

# Nano-Zeolite Additive Effects on Rheological and Filtration Attributes of Ca-Bentonite Solutions

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## Abstract

*In the drilling fluid industry, nanoparticles (NPs) are among the most promising additives for improving the properties of drilling fluids. The present study aims at investigating the impacts of clinoptilolite, as a prevalent type of zeolite, on the flow behavior and filtration attributes of water-based drilling muds (WBM). The nano-clinoptilolite was prepared and added to selected WBM samples at different concentrations. The results revealed that the plastic viscosity increases due to the addition of nano-clinoptilolite. This improvement helps the removal of cuttings although it could lead to pressure spikes at the beginning of the circulation. The gel strength and yield stress also increase with increasing nano-clinoptilolite content. Furthermore, these two parameters increase with increasing temperature. The plastic viscosity is adversely affected by increasing temperature. The improved rheological parameters are important in enhancing the cutting transport capacity of drilling fluids and the efficient hole-cleaning process. Furthermore, detailed curve-fitting analyses suggested the Herschel-Buckley equation as the best-fit model to the measured data. In addition, the results of filtration analyses showed that the application of nanomaterials in the selected WBMs resulted in the creation of thin impermeable mud cakes across the formation. A significant reduction in the filtrate volume of drilling fluids is also observed. The reduction in filtration volume resolves the issues related to the formation damage and improves the efficiency of reservoir production.*

**Keywords:** Water-based drilling fluids, Nano-zeolite, Rheological behavior, Filtration properties.

## 1. INTRODUCTION

About ten percent of the overall costs for drilling a well are related to drilling fluids. These expenses have been spent for formulating drilling fluids to accomplish an optimum drilling process [1-3]. The drilling fluids market is worth more than 7.2 billion dollars expected to reach 12.31 billion dollars shortly. It shows an equivalent of about a 10 % increase per year [4]. Drilling fluids are usually prepared through various formulations and play a crucial role in cleaning the bottom hole, cooling and lubricating the drill bit, providing well stability during the drilling operation, and maintaining the hydrostatic pressure of wells [5-8]. Water-based muds (WBMs) are

among the most common drilling fluids used in drilling almost 80% of all wells [9, 10]. It has been always tried to improve the properties of drilling fluids [11].

Bentonite, a smectite-type clay, is one of the most efficient additives used as a viscosity modifier in WBMs. It consists mainly of hydrous silicate of aluminum and shows a range of color from gray to brown [12-14]. It is formed from the weathering of volcanic ashes and mineralogically is divided into two major types of sodium and calcium bentonite [9, 15]. The bentonite particles usually have negative charges on their faces mainly due to substitution of  $Al^{3+}$  with  $Si^{4+}$  in tetrahedral sites and  $Mg^{2+}$  with  $Al^{3+}$  in their octahedral sites. This property

allows the platelets of bentonite to efficiently absorb water, swell, and subsequently, enhance the drilling mud viscosity [16, 17].

Montmorillonite  $[(Al, Mg)_2(OH)_2(Si, Al)_4O_{10}(Ca)_x \cdot nH_2O]$ , as the principal mineral component of a high-grade bentonite [15, 18], is a layered structure mineral that is expected to be broken in contact with water leading to the construction of a house-of-cards structure that is proven to increase the viscosity of drilling [19]. However, some other minerals such as illite, kaolinite, chlorite, and non-clay components in bentonite structure may have detrimental effects on the drilling fluids' rheological properties. In this case, proper additives must be chosen to achieve the desired rheological properties [18, 20, 21].

Nanomaterials, due to their excellent physical, chemical, electrical, and thermal properties, are the additives that have received special attention in recent years [22-26]. Besides, the addition of nanomaterials is believed to effectively amend the rheological properties of drilling fluids and to mitigate issues related to the formation-damage [1-3, 25, 27]. High ratios of surface area to volume, effectiveness in low concentrations, minor erosion in the equipment, and minimized environmental impacts justify the application of nanomaterial additives in drilling fluids [1, 3, 28-30]. It was shown that nano clay controls fluid loss and is resistant to high temperatures [31]. Nanomaterials decrease friction and improve heat conductivity to boost cooling in downhole equipment. NPs provide larger surface areas that facilitate heat transfer [32].

