

Designing Smart drilling fluids using modified nano silica to improve drilling operations in Geothermal wells.

C. Martin*, **M. Babaie**, **A. Nourian**, **G. G. Nasr**, School of Science Engineering and Environment (SEE), University of Salford, Manchester, UK.

Abstract

High pressure and high temperature (HPHT) conditions in geothermal wells have necessitated the need to develop thermally stable geothermal drilling mud systems to combat potential drilling complications. This is because mud fluids degrade under HPHT conditions due to high temperature effects. This study therefore aims to establish the optimum concentration of a cationic surfactant that would successfully modify the surface of silica nanoparticles and thereafter, evaluate the performance of modified nano silica as a rheological and filtration property enhancer in water-based muds (WBMs). The surface of silica nanoparticle was successfully modified by adding Hexadecyltrimethylammonium bromide (CTAB) to silica solution. Different mud formulations containing modified nano silica with varying zeta potential values, SNP3 -S2, SNP3 -S4, SNP3 -S5, SNP3 -S6, and SNP3 -S7 with -17.7mV, 20mV, 28.2mV, 35.4mV, and 37.1mV respectively were investigated. Results showed that modified nano silica with the highest absolute value of zeta potential enhanced drilling mud rheology as temperature increased from 149 °C to 232 °C. The optimal amount of CTAB was found to be between 1.0 and 2.0 wt.%. Filtration loss was reduced by 11.4, 17.6, and 29.5% on average for mud samples SNP3-S5, SNP3-S6, and SNP3-S7, respectively, at all temperatures. Mud cake thickness was reduced by 19.9, 11.6, and 28.7% on average by mud samples SNP3-S5, SNP3-S6, and SNP3-S7 respectively at all temperatures.

Keywords: Geothermal, Drilling fluid, Silica nanoparticles, Rheological properties, Zeta potential, Cationic surfactant

1. Introduction

Due to the increasing energy demands and the stringent environmental regulations associated with the oil and gas industry, geothermal wells have been viewed as a clean and renewable energy source. As a result, there has been an increase in the number of geothermal exploration and drilling operations to reach geothermal reserves. Geothermal energy is produced by drilling geothermal wells and transferring natural heat from the earth using a circulation fluid injected from the surface or produced from geothermal reservoirs ([Finger and Blankenship 2010](#), [Paulillo, Cotton et al. 2020](#), [Fallah, Gu et al. 2021](#)). Geothermal wells are drilled in the similar way as oil wells ([Capuano Jr 2016](#), [Bavadiya, Srivastava et al. 2019](#)). As a result, developments in crude oil drilling technologies is critical to the development of geothermal well drilling techniques ([Teodoriu 2013](#), [Teodoriu, Yi et al. 2018](#)). Engineers can correlate technical problems and lessons learned in drilling high pressure and high temperature (HPHT) oil wells to better understand the difficulties in drilling geothermal wells since high pressure and high temperature oil and gas and geothermal wells have similar downhole conditions ([Vollmar, Wittig et al. 2013](#), [Capuano Jr 2016](#), [Allahvirdizadeh 2020](#)). However, with geothermal wells, the temperature can rise over the critical temperature of the water making drilling and completion activities more difficult ([Kruszewski and Wittig 2018](#), [Moya, Aldás et al. 2018](#)). During drilling operations, geothermal reservoir environments present numerous challenges, including well control, loss of circulation, and well integrity. ([Finger and Blankenship 2010](#), [Chemwotei 2011](#), [Shadravan and Amani 2012](#), [Kiran and Salehi 2020](#)). Hard formations, in addition to high temperatures impose additional technical constraints on the selection of drilling bits, drilling mud, casing material, and cement formulation. Therefore, in order to deal with the HPHT problems and reduce drilling problems, more technology advancements are needed ([Finger and Blankenship 2010](#), [Archer 2020](#)). To perform in HPHT environments and avoid mud degradation, advanced drilling mud systems with high thermal stability are required. These extreme conditions may destroy the downhole tools, casing and cement sheaths ([Vollmar, Wittig et al. 2013](#)). Drill string vibration is increased by the hardness of the drilled formation, resulting in downhole tool failure. Observations noted that variations in HPHT geothermal wells initiate thermal stresses on the casing ([Bavadiya, Alsaihati et al. 2017](#)). Therefore, failure of the casing is as a result of thermally induced stress fatigue when stresses or forces surpass the yield stress of the casing material ([Shadravan and Amani 2012](#), [Teodoriu 2013](#), [Wu, Patel et al. 2020](#)). Another issue encountered in the geothermal business are the high increased capital costs due to drilling operations ([Randeberg, Ford et al. 2012](#), [Vollmar, Wittig et al. 2013](#), [Bavadiya, Srivastava et al. 2019](#)). Also, the high cost of constructing geothermal power plants makes them more expensive compared to conventional power plants. The drilling of geothermal walls is a significant part of a geothermal well construction total cost. Drilling costs are some of the most expensive capital costs in the development of a well, accounting for up to 60% of the total cost ([EIA 2016](#), [Mohamed, Salehi et al. 2021](#)). Cost and depth of drilling according to API data indicates that the cost of drilling increases exponentially and about (56%) is linked to well depth ([Cedric 2010](#), [Gul and Aslanoglu 2018](#)). As a result, one of the requirements for keeping costs low is a mud system that gives good stability in bottom hole conditions and reduces non-productive time ([Shaughnessy, Romo et al. 2003](#)).

Geothermal and oil companies' attention has recently shifted to deeper wells, which can typically reach extreme temperatures ([Falcone, Liu et al. 2018](#), [Mohamed, Salehi et al. 2021](#)). As a result, the industry must devise viable solutions to keep mud fluid costs low. Bentonite water-based mud fluids (WBMs) are still regarded as the best option for drilling through complex formations ranging from HPHT formations to active shale formations due to their ease of modification and environmental friendliness. However, due to bentonite degradation, which may affect filtration properties and reduce the mud's ability to transport cuttings to the surface,

more modification may be required when using WBM in elevated conditions. These issues could have been resolved using polymers which are thermal insulators, but they have limited stability under elevated borehole conditions. Furthermore, polymers are poor at regulating fluid loss in permeable formations due to their micro-particle size ([Abdo and Haneef 2013](#), [Karakosta, Mitropoulos et al. 2021](#)). As a result, modifying the surface of bentonite particles may be the solution to improving the filtration and rheological properties of mud fluid ([Barry, Jung et al. 2015](#), [Mahmoud, Nasr-El-Din et al. 2018](#)) or that of silica nano particles. Nanoparticles have made their way into the drilling industry, where they have been used to enhance the properties of mud fluids. Nano silica is a useful filler, pigment, and catalyst that has been widely used in a variety of fields ([Castellano, Conzatti et al. 2005](#), [Lee, Du et al. 2006](#), [Bhagat, Kim et al. 2008](#)). Hydroxyl group (-OH) around silica nanoparticle (NP) surface on the other hand absorbs moisture and causes nanoparticle agglomeration. Agglomeration reduces their dispersion capability in the organic matrix hence limiting the application of silica nanoparticles in different applications.

