLM and hyperbolic relationships were 4.76 lb/100ft<sup>2</sup> and 4.73 lb/100ft<sup>2</sup> respectively as summarized in Table 1.

### Fluid Loss

The relationships between the fluid loss with time for 2% and 8% bentonite drilling mud with and without nanoclay content was modeled using the Eqn. (1) as shown in Fig. 10 and Fig.11. The model parameters and coefficient of determination ( $R^2$ ) varied from 0.98 to 0.99 as summarized in Table 2. The root mean square of error (RMSE) varied from 0.9 mL to 4.5 mL as summarized in Table 2. The filtrate volume (mL/30 min.) of the 2% bentonite drilling mud without and with 0.6% nanoclay at room temperature was 27.8 mL and 14 mL respectively, a 50% reduction and it increased to 40 mL with increasing the temperature to 85°C as shown in Fig. 12 (b). The model parameter E for drilling mud with 2% of bentonite without and with 0.6% nanoclay at temperature of 25°C were 1.22 and 0.72 respectively, a 41% reduction also the parameter F for drilling mud with 2% of bentonite without and with 0.6% nanoclay at temperature of 85°C was 0.02 and 0.01 respectively, a 50% reduction as summarized in Table 2.

### Conclusions

In this study, rheological properties of nanoclay modified bentonite based drilling muds were related to the electrical resistivity, the sensing property identified for real-time monitoring the drilling muds during construction. Based on the experimental study and analytical modeling following conclusions are advanced:

1. Electrical resistivity of the drilling mud decreased with increasing bentonite content, nanoclay content and

temperature and it was a good sensing parameter for real-time monitoring during construction for quality control of the drilling mud and also to predict the rheological properties of drilling mud in the field.

2. Yield point (YP) of drilling mud increased with increasing of bentonite and nanoclay contents. Increasing the bentonite content in the drilling mud from 2% to 8% increased the yield stress from 2 Pa to 31 Pa. Additional of 0.6% nanoclay increased the YP up to 62% based on the bentonite content and temperature.
3. Plastic viscosity (PV) of drilling mud increased by 45% when the bentonite content increased from 2% to 8% at room temperature. The PV increased by 43% to 65% based on the bentonite content and the temperature of the drilling mud.
4. Apparent viscosity (AV) of drilling mud increased by 45% when the bentonite content increased from 2% to 8% at room temperature. The AV increased by 43% to 65% based on the bentonite content and the temperature of the drilling mud.
5. Electrical resistivity was directly related to rheological properties of the bentonite drilling mud using the nonlinear power and hyperbolic relationships.
6. The hyperbolic model better predicted the rheological properties based on the electrical resistivity of the bentonite based drilling muds with and without nanoclay based on the coefficient of determination and root mean square of error (RMSE).
7. Nanoclay did have appreciable effect on controlling the fluid loss from the drilling muds. The nanoclay was effective in reducing the fluid loss in all four bentonite contents investigated in this study.