It should be noted that zeolites are valuable minerals with applications in various industries, such as in making molecular sieves, adsorbents, and catalysts [33]. Natural zeolites are hydrated aluminosilicate minerals with a crystalline tetrahedral structure  $TO_4$  (T: Si, Al) produced from diagenetic alterations of volcanic materials [34]. As a result of its tetrahedral structure, Zeolite contains a

wide pore size distribution ranging from micro- (less than 2 millimeters) to meso-size (between 2 to 50 nanometers) resulting in an increased internal surface area [35]. Clinoptilolite  $((Na, k)_6Si_{30}Al_6O_{72} \cdot nH_2O)$  is one of the most common types of zeolites that is frequently found in sedimentary rocks with volcanic origin. In recent years, Nano-clinoptilolites has been used more than conventional zeolites due to their advantages [36]. The nano-clinoptilolites have a high external surface area resulted from the reduced particle sizes in nano-treatment, and a high internal surface area of natural zeolites caused by the existence of microporosity in their structure., They exhibited outstanding features in different fields of industry but their performance in the drilling fluid industry has not yet been investigated [35, 37-39].

This study aims to fill the gap by designing a set of experiments for identifying the effect of nano-clinoptilolite, as a prevalent type of zeolite, on rheological properties of WBMs at various temperatures as well as analyzing the filtration properties of drilling fluids formulated with the synthesized NPs. The methodology of the experimental work is as follows:

- a) Firstly, nano-clinoptilolites were synthesized through a ball milling process and then characterized using XRF, SEM, and EDS analyses.
- b) Next, the flow behavior of drilling fluid samples was analyzed based on NPs' content and temperature.
- c) Finally, the second set of tests was performed on the effect of prepared NPs on the filtration properties of drilling fluids against the concentration of the nanoparticles.

## 2. MATERIALS AND METHODS

### 2.1. Materials

Bentonite was obtained from a local mine (Sabzevar, Khorasan Razavi, Iran). Based on our previous studies, the quality of the selected bentonite was found appropriate enough to be used in drilling fluids [1, 2].

The nanozeolite, clinoptilolite, was also supplied from another local mine near Sabzevar (Khorasan Razavi, Iran). To prepare the nano-clinoptilolite particles, a planetary ball milling apparatus (PM100; Retsch Corporation) was employed and NPs were prepared by a 3-hour wet milling of clinoptilolite particles (larger than 1 mm) in a water medium using a zirconium oxide coated steel jar (see Table 1). It should be noted that the jar was sealed and the ball milling started operating under ambient conditions immediately after placing 3 mm in diameter zirconium oxide balls, clinoptilolite, and water. Then, the ground powders were dried for 24 hours at 30 °C to follow the characterization step. Other chemicals were purchased from Sigma-Aldrich Company without any further treatment.

**Table 1.** Ball milling conditions for the preparation of nano-clinoptilolite.

Zeolite amount (g)	Balls weight (g)	Rotational speed (rpm)	Water volume (cm <sup>3</sup> )	Duration (hr)
100	500	450	100	3

## 2.2. Characterization

### 2.2.1. NP characterization

The quantitative determination of the major elements in clinoptilolite was performed using the wavelength dispersive X-ray Fluorescence (XRF) apparatus (CE3021, CECIL Instruments, US) as well as scanning electron microscope (SEM)/energy dispersive spectroscopy (EDS) apparatus (TESCAN, Vega 3, Czech Republic). Table 2 presents the results of detailed elemental composition analysis on the clinoptilolite sample showing a mass ratio of 6.55 for SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> which is highly affected by the base rock mineralogy and its quartz content. L.O.I. is defined as the percentage of volatile components, mainly the crystal-bound water and organic carbon (such as CO<sub>2</sub>), driven from a sample when heated to 1000 °C.

Figures 1 and 2 are also the representative of EDS and SEM analyses of the prepared clinoptilolite, respectively. With a glance at

the results obtained from the EDS experiments, it can be seen that the aforementioned zeolite can be considered a Calcium-type one that is consistent with the results obtained from the XRF analysis. It is evident from SEM results that using the planetary ball milling process has provided the nano-sized zeolites with a size range from 11.11 to 20.84 nanometers. It is worth noting that the larger sizes of nano zeolites observed in the SEM images than those in SEM are pertinent to the undesirable agglomeration of the particles. Besides, the SEM images confirm the plate-like morphology of nano zeolites that show the laminated features of the clays [2].