Presently, there has been several studies on the integration of nanoparticles with drilling mud formulations. Even though a lot of success has been achieved in filtration loss improvement by researchers ([Mahmoud, Nasr-El-Din et al. 2017](#), [Smith, Rafati et al. 2018](#), [Edalatfar, Yazdani et al. 2021](#), [Martin, Babaie et al. 2022](#)), there are still concerns about the reducing cutting carrying capabilities of WBM with the addition of nanoparticles ([Ghasemi, Mirzaee et al. 2018](#), [Mahmoud, Nasr-El-Din et al. 2018](#), [Maiti, Bhaumik et al. 2021](#)). This is due to the interaction of nanoparticles with bentonite's negative surface charge, which results in either increased repulsive or attractive forces. Bentonite surface charge is negative due to the replacement of low valence atoms in its lattice ([Zhang, Xu et al. 2020](#), [Rana, Murtaza et al. 2022](#)). The charge on bentonite surface and the pH of the aqueous system influences the stability of colloidal suspension ([Zhang, Xu et al. 2020](#)). Because of that, bentonite solutions flocculate and aggregate in HPHT environments leading to decreasing yield point (YP) of the mud fluid and its ability to control filtration loss. ([Zhang, Xu et al. 2020](#)) and ([Barry, Jung et al. 2015](#)) highlighted the negative surface charge face and charged edge of bentonite clay platelets. The mode of interaction of hydrated bentonite which is due to the edge-to-face (E-F) and edge-to-edge (E-E) associations due to unbalanced net charges on the edge and surface of bentonite platelets was explained by ([Bourgoyne Adam, Chenevert et al. 1986](#)). As a result, in high pH and high temperature environments with the presence of cations, bentonite solution aggregates and flocculates leading to increased YP and decreasing filtration properties. Once nanoparticles (NPs) with a negative surface charge are introduced to the mud fluid, the situation becomes considerably worse because the electrostatic repulsive forces become more stronger and dominant ([Liu, Yao et al. 2021](#), [Ibrahim, Jaafar et al. 2022](#)). ([Mahmoud, Nasr-El-Din et al. 2016](#)) and ([Vryzas, Mahmoud et al. 2015](#)) showed that deflocculation occurs as a result of the repelling forces resulting in an increase in viscosity and a decrease in yield point hence lowering the cutting carrying ability during drilling. ([Elochukwu, Gholami et al. 2017](#)) conducted several experiments to improve WBM cutting transportation abilities by incorporating nano silica. They stated that the properties of WBM such as yield point had reduced affecting WBM's ability to transport cuttings to the surface. They applied alkylbenzyltrimethylammonium chloride (ABDACI) as a cationic surfactant to modify the surface of silica and successfully enhanced the yield point (YP) and plastic viscosity (PV) of the drilling mud. They pointed out that by adding modified nano silica at 2.0 wt.% concentration, filtration loss was reduced by 45.2% compared to unmodified nano silica and a thinner mud cake was produced.

In recent years, the majority of studies have focused on changes in either rheology or filtration loss individually. Therefore, more research into the nature of bentonite and its interaction with nanoparticles is still required. The aim of this work therefore is to develop a detailed study

about the interaction of nano silica in geothermal WBMs and provide an approach of enhancing the fluid loss and rheological properties of geothermal WBMs under HPHT geothermal conditions by adding silica nanoparticles. To accomplish this goal, a comprehensive experimental study with various mud samples containing unmodified and modified nano silica were developed and analysed under low pressure and low temperature (LPLT) and under high pressure and high temperature (HPHT) conditions to understand their rheology and filtration properties. In the following sections, Silicate muds are introduced and a technique for resolving the issue of adding nano silica to WBMs was investigated with the aim of enhancing the filtration properties without affecting rheology.

2. Silicate muds fluids

2.1. Applications

Because of their inhibitive and fluid loss control properties, potassium or sodium silicate-based mud fluids have been successfully used in drilling through reactive and low/high permeable formations. ([McDonald 2007](#)). The following are the processes by which silicates can reduce mud filtrate loss and water hydration.

- **Pore plugging:** This is one of the most vital characteristics of silicate drilling muds. Soluble silicates solutions begin as mono silicates that partly polymerises and creates negatively charged silicate oligomers. Because of mutual repulsion, the process comes to a halt at pH 11-12, leaving oligomers that can partly penetrate the micropore structure. The fluid loss containing the oligomers is provided by hydraulic flow or diffusion into the pore structure where:
 - a) The filtrate is diluted by pore fluid (pH +/-7), allowing the oligomers to overcome mutual repulsion and form silicate gels.
 - b) Silicate gels are formed when free available polyvalent cations in association with clay surfaces (or edges) react with oligomers.
 - c) The precipitated silicates (gel) act as a physical barrier, preventing additional pore penetration and filtrate invasion. As a result, the wellbore and formation are pressure separated, and fluid loss is halted.
- **Osmotic dehydration:** The precipitated silicates (gel) barrier also functions as a highly osmotic membrane, reducing drilling mud fluid (H₂O) activity. This creates an osmotic pressure, which drives osmotic movement of water from the formations to the drilling mud over the silicate barrier. Despite the small amount of water involved, this method effectively dehydrates the near wellbore: Dehydration results in increased near-wellbore effective stresses and shale strength, both of which are helpful to stability ([Alford, Asko et al. 2005](#)).
- **Ion Exchange:** Monovalent ions in a silicate base mud fluid, for example, K +, have the added benefit of being exchanged for Ca +2 and Mg +2 at the clay surface, allowing these ions to precipitate. The high salinity will also reduce silicate gelation times and boost silicate gel deposition ([Fritz and Jarrett 2012](#)).

Silicate mud fluids are less expensive than synthetic mud fluids commonly preferred for drilling HPHT wells, and can give excellent wellbore stability as well as good metal/shale and metal/sand stone lubricity ([McDonald 2007](#)). They are less prone to bit balling, which is needed for high rate of penetration (ROP), and they are also eco-friendly. However, more attention should be given for silicate-based drilling mud's hole cleaning capabilities because of the decrease in yield point of the muds ([Soric, Marinescu et al. 2004](#)). In comparison to typical silicate, nano silica possesses excellent thermal stability and is affinitive to acidic gases like CO₂ and H₂S. This means that nano silica drilling muds can overcome many of the drawbacks

of conventional drilling muds while keeping all their advantages. However, there are still issues concerning nano silica rheology and dispersion that must be addressed.

3. Experimental

3.1. Materials

The materials used in the mud formulations and chemicals used in the synthesis of silica nanoparticles were purchased from Fisher Scientific and SLS-Sigma-Aldrich. The synthesis of silica nanoparticles took place at the University of Salford petroleum lab. Table 1 below presents the materials and chemicals used in this experimental work.

Table 1: Materials and chemicals used in the study.