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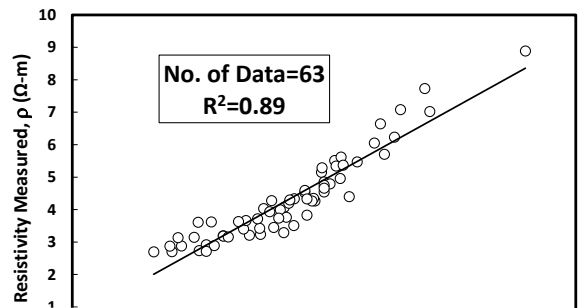
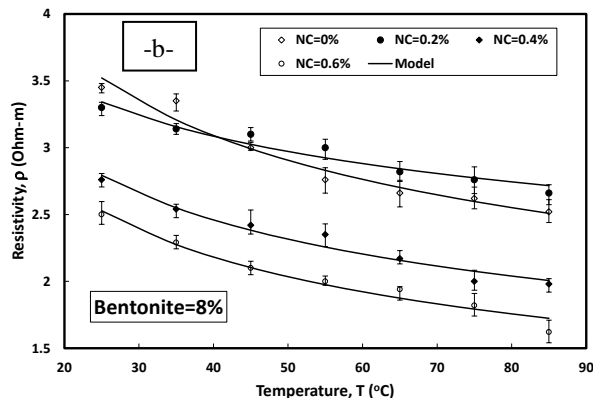
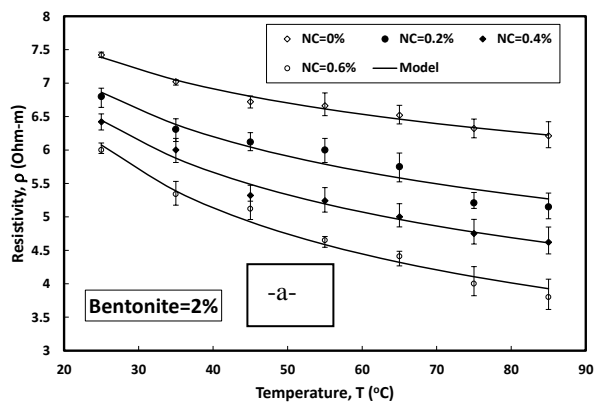
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**Table 1. Rheological and Resistivity Model Parameters for the Bentonite Drilling Mud with Nanoclay**

| Rheological Properties (Y)       | Nonlinear Model (NLM) (Eqn. 4) |       |       |       |                |      | Hyperbolic Model (Eqn. 5) |       |       |                |      | No. of Data (N) |
|----------------------------------|--------------------------------|-------|-------|-------|----------------|------|---------------------------|-------|-------|----------------|------|-----------------|
|                                  | h                              | m     | p     | q     | R <sup>2</sup> | RMSE | A                         | C     | D     | R <sup>2</sup> | RMSE |                 |
| Yield Point (YP), Pa             | 790.7                          | -7.50 | 113.1 | -1.50 | 0.83           | 3.63 | 337.9                     | 0.001 | 0.003 | 0.82           | 3.57 | 28              |
| Plastic Viscosity (PV), cP       | 328.0                          | -6.20 | 198.7 | -1.64 | 0.83           | 6.64 | 339.5                     | 0.001 | 0.003 | 0.78           | 4.23 | 43              |
| Apparent Viscosity (AV), cP      | 522.3                          | -7.70 | 209.9 | -1.40 | 0.84           | 9.83 | 328.3                     | 0.002 | 0.003 | 0.82           | 9.34 | 37              |
| Gel 10" (Ib/100ft <sup>2</sup> ) | 89.6                           | -0.98 | 4.72  | -0.98 | 0.84           | 4.32 | 329.4                     | 0.001 | 0.003 | 0.85           | 4.17 | 37              |
| Gel 10' (Ib/100ft <sup>2</sup> ) | 80.7                           | -0.83 | 5.18  | -0.83 | 0.83           | 4.76 | 324.6                     | 0.001 | 0.003 | 0.84           | 4.73 | 38              |

**Table 2. Fluid Loss Model Parameters for the Bentonite Drilling Mud with Nanoclay**

| Bentonite (%) | NC (%) | T (°C) | E    | F    | RMSE (mL) | R <sup>2</sup> |
|---------------|--------|--------|------|------|-----------|----------------|
| 2             | 0      | 25     | 1.22 | 0.03 | 2.8       | 0.99           |
|               | 0      | 85     | 0.86 | 0.02 | 4.5       | 0.99           |
|               | 0.6    | 25     | 0.72 | 0.01 | 0.9       | 0.99           |
|               | 0.6    | 85     | 0.50 | 0.01 | 2.0       | 0.98           |
| 8             | 0      | 25     | 2.59 | 0.03 | 1.1       | 0.99           |
|               | 0      | 85     | 1.96 | 0.03 | 1.2       | 0.98           |
|               | 0.6    | 25     | 0.84 | 0.02 | 1.0       | 0.99           |
|               | 0.6    | 85     | 0.61 | 0.02 | 1.1       | 0.98           |