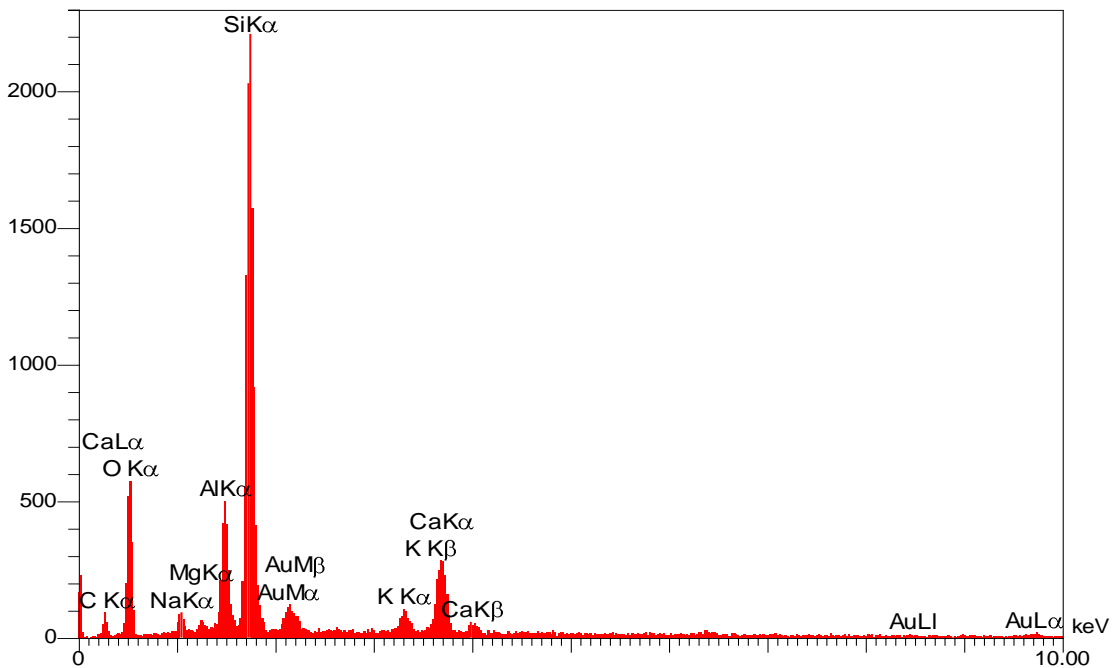
### 2.2.2. Drilling Fluid Characterization

In this study, a Brookfield RST-CC Rheometer, including a cylindrical sample holder, a water jacket, and a spindle (Measuring bob CC3-40), was used to measure the rheological properties of drilling fluid samples. Moreover, the temperature was adjusted using a WiseCircu circulating water bath between 30 and 40 °C and the water jacket of the rheometer. All measurements were conducted in a speed range of 0.01-1000 rpm.

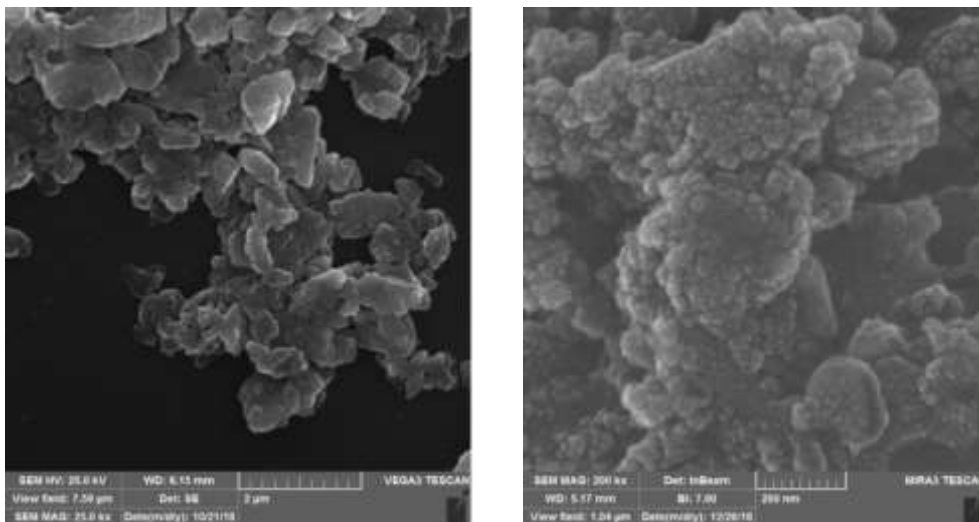
A low-pressure-low-temperature API filter press apparatus was employed to analyze the filtration properties of nano-based drilling fluids. The filtration volume was simultaneously measured every 5 minutes based on API standards. At the end of each experiment, the thickness of the mud cake was measured using a digital caliper. The quality of the bentonite sample was assessed using XRF (PANalytical XRF spectrometer, Netherlands). It should be emphasized that the XRF analyses of samples were conducted through the pressed powder pellets method. The results of XRF analysis on the local bentonite sample, as shown in Table 3, suggest a ratio of about 4.7 for SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, and a 0.78 ratio for the (Na<sub>2</sub>O+K<sub>2</sub>O)/(MgO+CaO) concentrations i.e., the sample is placed in Ca-bentonite category.