Components	Purity	Molecular weight (g/mol)	Density	Brand	Purpose
Bentonite	80-90%	180.1	600 - 1100 kg/m ³	Fisher scientific UK	Filtrate loss preventer, Viscosifier
Barite	98%	233.4	4500 kg/m ³	Fisher scientific UK	weight material
polyanionic cellulose	>98%	1.146	0.7- 2.85 kg/m ³	Fisher scientific UK	Filtrate loss preventer,
Hydrochloric acid (HCl)	37%	36.46	1200 kg/m ³	Fisher scientific UK	pH modifier
Sodium Hydroxide (NaOH)	99%	39.997	2130 kg/m ³	Fisher scientific UK	pH modifier
Flash water	- 99.96%	18.015	1000 kg/m ³	-	Base fluid for mud preparation
Tetraethyl orthosilicate (TEOS)	> =99.0%	208.33	940 kg/m ³	SLS-Sigma-Aldrich	Silica precursor
Hexadecyltrimethylammonium bromide (CTAB)	>95%	364.45	500 kg/m ³	SLS-Sigma-Aldrich	Surface charge modifier
Ethanol	>99.8%	46.069	780 kg/m ³	SLS-Sigma-Aldrich	Solvent
Ammonia 28%	28%	35.05	900 kg/m ³	SLS-Sigma-Aldrich	Catalyst in the silica synthesis
Milli-Q water	18.2 MΩ-cm	18.02	1000 kg/m ³	Millipore	Solvent

3.2. Methodology

3.2.1. Silica nanoparticle synthesis

This experimental study adopted the sol-gel process on the basis of a Stöber method of synthesising silica nanoparticles ([Stöber, Fink et al. 1968](#)). The synthesis of nanoparticles consisted of two stages: (1) hydrolysis of the precursor tetraethyl orthosilicate (TEOS) and (2)

condensation to form the silica nanoparticle structure ([Rahman and Padavettan 2012](#)). A gel is formed during the chain network formation process because a large amount of the solvent is added in the network. In this research, 3.35 grams of TEOS and 14.5 grams of ethanol were added and stirred for 1.5 hours at ambient conditions. Another 14 grams of ethanol, 0.57 grams of ammonia hydroxide (NH₄OH) and 0.5 grams of Milli-Q water were added dropwise, and the mixture was magnetically stirred for another 2 hours. A gel-like solution was formed which was centrifuged and then kept in the oven for 3 hours at 100 °C. Ethanol and water were used as solvents and ammonia hydroxide solution as a catalyst to initiate the reaction. Figure 1 shows the sol-gel process of synthesising silica nanoparticles.

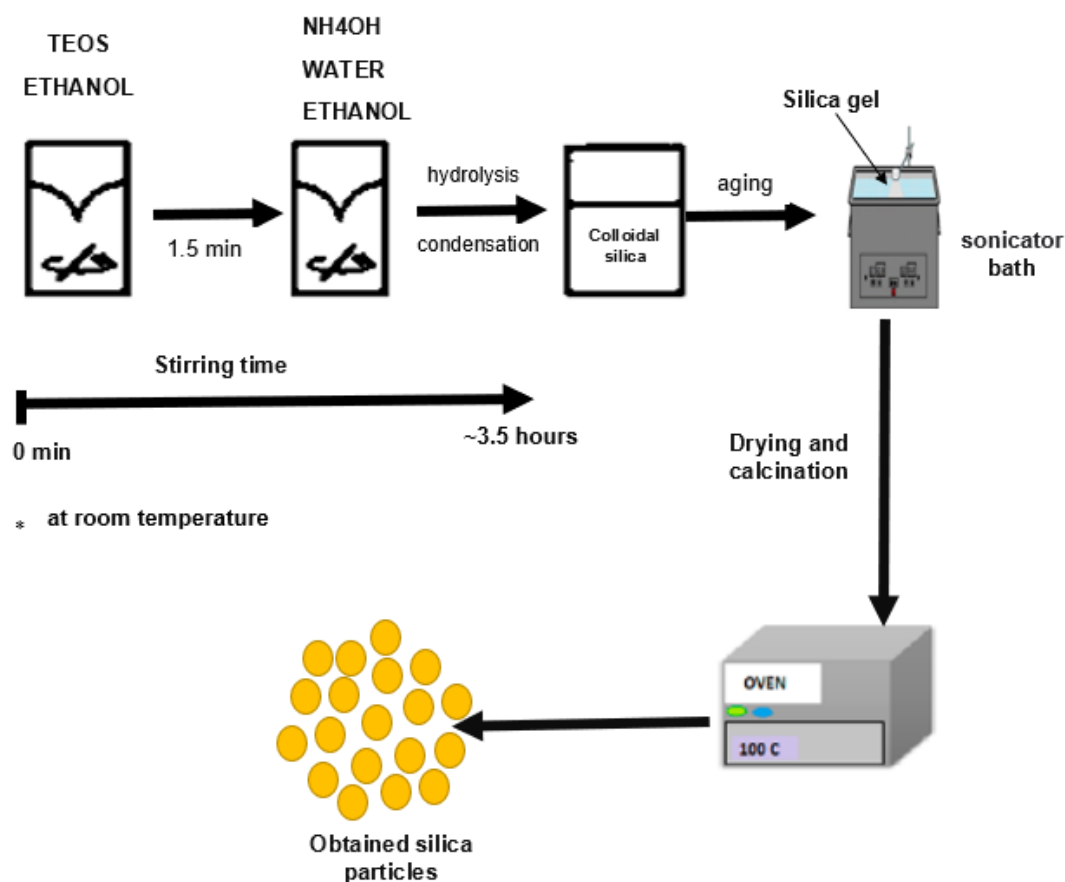


Figure 1. Flow chart of a typical sol-gel process.

3.2.2. CTAB solution formulation

To modify the surface charges, Hexadecyltrimethylammonium bromide (CTAB) cationic surfactant was used to improve the interaction between colloidal particles and silica NPs in drilling mud. Positively charged cationic functional groups are found at the heads of cationic surfactants. Cations possess a higher surface wettability, emulsifying and solubilization ability, and are pH resistant ([Wang, Meng et al. 2016](#)). They are also thought to be a biodegradable material ([Scott and Jones 2000](#)). According to ([Alemdar, Atc, & Güngör, 2000](#)), surfactant adsorption grafted around the surface of a charged particle can change the charge distribution and affect particle interactions. As a result, the rheology and fluid loss properties of WBMs can be improved with the addition of a suitable surfactant. CTAB concentration dissolved in 50 ml of deionized water was 5.0 wt. %. According to ([Guan, Gholami et al. 2020](#)), the authors determined the Critical Micelle Concentration (CMC) of CTAB to ascertain the saturation limit of surfactants in water. The authors found out that, CTAB at 5.0 wt.% was appropriate as

above that, surfactant's monomers called micelle start to aggregate resulting to unwanted changes to the properties of the solution such as , absorption, surface tension, conductivity and osmotic pressure ([Karimi, Mozaheb et al. 2015](#)).

3.2.3. Modification of nano silica

Various concentrations of CTAB (0.25 wt. percent, 0.5 wt. percent, 1.0 wt. percent, and 2.0 wt. percent) were added to silica solution to ascertain the best concentration that could effectively alter the surface of silica nanoparticles. The mixtures were stirred constantly for 10 min with the Homogenizer at a constant rotational speed of 2000 RPM, followed by 15 minutes of sonication to produce a well-distributed solution. The solutions were then dried in the oven at 100 °C for 3 hours to formulate powdered silica and after, silica was added in bentonite mud formulations for analysis. The samples prepared for this study are summarized in Table 3.