**Figure 1. Relation between Measured and Predicted Electrical Resistivity of Bentonite Drilling Mud Modified with Nanoclay****Figure 2. Variation of the Electrical Resistivity (Measured and Predicted Eqn. (10)) with Nanoclay Content (NC %) and Temperature for Bentonite Drilling Muds (a) 2% Bentonite and (b) 8% Bentonite**

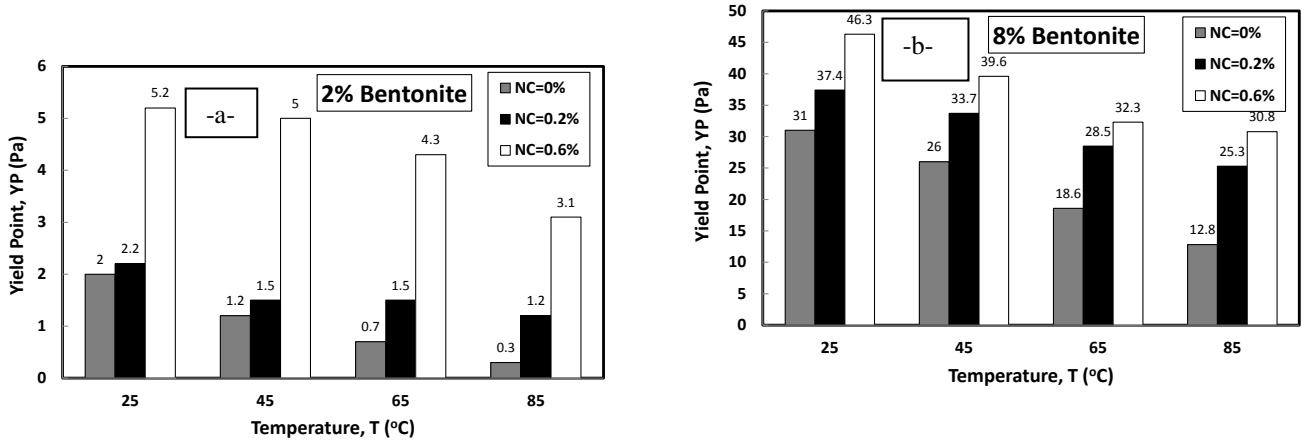


Figure 3. Variation of Yield Point with Temperature for the Bentonite Drilling Muds Modified with Nanoclay (a) 2% Bentonite and (b) 8% Bentonite