**Table 2.** Chemical analysis of the clinoptilolite sample.

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	MgO	CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub>	L.O.I
Percentage	62.68	9.57	2.43	0.77	5.51	1.76	0.17	0.09	0.03	0.041	0.011	16.94



**Figure 1.** EDS results for nano-Zeolite.



**Figure 2.** SEM results for nano-Zeolite used in the experiments in two different resolutions.

**Table 3.** Chemical analysis of the local bentonite.

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	MgO	SO <sub>3</sub>	TiO <sub>2</sub>	Cl	L.O.I
Percentage	63	13.2	3.71	2.75	2.02	1.95	1.36	0.477	0.372	0.247	10.914

### 2.3. Preparation of Drilling Fluid Samples

Following a pre-designed experiment, various amounts of nano-clinoptilolite were added to 350 mL of deionized water. The nanoparticles were dispersed using an

ultrasonic processor of UP200S (Hielscher brand, 200 W, 24 kHz) to make a homogeneous solution. Then, different amounts of local bentonite were dispersed

in the aqueous solutions using a WiseCircu stirrer at 500 rpm to obtain the desired density of drilling fluids. In this method, nano-based drilling fluids were prepared

with a concentration of nanoparticles ranging from 0 to 4 wt.% with a fixed drilling fluid density of 68 lb<sub>m</sub>/ft<sup>3</sup> (PCF) (See Table 4).

**Table 4.** Details of designed experiments and overall conditions in the measurement of solution properties (DF stands for drilling fluid).

Nomenclature	Formulation of drilling fluid systems	Operating Conditions
Base fluid	Deionized water + 13 wt% bentonite	<ul style="list-style-type: none"> <li>Rheological properties were determined at 30, 35, and 40 °C.</li> <li>Filtration properties were examined at ambient temperature and 100 psi (API standard conditions).</li> </ul>
DF-1	Base fluid+ 1 wt% nano zeolite	
DF-2	Base fluid+ 2.5 wt% nano zeolite	
DF-3	Base fluid+ 4 wt% nano zeolite	

## 2.4. Rheological Modeling

Drilling fluids commonly exhibit non-Newtonian rheological behavior. Due to the high solid contents of clay-based drilling fluids, they typically behave according to pseudoplastic models for which threshold stress must be met before flowing [39]. Pseudoplastic model assumes a linear relationship between shear stress and shear rate [3, 22]. Bingham plastic, as a two-parameter model, can describe such behavior of water-based drilling fluids and is defined as follows:

$$\tau = \tau_0 + \mu_p \gamma \dots\dots\dots (1)$$

Where  $\tau$  is the shear stress,  $\tau_0$  is the yield stress or yield point,  $\mu_p$  is the plastic viscosity and  $\gamma$  is the shear rate. The plastic viscosity (which is commonly shown by PV) is defined as the resistance of the fluid to flow due to the presence of mechanical friction between the fluid molecules. In addition, water-based drilling muds are suspensions of bentonite dispersed in water. There exists a natural resistance to flow, referred to as either yield stress or yield point. The yield stress mainly results from the electrochemical interactions among the mentioned drilling mud particles. Yield point (YP) can be determined using the shear stress-shear rate diagram at zero shear rate.

Another well-known rheological model, well-fitted to the flow behavior of many drilling fluids, is Power law which is defined as follows:

$$\tau = K\gamma^n \dots\dots\dots (2)$$

Where  $\gamma$ ,  $K$ , and  $n$  are shear rate, consistency index, and flow behavior index, respectively. Herschel-Bulkley (HB) model is also widely accepted as an appropriate alternative model which is developed according to the combination of both the above-mentioned models and is defined as:

$$\tau = \tau_0 + K\gamma^n \dots\dots\dots (3)$$

Where  $\tau_0$ ,  $K$ , and  $n$  are HB yield stress, HB viscosity (or consistency index), and HB flow behavior index, respectively [1, 3].

Gel strength is considered another important parameter that is frequently reported for drilling fluid samples. It is defined as the shear stress of drilling fluid measured at a low shear rate immediately after drilling mud has remained static for a certain period (10 seconds and 10 minutes) [2, 3].