3.2.4. The Reaction processes

The nano particle size modified was 67.54 nm hence the contact area between CTAB and silica NP would be large enough as compared to larger sizes leading to a large surface area for interaction. Furthermore, the pH value was maintained at 10 by adding 0.1 M NaOH to enable enough hydroxyl groups to occur on the silica surface. Since silica surface charge is negative, addition of CTAB to the system will lead to formation of the organic chain of CTAB array around nano silica due to the ionic interaction between the negative and positive charges on the surface of silica NPs. Lastly, cation reacts with the hydroxyl groups on the silica surface, resulting in the surfactant being grafted on the silica surface and thus lowering the surface energy of silica NPs. On the other hand, after the organic chain of CTAB grafting on the surface of silica NPs, the steric among the NP increases, resulting in a more mono-dispersed colloidal solution. As a result of these factors, the stability of silica NPs increases, and the dispersed state improves. ([Ma, Lee et al. 2010](#)).

3.2.5. Mud sample formulations

3.2.5.1. Reference mud

The WBM developed for this investigation adhered to the ([API 13B-1 2009](#)) standard and composed of 22.5g bentonite, 20.3g barite, 0.5g polyanionic cellulose and 350 ml deionized water. The Hamilton Beach mixer was used to mix bentonite, water, and other additives for half an hour at room temperature. All drilling fluid formulations were mixed at the same rate of 11,500 RPM to enable the muds to mix well without coagulation or forming of solids of bentonite. The pH of all the mud formulations was kept in the range of 9.5 – 10 for better colloidal solution stability by adding Sodium hydroxide and sulfuric acid. The samples were kept to age for 16 hours at normal temperature to fully hydrate. Tables 1 and 2 shows the chemical components and a list of apparatuses used to prepare drilling mud samples respectively. The experimental results were measured using the M1100 viscometer. All tests were repeated 3 times to check repeatability and reproductivity of the results to ensure that accuracy is maintained.

3.2.5.2. Mud with unmodified silica

Silica nanoparticles used in this experimental work were synthesized in the lab. The NP size as measured by the DLS was 67.54 nm. WBMs with unmodified silica nanoparticles were designed by adding 0.5 wt.% of unmodified silica NPs to the reference mud at the same rate of 11,500 RPM to enable the muds to mix well without coagulation or forming of solids of bentonite and other additives. The concentration of silica nanoparticles was selected basing on the authors previous study ([Martin, Babaie et al. 2022](#)) which concluded that any

concentration below 0.5 wt.% had no visible effect and any concentration above 1 wt.% would not be cost effective. Sodium hydroxide and sulfuric acid were added to modify the mud fluid pH in the range of 9.5 – 10 for better colloidal solution stability. The same procedure as mentioned earlier for the preparation of the reference mud was followed thereafter.

3.2.5.3. Mud with modified silica

WBMs with modified silica NPs were designed by adding 0.5 wt.% of modified nano silica dispersed in the CTAB surfactant prepared earlier to the reference mud at the same rate of 11,500 RPM to enable the muds to mix well without coagulation or forming of solids of bentonite and other additives. To improve colloidal solution stability, sodium hydroxide and sulfuric acid were added to the mud fluid to raise the pH to 9.5 - 10. The same procedure as mentioned earlier for the preparation of the reference mud was followed thereafter.

Table 2: List of apparatuses used in this study.

Equipment	Purpose
Electric scale	To measure the amounts of additives
Hamilton beach mixer	To mix the bentonite solution
Homogenizer	To stir the mixture of silica NP in the mud to prevent flocculation
Branson 1510 Bransonic Ultrasonic	For sonicating the silica solution into well dispersed solution
Magnetic plate stirrer	For mixing and synthesis of nanoparticles
Dynamic light scattering (DLS) (Malvern Nano Zetasizer)	To characterise silica NP size and analyse the zeta potential of the silica NP solution
MISTRAL 1000 centrifuge	To separate the solids from the solution
Model M1100 viscometer	To analyse the rheology of the mud fluid
Hot roller oven	To expose the mud samples to bore hole conditions
API HPHT filter press	To analyse the filtrate properties of the mud fluid

Table 3: Mud samples prepared for this study.

Sample	Zeta Potential	Abbreviated Name
22.5 g Bentonite + 20.3 g Barite + 0.5 g PAC + 350 mL water	Reference Mud (R)	S 1
22.5 g Bentonite + 20.3 g Barite + 0.5 g PAC + 350 mL water + 0.5 wt.% SNPs (67.54 nm)	SNP3 (-17.7 mV)	S 2
22.5 g Bentonite + 20.3 g Barite + 0.5 g PAC + 350 mL water + 0.5 wt.% SNPs + 0.25 wt.% CTAB	SNP3 (20 mV)	S 4
22.5 g Bentonite + 20.3 g Barite + 0.5 g PAC + 350 mL water + 0.5 wt.% SNPs + 0.5 wt.% CTAB	SNP3 (28.2 mV)	S 5
22.5 g Bentonite + 20.3 g Barite + 0.5 g PAC + 350 mL water + 0.5 wt.% SNPs + 1.0 wt.% CTAB	SNP3 (35.4 mV)	S 6

4. Results and Discussions

During the experimental work, various concentrations of Hexadecyltrimethylammonium bromide (CTAB) were added to modify the surface of silica nanoparticles. A range of different temperatures and silica nanoparticles in drilling mud formulations were tested to ascertain the effect of silica nanoparticle surface modification on drilling mud properties under HPHT bore hole conditions. The mud samples' fluid loss properties and rheology were investigated. The result's repeatability was guaranteed by repeating the experiments three times and conducting statistical analysis on the results. For all the experiments, the computed standard deviation (SD) was minimal, indicating that the data was very reliable. The obtained results are presented and analysed in the sections that follow.

4.1. CTAB concentration

When particles are dispersed in a solution, their surface charge is often different from the solution's surface charge which can lead to undesirable interactions in the aqueous system. According to ([Hunter 2013](#)) the stability of scattered particles in an aqueous medium is represented by the zeta potential. It is stated that the bigger the zeta potential (ZP) value is, the better the electrostatic stability and more stable the particle dispersion in the solution becomes. Bentonite suspensions have been found to have a negative zeta potential ([Al-Risheq, Shaikh et al. 2022](#)). As mentioned earlier, ZP plays a vital role in the performance of the rheological behavior. Therefore, addition of silica nanoparticles may lead to increasing repulsive forces between the bentonite clay platelets and the negative surface charge of silica NPs which might result to deflocculation of platelets and hence lead to weaker yield structure and higher viscosities ([Abu-Jdayil, Ghannam et al. 2016](#), [Mahmoud, Nasr-El-Din et al. 2016](#)). From Figure 2, addition of CTAB in the nanoparticle solution led to increase in the zeta potential value. It should be noted that silica NP without CTAB had a negative zeta potential of -17.7 mV and with CTAB, the zeta potential changed because of the decreasing surface energy of silica NPs with addition of CTAB as seen from Figure 2. This is because, the cation molecules initially dissociate into positively charged Centrimonium ions due to the electrostatic attraction between the positively charged Centrimonium ions and the negatively charged surface of silica NPs. Ionic interaction then occurs as a result of the formation of an organic chain of CTAB arrays which reduces the surface energy of silica NPs. This causes the arrangement of atoms in the molecules among silica NPs to change causing silica NPs to appear monodispersed and thus improving the solution's stability. ([Ma, Lee et al. 2010](#)). Furthermore, the grafting of the organic chain of the cation on the surface of silica nanoparticles causes the steric among silica NPs to become bigger which also increases silica mono-dispersity. Because of these factors, the stability of silica NPs improves, as does the dispersed phase. ([Ma, Lee et al. 2010](#)).