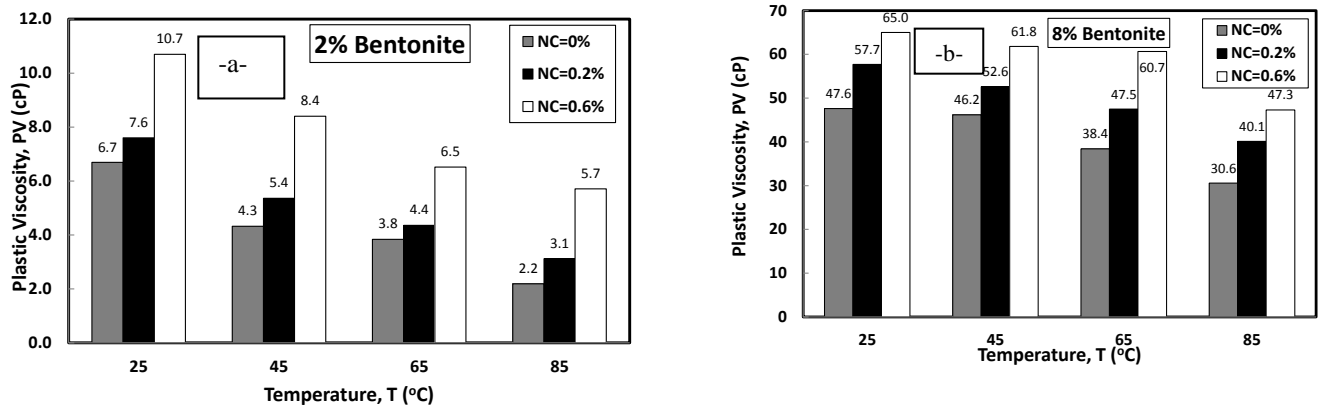


Figure 4. Variation of Plastic Viscosity with Temperature for the Bentonite Drilling Muds Modified with Nanoclay (a) 2% Bentonite and (b) 8% Bentonite

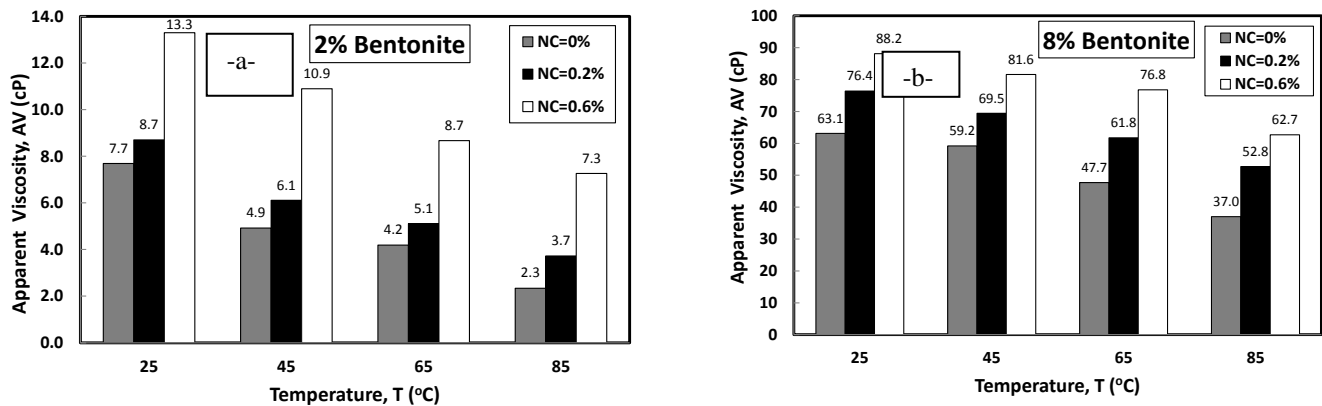


Figure 5. Variation of Apparent Viscosity with Temperature for the Bentonite Drilling Muds Modified with Nanoclay (a) 2% Bentonite and (b) 8% Bentonite