The Casson model is used for the prediction of the oil suspensions. However, this model is rarely applied to drilling muds. It is also used for characterizing the behavior of the cement slurry. This model is expressed as follows [26, 40]:

$$\tau^{0.5} = \tau_0^{0.5} + (\mu_0 \gamma)^{0.5} \dots\dots\dots (4)$$

Where,  $\tau_0$  and  $\mu_0$  are two constants representing the yield stress and the consistency, respectively. The Robertson-Stiff model is described as:

$$\tau = K(\gamma + \gamma_0)^n \dots\dots\dots (5)$$

Where,  $K$ ,  $\gamma_0$ , and  $n$  are the fitting parameters [26].

### 3. RESULTS AND DISCUSSIONS

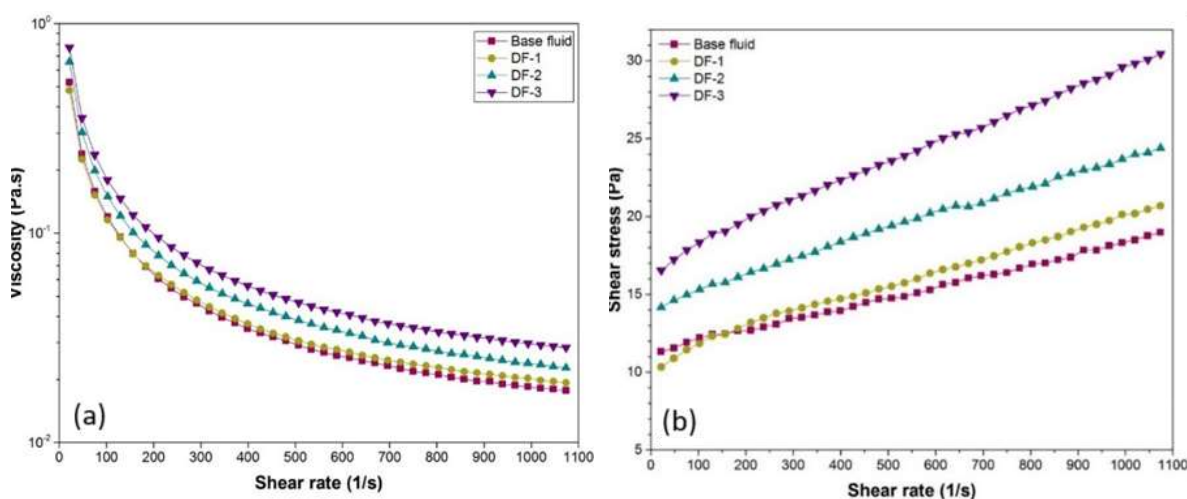
#### 3.1. Rheological Analysis of Drilling Fluids

As shown in Figure 3a, the viscosity of all drilling fluid samples was decreased by increasing the shear rate. This behavior demonstrates the shear-thinning nature of samples which is desirable to remove cuttings, and subsequently ensure a suitable hole cleaning efficiency [41, 42]. It was observed that the higher nanoparticle contents cause higher viscosities. This is probably due to more interparticle interactions, and subsequently higher frictions among particles [23].

Besides, Figure 3b illustrates the flow curves of different samples at 30 °C. The flow curve is the plot of shear stress versus shear rate. In the case of pseudoplastic fluids, the slope of the flow curves indicates the plastic viscosity of samples and the intersection of these curves with the shear stress axis depicts the yield stress of fluids. As shown in Figure 3b, the plastic viscosity of drilling fluid samples increases with any growth in the shear rate which is mainly due to high resistance to flow resulting from the

large mechanical friction among the solution components, including the bentonite platelets, nano-clinoptilolite particles, and the liquid phase of the fluid. The high amounts of nano-clinoptilolite resulted in an increase in the plastic viscosity of fluid samples due to the higher surface area of nanoparticles compared to the clay particles.

Nevertheless, yield stress values increase by increasing the nano-clinoptilolite concentration. The increase in the yield stress is probably related to the increase in the amount of cohesion among the particles results from the penetration of nanoparticles into between the layers of clay. The nano-clinoptilolite particles can move between the bentonite platelets due to their extremely small dimensions, and create stronger bonds between the layers. This phenomenon increases the adhesive forces. The nano-clinoptilolite may interact with the bentonite layers by establishing hydrogen bonds between the hydroxyl groups of zeolite and the oxygen atoms of the clay platelets [43].



**Figure 3.** (a) Viscosity- shear rate plot for different drilling mud samples at 30 °C. (b) Shear stress- shear rate plot for drilling fluid samples.