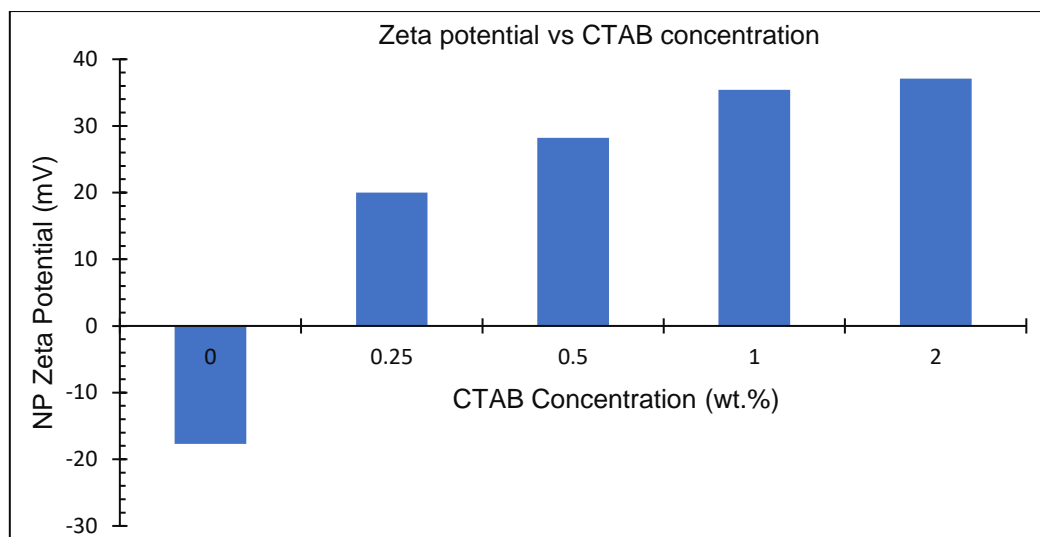


Figure 2: Analysis of zeta potential at different CTAB concentrations (wt.%)

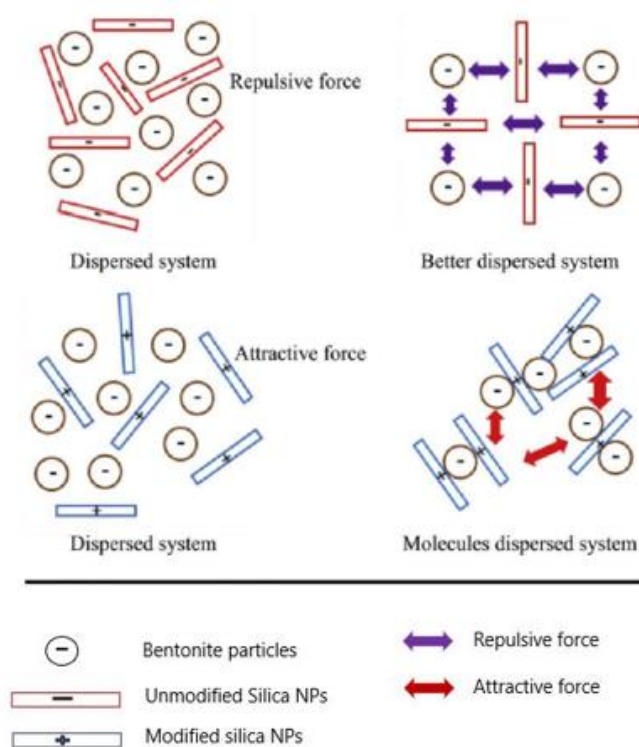


Figure 3. Interaction between unmodified silica NPs and bentonite (top) and Interaction between modified silica NPs and bentonite (bottom) (Guan, Gholami et al. 2020)

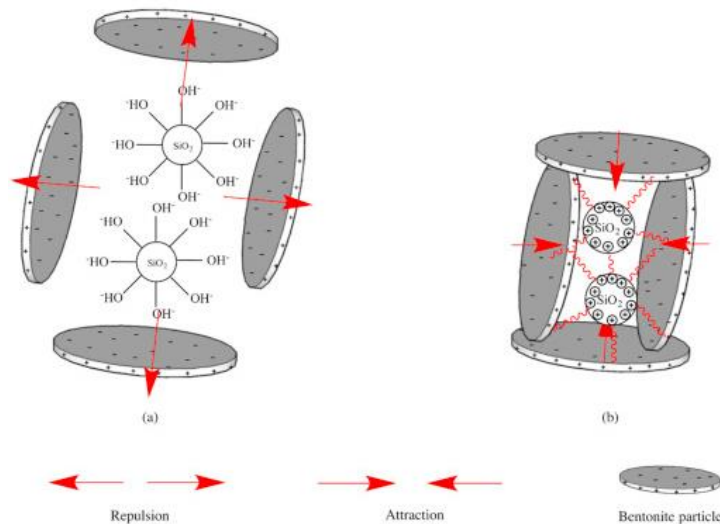


Figure 4. Repulsion and attraction between bentonite particles and (a) unmodified (b) modified nano silica (Elochukwu, Gholami et al. 2017)

4.2. Effects of modified NPs on drilling mud before hot rolling (BHR)

Table 4 presents the rheological values of the mud samples taken at normal conditions. When compared to other models, the Herschel-Bulkley which contains Bingham plastic and Power law is the most accurate in describing the rheological behavior of the mud fluids because it provides the best match to the viscometer data.

Table 4: Rheology of mud samples before aging

Samples	Herschel-Bulkley		Mud cake (mm)	10sec Gel (lb/100ft ²)	Fluid loss (ml)
	YP (lb/100ft ²)	PV (cP)			
Ref mud - S 1 (R)	16.5 (SD=0.63)	11.50 (SD=0.21)	0.35 (SD=0.005)	9.5 (SD=0.24)	9 (SD=0)
SNP3 - S 2 0.5wt. %	8.19 (SD=0.55)	14.69 (SD=0.07)	0.2 (SD=0.005)	5.30 (SD=0)	9 (SD=0)
SNP3 - S 4 0.5wt. %	7.04 (SD=0.84)	13.82 (SD=0.29)	0.3 (SD=0)	6.5 (SD=0)	10 (SD=0)
SNP3 - S 5 0.5wt. %	6.46 (SD=0.70)	9.96 (SD=0.25)	0.3 (SD=0)	5 (SD=0.47)	9.3 (SD=0)
SNP3 - S 6 0.5wt. %	18 (SD=0.82)	11 (SD=0.82)	0.47 (SD=0.47)	12 (SD=0)	9.72 (SD=0)
SNP - S 7 0.5wt. %	7.2 (SD= 0.31)	9.2 (SD=0.27)	0.33 (SD=0.05)	9 (SD=0)	10.04 (SD=0)

From Table 4, changes in surface modification did not result in rheological enhancement of the drilling mud samples at low pressure, low temperature (LPLT) conditions. There was not much difference in the rheology of the reference mud and the muds with modified silica nanoparticles. From the results, the reference mud performed equally to the muds with silica NPs and in some cases better than the silica muds. Furthermore, when compared to the muds

with silica nanoparticles, the filtration properties of the reference mud and the mud sample with unmodified silica NPs were better, as less filtrate was lost, as shown above.