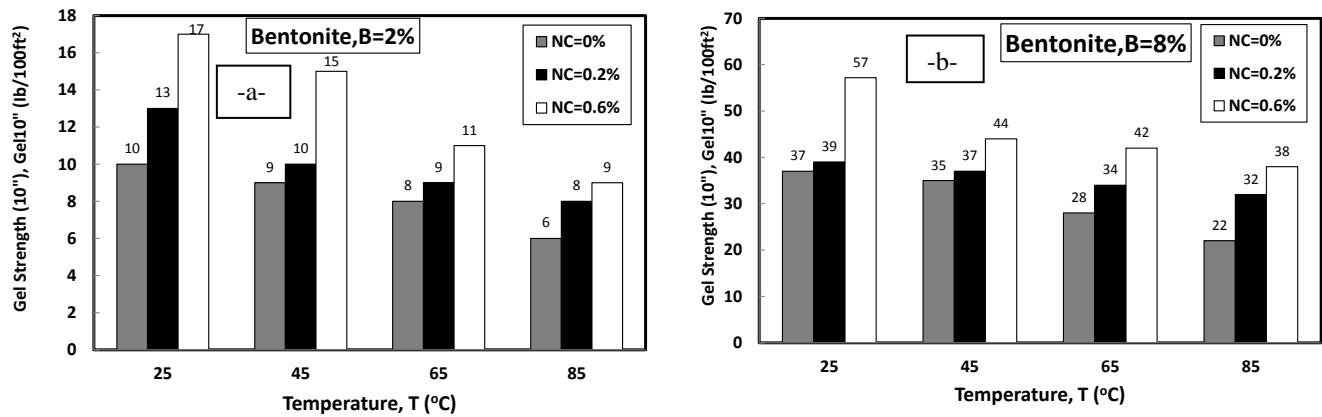


Figure 6. Variation of Gel Strength (10 sec.) with Temperature for the Bentonite Drilling Muds Modified with Nanoclay (a) 2% Bentonite and (b) 8% Bentonite

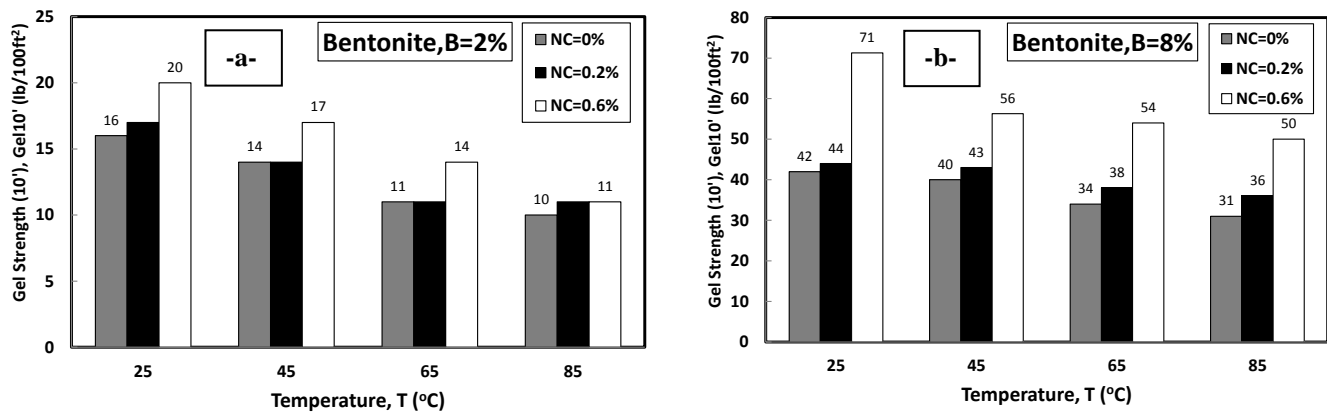
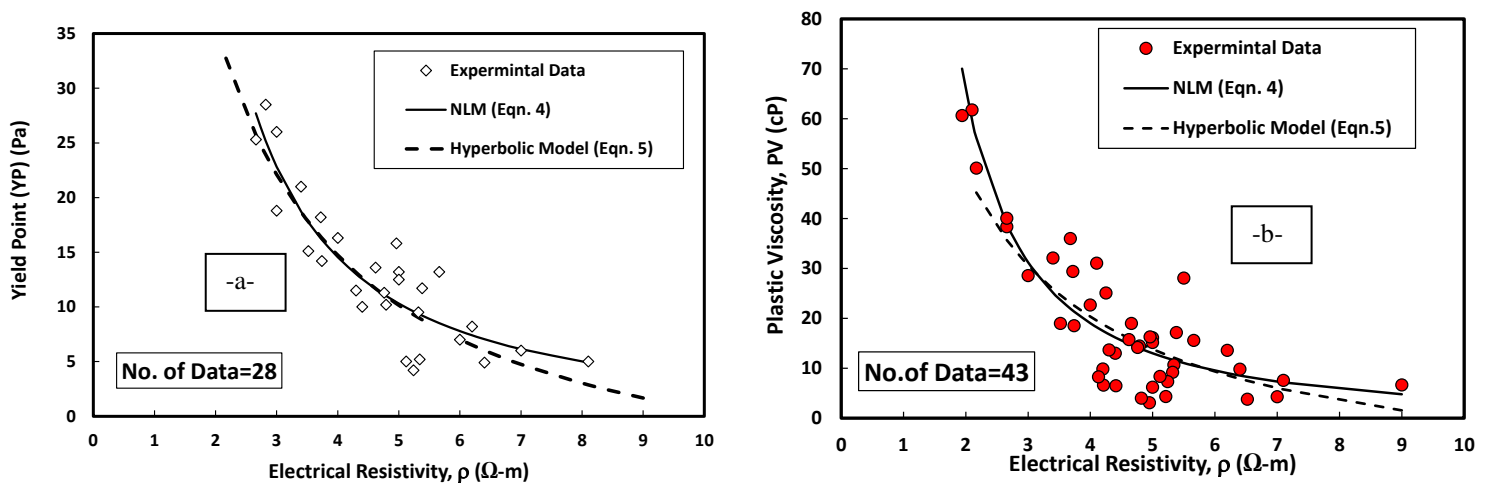