Figure 4 shows the detailed results of the rheological experiments that are explained in the following paragraphs:

- **Plastic viscosity:** Figure 4a displays the effects of temperature and concentration of nano-clinoptilolite on the plastic

viscosity of drilling fluid samples. After adding dry bentonite to an aqueous medium, it swells by absorbing water in its interlayer region. The separation of parallel layers of clay particles, especially under a given stress, can result in the swelling of

bentonite which increases the mechanical friction of the solution. This colloidal structure may increase the plastic viscosity of drilling fluids. The results indicate that adding various amounts of nano-clinoptilolite at different temperatures improved the plastic viscosity of bentonite solutions. As mentioned previously, the reason is that the nano-clinoptilolite increases the interparticle friction in the solution medium, and enhances the mechanical resistance to flow. Another factor that increases the plastic viscosity is the large surface area of nano-clinoptilolite in unit volume. The high pore volume in the network structure of clinoptilolite increases its internal surface area. Consequently, it increases the water absorption of particles. In addition, the preparation of nano-sized zeolites increases its external surface area. Temperature also affects the plastic viscosity. The plastic viscosity of solutions reduces with increasing temperature. This issue probably arose from a decrease in the viscosity of the continuous phase.

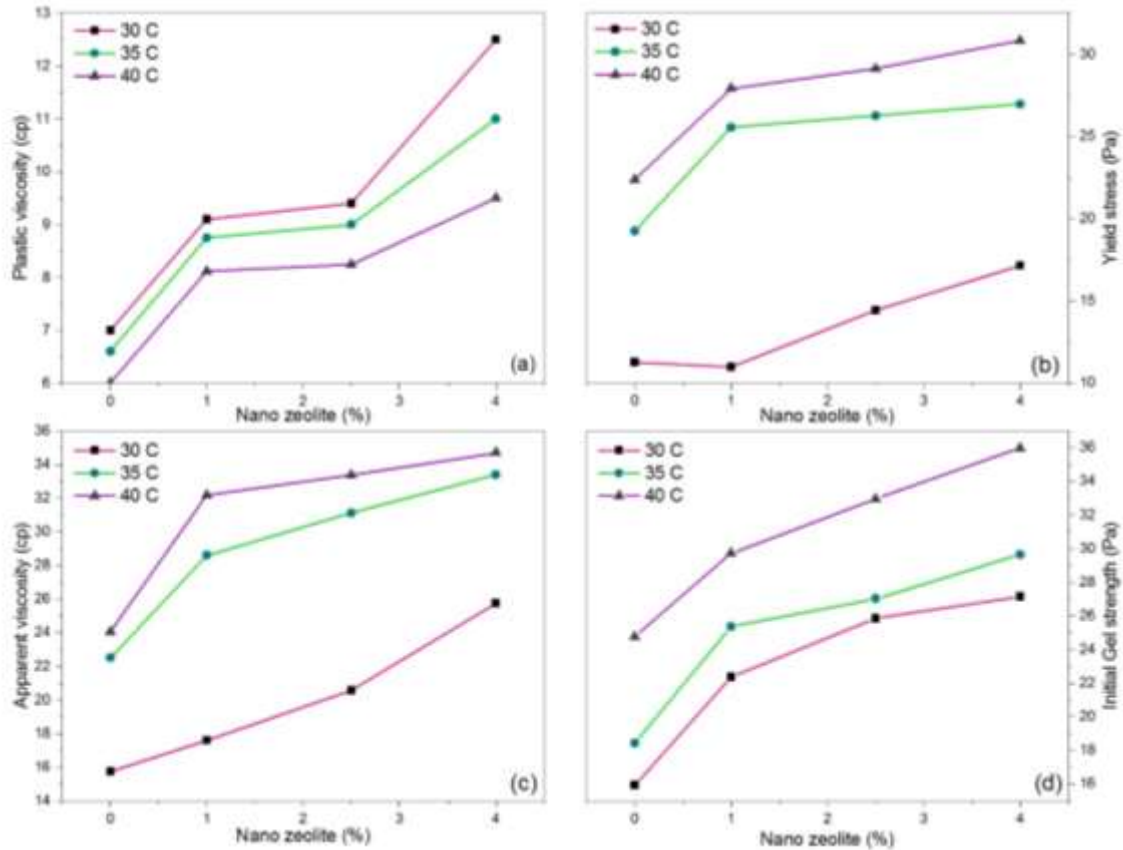
- **Yield stress:** Figure 4b shows that adding nano-clinoptilolite increased the yield point of the drilling mud samples. The addition of these nanoparticles increases the attractive forces among drilling mud particles and improves the adhesive forces in the suspension. Therefore, a higher amount of shear stress will be required to exceed this resistance compared to simple drilling mud. As a result, the yield stress of the samples will be increased. Indeed, the high concentration of nanoparticles will lead to an increase in all rheological properties [19]. In addition, an increase in temperature increases the yield point values for all types of drilling fluid samples. Generally, an increase in the temperature results in a consequent change in ionic activities inside drilling fluids and alters the balance between attractive and repulsive forces between clay particles. Therefore, it influences the rheological properties of drilling fluids particularly yield point [39].