4.3. Effects of increased temperature on drilling mud samples

As seen below in Table 5, the rheological properties of the drilling mud were presented after aging the mud samples at different temperatures and pressure. All nanoparticle mud samples maintained their rheology to the required standard. The data also confirms that the reference mud maintained its properties with increased temperature to a certain degree. The stability of a mud system is a vital requirement for a successful drilling operation to be achieved. The mud fluid's ability to retain half of its viscosity or filtrate loss after aging for 16 hours at a chosen temperature is referred to as its stability ([Howard 1995](#)). With increasing temperature, some rheological property readings of the mud samples increased. This is because, temperature has a tendency of changing the behavior of the mud by exerting a complex high temperature thickening behavior leading to viscosity increase after aging as witnessed from the reference and unmodified silica mud formulations for they exhibited higher viscosities with increase in temperature. The YP of the unmodified mud sample was lower compared to modified silica nanoparticles as temperature increased. This is because of the repulsive forces existing between the unmodified silica NPs and bentonite which resulted in reduced YP and increased PV due to the formation of a deflocculated particle structure. For the reference mud, there was an increase in YP up until the temperature of 121 °C and thereafter, a decrease in YP was observed. This is due to the fact that up to a temperature of 121°C, bentonite WBMs maintain their stability and show signs of shear thickening behaviour above 121°C. This results in gelling and solidification of the mud which leads to filtration problems in the borehole ([Smith 2001](#)). This also explains the increase in plastic viscosity of the reference mud with increased as temperature increased above 121°C.

Table 5: Effects of increasing temperature on the rheology of drilling mud.

Herschel -Bulkley						
Drilling fluid	Temperature (°C)	Yield point (lb/100ft ²)	Plastic viscosity (cP)	Mud cake (mm)	10sec Gel (lb/100ft ²)	HPHT Fluid loss (ml)
Ref mud - S 1 (R)	BHR	16.5 (SD=0.63)	11.50 (SD=0.21)	0.35 (SD=0.005)	9.5 (SD=0.24)	9 (SD=0)
	AHR @ 100 °C	14.99 (SD=1.4)	18.02 (SD=0.36)	0.4 (SD=0)	11.75 (SD=0.43)	9.7 (SD=0)
	AHR @ 121 °C	12.58 (SD=0.73)	19.5 (SD=0.24)	0.5 (SD=0.1)	6 (SD=0)	16.7 (SD=0)
	AHR @ 149 °C	5.66 (SD=0.43)	25.9 (SD=0.16)	0.55 (SD=0.04)	6.2 (SD=0)	17.5 (SD=0)
	AHR @ 179 °C	6.30 (SD=1.46)	26.20 (SD=0.66)	0.89 (SD=0)	3 (SD=0)	19.6 (SD=0)
	AHR @ 204 °C	7.10 (SD=2.48)	27.30 (SD=2.47)	0.95 (SD=0)	4.5 (SD=0.5)	20.85 (SD=0)

	AHR @ 232 °C	7.30 (SD=0.96)	26.82 (SD=2.93)	1.1 (SD=0)	37.37 (SD=4.18)	25 (SD=0)
SNP3 - S 2 0.5 wt. %	BHR	8.19 (SD=0.55)	14.70 (SD=0.07)	0.2 (SD=0.005)	5.3 (SD=0)	9.0 (SD=0)
	AHR @ 100 °C	10 (SD=2.18)	30.65 (SD=0.82)	0.6 (SD=0)	8 (SD=0)	13 (SD=0)
	AHR @ 121 °C	13.2 (SD=3.77)	26.1 (SD=1.44)	0.6 (SD=0)	5 (SD=0)	13.5 (SD=0)
	AHR @ 149 °C	13.5 (SD=1.77)	26.20 (SD=0.58)	0.65 (SD=0)	22.5 (SD=2.96)	19.06 (SD=0)
	AHR @ 179 °C	11.3 (SD=0.117)	28.5 (SD=0.3)	0.67 (SD=0.05)	11 (SD=0)	17.4 (SD=0)
	AHR @ 204 °C	10.20 (SD=0.59)	30.9 (SD=0.23)	0.72 (SD=0.02)	24.5 (SD=0.5)	20.22 (SD=0)
	AHR @ 232 °C	9.2 (SD=1.59)	32.60 (SD=0.3)	0.85 (SD=0)	25.75 (SD=0.83)	22.95 (SD=0)
SNP3 - S 4 0.5 wt. %	BHR	7.04 (SD=0.84)	13.82 (SD=0.29)	0.3 (SD=0)	6.5 (SD=0)	10 (SD=0)
	AHR @ 100 °C	14.91 (SD=0.051)	25.53 (SD=0.064)	0.6 (SD=0)	6.0 (SD=0)	10.33 (SD=0)
	AHR @ 121 °C	25.20 (SD=1.83)	24.23 (SD=1.09)	0.53 (SD=0.02)	7.75 (SD=0.43)	9.24 (SD=0)
	AHR @ 149 °C	10.3 (SD=0.5)	25.29 (SD=0.63)	0.6 (SD=0)	19.5 (SD=0.47)	14.32 (SD=0)
	AHR @ 179 °C	9 (SD=1.77)	19.64 (SD=0.8)	0.62 (SD=0.02)	28.5 (SD=0.87)	14.81 (SD=0)
	AHR @ 179 °C	10 (SD=7.83)	16.25 (SD=3.94)	0.63 (SD=0)	22.25 (SD=1.79)	20.12 (SD=0)
	AHR @ 179 °C	9.60 (SD=7.5)	15.20 (SD=3.32)	0.65 (SD=0.25)	34.75 (SD=8.58)	23.10 (SD=0.72)
	BHR	6.46 (SD=0.70)	9.96 (SD=0.25)	0.3 (SD=0)	5 (SD=0.47)	9.3 (SD=0)