Figure 7. Variation of Gel Strength (10 min) with Temperature for the Bentonite Drilling Muds Modified with Nanoclay (a) 2% Bentonite and (b) 8% Bentonite



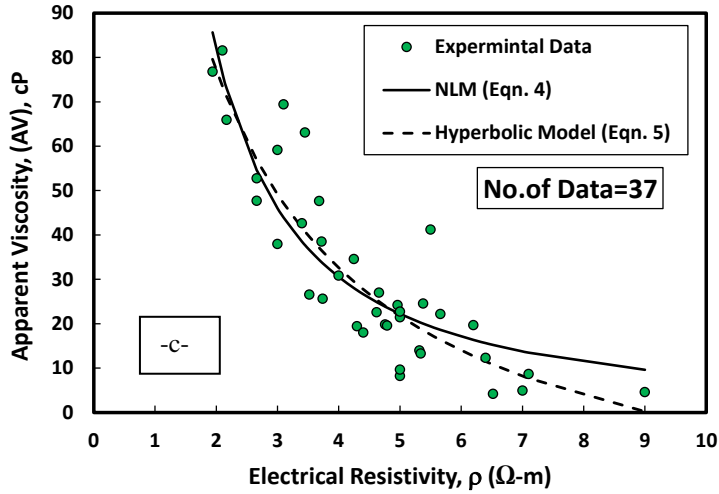


Figure 8. Relationship between the Electrical Resistivity and Rheological Properties of Drilling Mud Modified with Nanoclay (a) Yield Point (b) Plastic Viscosity and (c) Apparent Viscosity

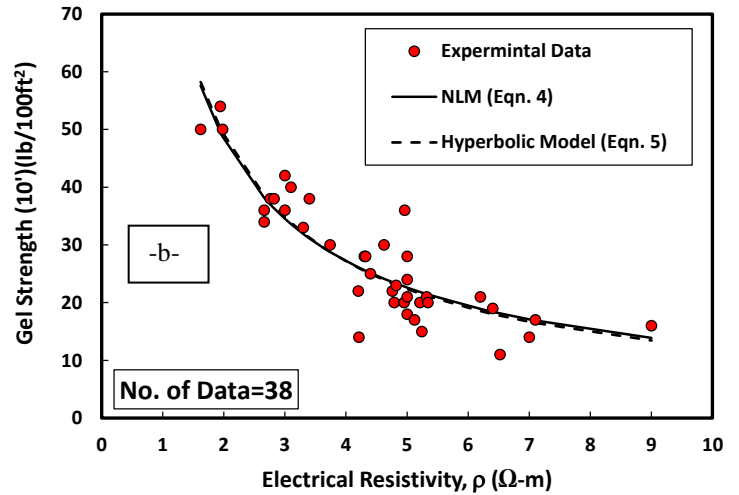
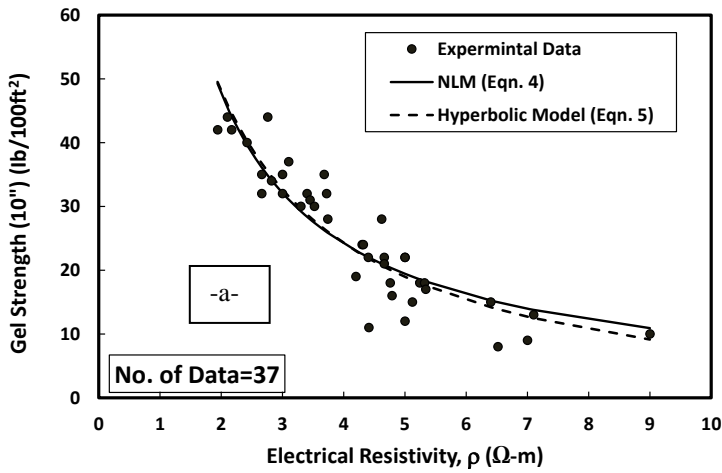