- **Apparent Viscosity.** As shown in Figure 4c, the apparent viscosities of

drilling fluid samples are significantly increased with increasing the concentration of NPs. The results are consistent with those achieved for the plastic viscosity of fluids. However, the apparent viscosity increases with increasing temperature.

- **Initial gel Strength.** Figure 4d illustrates the gel strength of drilling mud samples at 10 sec (initial gel strength). According to the results obtained from conducted experiments, increasing the concentration of nano-clinoptilolite directly impacts the thixotropic behavior of mud samples. The addition of nano-clinoptilolite improved the Gel 10s of all drilling fluids at various temperatures. By comparing the curves, it can be found that increasing the temperature will tend to increase the gel strength of all samples. Gel strength indicates the capacity of drilling mud to suspend drilled cuttings and prevent them from falling once the circulation has stopped. In other words, the gel strength and the yield stress are naturally the same, except that gel strength is measured in static conditions whereas the yield stress is in dynamic mode. Therefore, the trends of gel strength must be similar to those for the yield stress.

- **Appropriate rheological model identification.** The most common rheological models used in drilling fluid studies were analyzed through a curve-fitting analysis to determine the best-fitted model to the rheological behavior of drilling mud samples (see Table 5). Based on the R-squared values, the best fitting achieved in the case of the Herschel-Bulkley model. However, as the amount of R-squared increases with the amount of any added predictor, the values might not be valid for choosing a model [44]. However, the adjusted R-squared, which is a more truthful value, confirmed the results. In addition, the high F-test values verify the suitability of Herschel-Bulkley model. However, the Bingham model shows similar results as Herschel Bulkley and there are no significant differences in their adjusted R-square values.



**Figure 4.** The rheological parameters of solutions at different concentrations of nano zeolite and varying temperature: (a) plastic viscosity, (b) yield stress, (c) apparent viscosity, and (d) initial gel strength.

**Table 5.** The results of curve fitting analysis for rheological behavior of the drilling fluid samples.

Model	Sample	Sum of Squares	Mean Square	F value	P value	Statistic	
						R-Square	Adj. R-Square
Bingham	DF-1	321.46	321.46	6770.84	0	0.9944	0.9942
	DF-2	343.46	343.46	12954.70	0	0.9970	0.9970
	DF-3	605.75	605.75	12254.54	0	0.9969	0.9968
Power Law	DF-1	10488.45	5244.22	8689.64	0	0.9290	0.9271
	DF-2	15661.01	7830.50	10140.30	0	0.9148	0.9125
	DF-3	11794.31	9525.94	9525.94	0	0.9225	0.9205
Herschel-Bulkley	DF-1	10510.18	3503.39	107529.25	0	0.9962	0.9960
	DF-2	15690.05	5230.01	647692.23	0	0.9991	0.9990
	DF-3	23634.98	7878.32	422906.04	0	0.9988	0.9988

### 3.2. Filtration Properties Evaluation

In this study, four clay solutions with varying concentrations of nano-clinoptilolite were prepared to analyze the filtration properties of water-based drilling muds. To compare the results, the density of all samples was again kept constant at 68 PCF. Table 6 reports the experimental results, while Figure 5 shows the total filtration volume of drilling fluids versus

time. The results show that the addition of nano-clinoptilolite resulted in decreased filtration volume of samples. It is assumed to be due to the penetration of nanoparticles between the layers of clay platelet deposited on the surface of filter paper (or walls of the wellbore in real conditions) and the reduction in permeability of mud cake. As a result, the volume of filter loss is decreased.