SNP3 - S 5 0.5 wt.%	AHR @ 100 °C	19 (SD=0)	26.34 (SD=0.47)	0.4 (SD=0)	8.67 (SD=0.47)	13 (SD=0)
	AHR @ 121 °C	21.93 (SD=0.09)	29.46 (SD=1.38)	0.4 (SD=0)	5 (SD=0)	9 (SD=0)
	AHR @ 149 °C	16.20 (SD=3.19)	25.12 (SD=2.81)	0.6 (SD=0.02)	2 (SD=0)	13.3 (SD=0)
	AHR @ 179 °C	15.20 (SD=0.5)	23.60 (SD=0.998)	0.7 (SD=0)	21.25 (SD=1.09)	16.92 (SD=0)
	AHR @ 204 °C	16 (SD=0.62)	25.23 (SD=0.51)	0.72 (SD=0.05)	23 (SD=0)	20.77 (SD=0)
	AHR @ 232 °C	20.3 (SD=4.11)	26.33 (SD=0.47)	0.69 (SD=0)	19 (SD=8.29)	22.56 (SD=0)
SNP3 - S 6 0.5 wt.%	BHR	18 (SD=0.318)	11 (SD=1.15)	0.47 (SD=0)	12 (SD=0)	9.72 (SD=0)
	AHR @ 100 °C	33.34 (SD=0.47)	22.3 (SD=1.25)	0.6 (SD=0)	21 (SD=0)	8.23 (SD=0)
	AHR @ 121 °C	29.34 (SD=2.49)	21.33 (SD=0.47)	0.56 (SD=0)	20 (SD=0)	15.31 (SD=0)
	AHR @ 149 °C	30.33 (SD=)	17.67 (SD=1.25)	0.52 (SD=0.04)	22 (SD=0)	15.20 (SD=0)
	AHR @ 179 °C	30.34 (SD=6.34)	19.33 (SD=0.47)	0.65 (SD=0.05)	21 (SD=0)	15.31 (SD=0)
	AHR @ 204 °C	30.20 (SD=0.82)	13 (SD=0.82)	0.72 (SD=0.05)	20.5 (SD=0)	15.85 (SD=0)
	AHR @ 232 °C	32.25 (SD=3.59)	13.81 (SD=3.78)	0.67 (SD=0.08)	19 (SD=4.56)	17.90 (SD=2.74)
SNP3 - S 7 0.5 wt.%	BHR	7.20 (SD= 0.31)	9.2 (SD=0.27)	0.33 (SD=0.05)	9 (SD=0)	10.04 (SD=0)
	AHR @ 100 °C	9.89 (SD=0.14)	16.18 (SD=0.27)	0.5 (SD=0)	10.20 (SD=0)	9.74 (SD=0)
	AHR @ 121 °C	16.14 (SD=3.65)	13.25 (SD=0.73)	0.35 (SD=0.05)	10.8 (SD=0)	6.55 (SD=0)
	AHR @ 149 °C	16.64 (SD=0.69)	15.78 (SD=1.93)	0.43 (SD=0.82)	14 (SD=0)	10.9 (SD=0)

AHR @ 179 °C	15.19 (SD=0.9)	14.66 (SD=2.9)	0.52 (SD=0)	20 (SD=0.8)	14.6 (SD=0)
AHR @ 204 °C	17.80 (SD=9.24)	12.50 (SD=7.3)	0.6 (SD=0.17)	19 (SD=0.82)	15 (SD=0)
AHR @ 232 °C	20 (SD=3.81)	11.96 (SD=2.63)	0.65 (SD=0.14)	25.70 (SD=0.47)	16.60 (SD=0)

4.4. Effects of Aging on mud rheology

Rheology was studied to see if modified silica NPs could maintain and stabilize WBM under HPHT conditions. This would help to determine the behavior of drilling muds during circulation and would play a major role in establishing the borehole cleaning abilities, rate of penetration, and cuttings carrying abilities of the mud formulations. Aging of the mud samples was performed using aging cells which were filled with the mud, pressurized, and inserted into the roller oven at different temperature and pressure for 16 hours. After, the cells were cooled down by placing them in a cold-water bath, agitated again for 10 minutes at 11, 500 RPM before analysis. The results from the analysis of the mud samples containing unmodified and modified silica were presented below.

Plastic viscosity (PV). Figure 5 below presents the effect of HPHT conditions on the mud fluids PV. Plastic viscosity is the total resistance to fluid flow which includes the sum of the friction of solids and liquid in a drilling mud system. Increase in plastic viscosity is unwanted as it affects the rate of penetration when drilling. Temperature increase affects the efficiency of mud fluid additives to protect bentonite clay particles. A high plastic viscosity is undesirable condition because it reduces the drilling mud pumpability, increases pump pressure expenses and jeopardizes drilling mud efficiency.

From Figure 5, it is evident that the unmodified silica NP mud exhibited higher viscosity at all temperatures compared to other mud formulations. The viscosity rise was even greater than the reference mud. Increase in plastic viscosity of unmodified NP mud was due to the electrostatic repulsive forces between silica NPs and bentonite as seen in Figure 3, preventing free movement of particles in the drilling mud leading to increasing PV. Temperature exerted a complex influence on the mud rheology. For the unmodified NP mud and reference mud, the effects were high temperature thickening and high temperature solidification instead of high temperature thinning ([Bland, Mullen et al. 2006](#)). For bentonite WBMs, they can withstand temperature effects up to 121 °C and will exhibit shear thickening at temperature above 121 °C hence leading to filtration and borehole problems ([Smith, Rafati et al. 2018](#)). Though modified silica NP muds exhibited the same trend up to a temperature of 149 °C, there was a steady decrease thereafter in plastic viscosity indicating stability of the mud systems. In this case, temperature exerted a high temperature thinning behavior. Stable viscosity at high temperature indicates the ability of NPs to suppress viscosity decrease therefore showing the same rheological behavior at various temperatures. This was because of the interaction of the negatively charged bentonite and positively charged silica NPs which led to the formation of larger size particles in the mud system as shown in Figure 3. Hence, the larger the particle size is, the lower the viscosity would be ([Ismail, Aftab et al. 2016](#)). Therefore, the mud containing silica NP with higher zeta potential SNP3-S7 exhibited a more stable profile

followed by formulation SNP3-S6 indicating that muds with modified silica perform better at all temperatures.