Figure 9. Relationship between the Electrical Resistivity and Gel Strength of Drilling Mud Modified with Nanoclay (a) Gel Strength (10 sec.) and (b) Gel Strength (10 min)

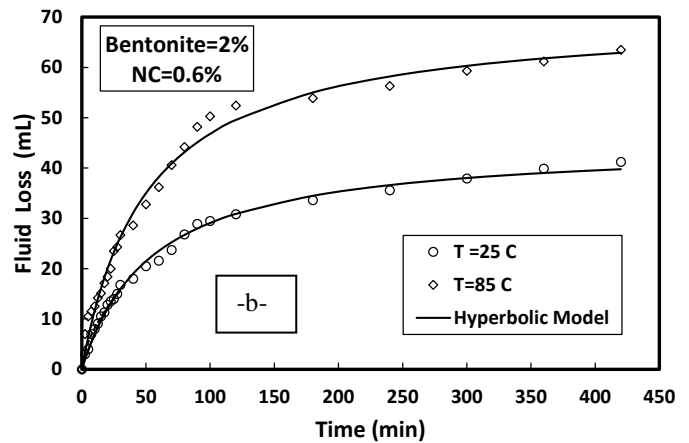
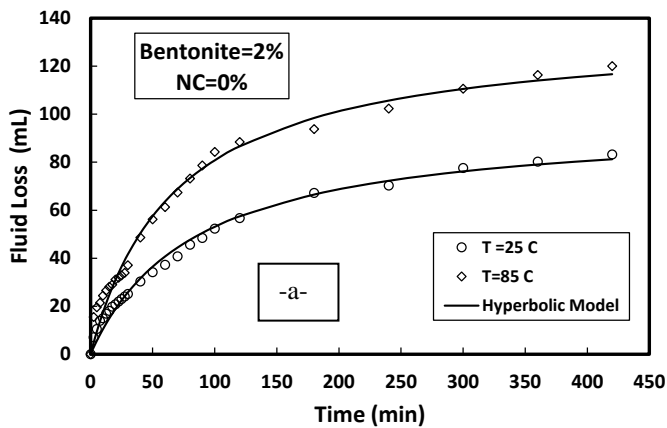


Figure 10. Measured and Predicted Kinetic of Fluid Loss for Drilling Mud with 2% of Bentonite Modified with Nanoclay at two Different Temperatures (a) NC=0% (b) NC=0.6%