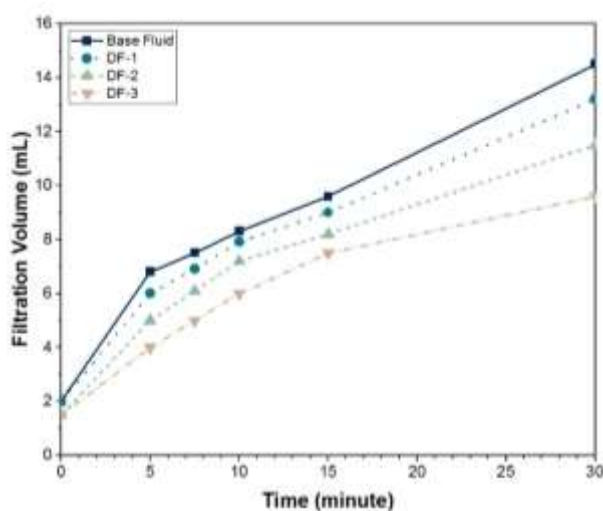
The lower volume of filter loss reduces the risk of differential stuck pipe in the hole and enhances the drilling fluid efficiency.

Further studies show that the thickness of mud cake is not affected by nano-clinoptilolite. Generally, additives with nano-sized dimensions can reduce the mud cake thickness while its permeability simultaneously decreases. Nano-clinoptilolite does not act such as other nanoparticles which is related to the clay

nature of this nano additive. Nano-clinoptilolite is a clay mineral similar to bentonite that swells by the adsorption of water [45]. The nano-clinoptilolite has a negligible effect on the mud cake thickness due to the swelling. It should be noted that the lower thickness of mud cake can lead to less friction while drilling a hole. This issue reduces the damage to the downhole equipment caused by erosion as the risk of stuck pipes [46, 47].

**Table 6.** Filtration properties of bentonite solutions at different concentrations of NPs.

Nomenclature	Initial filter loss (spurt loss) (mL)	Filtration volume (mL)	Final filtration rate (mL/min)	Mud cake thickness ( $\mu\text{m}$ )
Base fluid	2	14.5	0.32	400
DF-1	2	13.2	0.28	383
DF-2	1.5	11.5	0.22	380
DF-3	1.5	9.6	0.14	375



**Figure 5.** The filtration volume of bentonite solutions versus time at different concentrations of NPs.

#### 4. CONCLUSIONS

In this study, the effects of nano-clinoptilolite concentration and temperature on the rheological and filtration characteristics of water-based drilling fluids are investigated. According to the results, the addition of nano-clinoptilolite significantly changes the rheological properties of drilling fluids. The plastic viscosity of drilling fluid samples increases with the addition of nano-clinoptilolite. This enhancement is reckoned to be due to the adsorption of water by the intrinsic pores of clinoptilolite. This phenomenon

reduces the amount of water available for coating particles inside drilling fluids. This issue results in increasing friction between particles and hence increasing the viscosity. However, it should be noted that increasing viscosity is not necessarily a positive criterion only because it can also lead to undesired pressure spikes at the start of the circulation. Therefore, a balance between positive and negative aspects of increasing viscosity should always be considered. Similarly, due to increasing interactions inside drilling fluids, the yield stress, and

the gel strength of solutions increase by the addition of nano-clinoptilolite. The unique structure of negatively charged nano-clinoptilolite, with cations in its framework, increases the attractive forces between the particles. Subsequently, it enhances the yield stress of mud samples.

Although the yield stress and the gel strength increase with increasing temperature, it is shown that the temperature detrimentally affects the plastic viscosity. In this study, the outstanding features of nano-clinoptilolite reduce the permeability of mud cake, and subsequently decreases the filtration volume of the solutions. Moreover, it is found that due to the swelling of nano-clinoptilolite, the thickness of mud cake is slightly decreased compared to that with the application of other nanoparticles. It should be mentioned that clinoptilolite is a naturally occurring clay that is cheap and available in large quantities. Therefore, the drilling industry can account for it to formulate the drilling fluids. Further studies on the rheological models revealed that the Herschel-Bulkley model fitted well with the shear stress-shear

rate data.

## NOMENCLATURE

$\tau$  = Shear stress, Pa  
 $\gamma$  = Shear rate,  $s^{-1}$   
 $\mu_p$  or PV = Plastic Viscosity, cp  
 $\tau_0$  or YP = Yield Point (Yield Stress), Pa  
 Gel 10 S = Initial Gel Strength, Pa  
 K= Consistency index, cp  
 n= Flow behavior index, dimensionless.

## SI METRIC CONVERSION FACTORS

cp $\times$ 1.0 *	E - 03 = Pa . S
lbm $\times$ 4.5359237	E - 1 = kg
ft <sup>3</sup> $\times$ 2.831685	E - 02 = m <sup>3</sup>
psi $\times$ 6.894757	E + 00 = kPa

\*Conversion factor is exact.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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