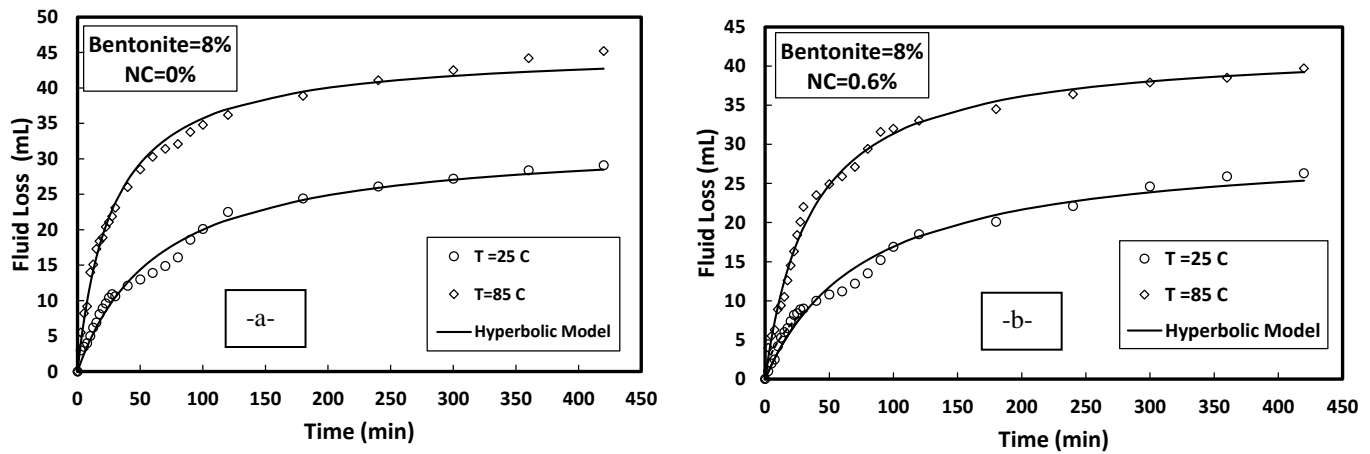


Figure 11. Measured and Predicted Kinetic of Fluid Loss for Drilling Mud with 8% of Bentonite Modified with Nanoclay at two Different Temperatures (a) NC=0% (b) NC=0.6%

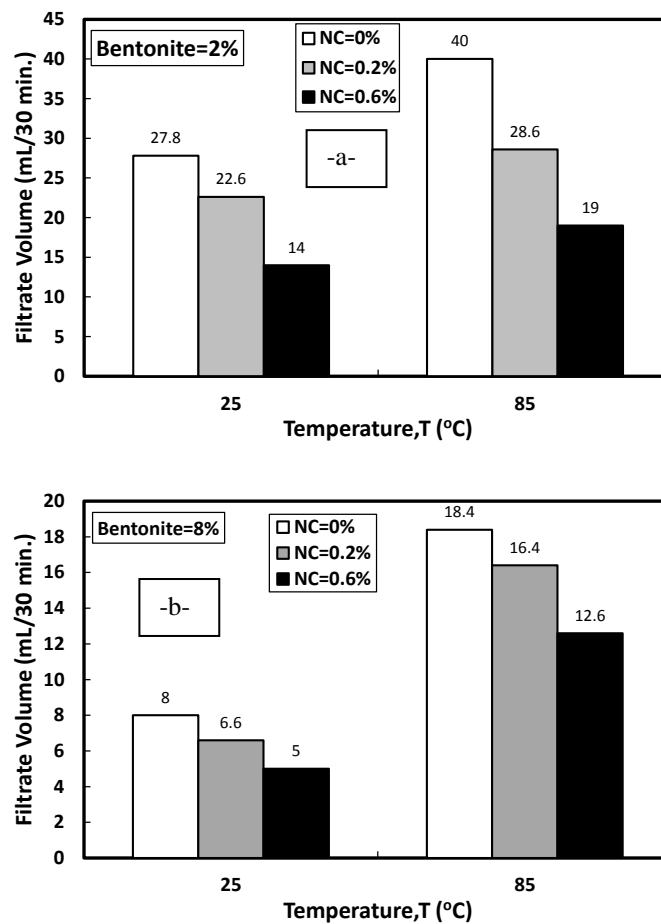


Figure 12. Fluid Loss Volume after 30 mints for Bentonite Drilling Mud Modified with Nanoclay at two Different Temperatures (a) Bentonite=2% and (b) Bentonite=8%