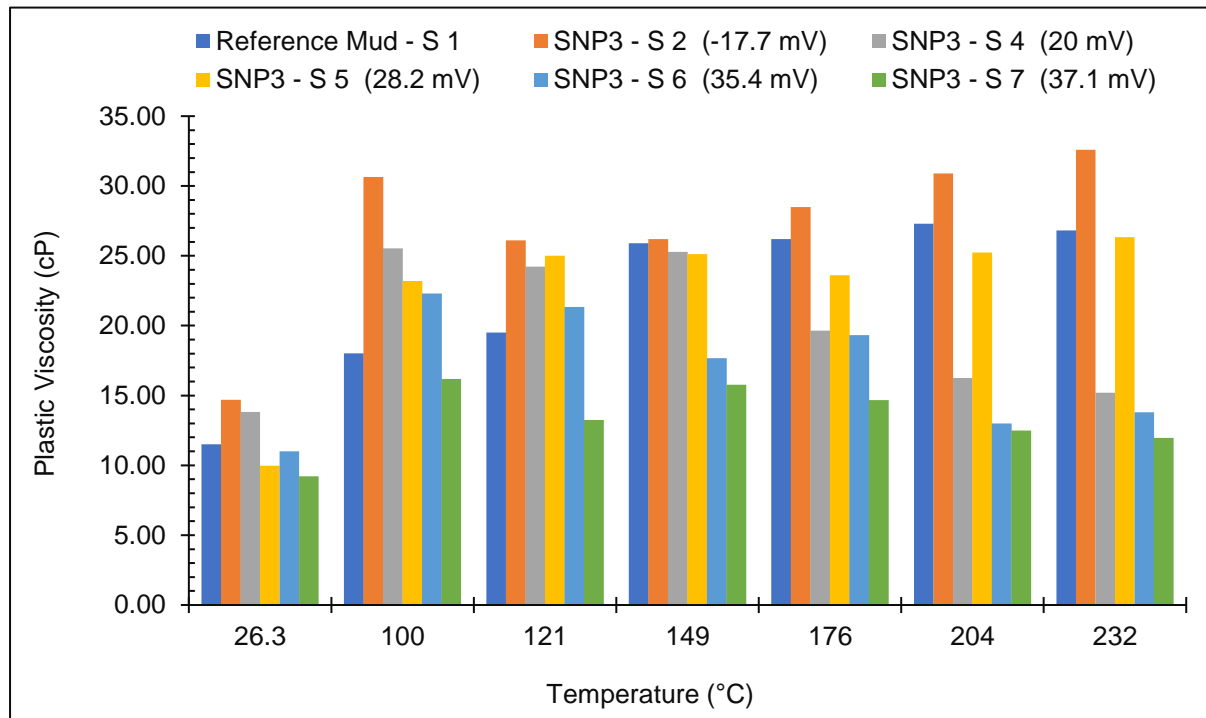


Figure 5: Comparative analysis of plastic viscosity at different aging temperatures at 25 psi, 50 psi, 100 psi, 150 psi, 250 psi, 300 psi.

Yield point (YP). It indicates the ability of the mud system to carry cuttings from the borehole to the surface during a drilling operation. A shear stress is needed to exceed a critical value for the initial fluid to flow. (Rafati, Smith et al. 2018). There are different mechanisms in play that cause a decrease or increase in mud properties and among them is the electrochemical attractive and repulsive forces. These forces are due to the surface charges of the particles in the dispersion and have a vital role to play in the stability of the mud system. From Figure 6 below, we observed a non-monotonic trend in the behaviour of mud fluid systems at all varying temperatures. The reference mud fluid provided better stability at temperatures up to 121 °C by exhibiting stable YP values. It was observed that the reference mud performed better than the muds with unmodified silica and some muds with modified silica at LTLP conditions. But above 121 °C, the reference mud YP started to decrease. This inconsistent in rheological profile indicates the start of rheological loss and the loss of the cut carrying abilities of the mud fluid system. Temperature changes facilitate the electrochemical effect that then speeds up the ionic activity of the electrolyte and the dissolving of any partially soluble salts present in the fluid. This alters the balance of the electrochemical forces in play therefore impacting on the degree of flocculation and dispersion of the mud fluid (Ibeh 2010). From temperatures of 149 °C to 232 °C NP muds exhibited better stability compared to the reference mud. More so, muds with modified silica performed better than muds with unmodified silica from the temperature of 100 °C all throughout indicating better stability at HPHT conditions. It is evident that the YP of modified NP muds was higher than the unmodified mud samples. That was because of the interaction of the negatively charged bentonite and positively charged modified nano silica which resulted in formation of bigger particles in the dispersion seen in Figure 3 leading to lower viscosity and higher yield point. More so, at higher temperatures, modified silica NPs displaced the dissociated cationic surfactant from the surface of bentonite (Ramos-Tejada, Arroyo et al. 2001, Laribi, Fleureau et al. 2006) which led to altering the clay platelet

structure resulting in higher yield point values (Jung, Son et al. 2011, Barry, Jung et al. 2015). On the contrary, adding unmodified negatively charged silica increased the electrochemical repulsive forces between the bentonite clay platelets and silica surface charge leading to deflocculation of the platelets hence resulting in lower yield point and higher viscosities. It was also observed that mud samples with modified NPs having a higher absolute zeta potential value performed better than other muds with a smaller absolute zeta potential value. According to (Hunter 2013), the author observed that zeta potential ranging from + 30 mV and - 30 mV demonstrates the instability of nano silica with the tendency to aggregate and flocculate well as nano silica surface with zeta potential larger than + 30 mV and less than – 30 mV are generally stable. These finding are evident in the current findings as demonstrated from the performance and stability of the modified mud samples with the highest absolute zeta potential values. Modified NP muds SNP3 – S 6 and SNP3 - S 7 with higher absolute zeta potential values performed better than other mud samples at HPHT conditions.

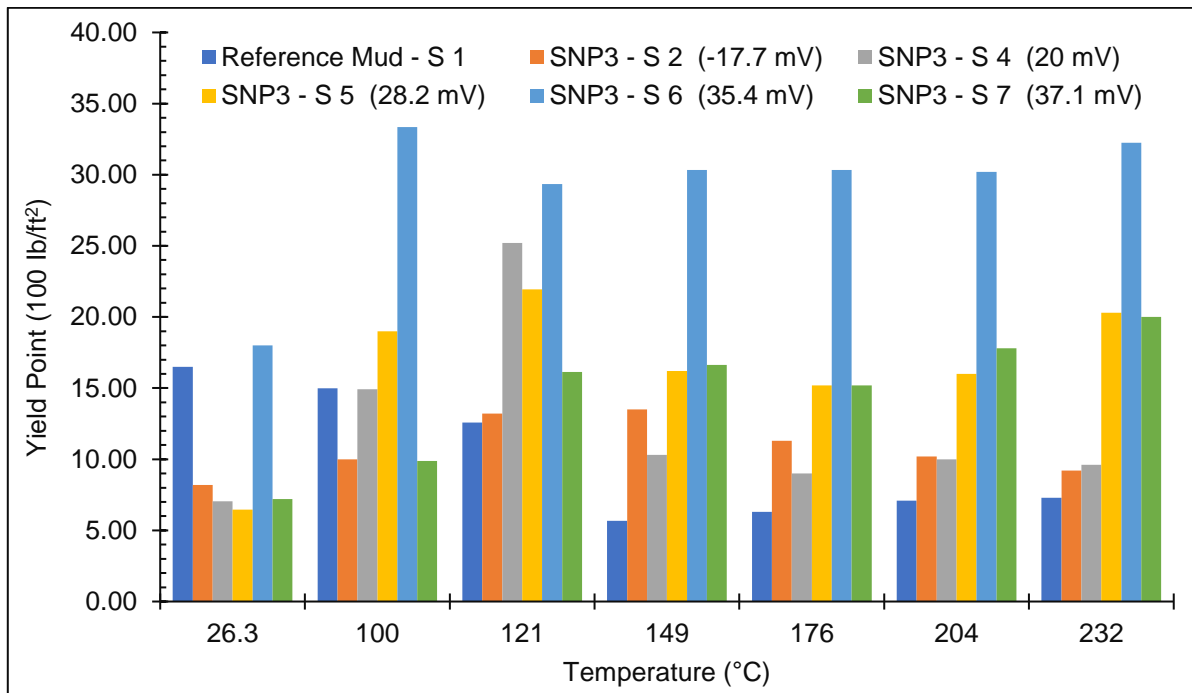


Figure 6: Comparative analysis of yield point at different aging temperatures at 25 psi, 50 psi, 100 psi, 150 psi, 250 psi, 300 psi.

Filtration Loss. This test was used to analyse the filtration properties of the mud samples using the HP/HT filtration test under a differential temperature condition and pressure of 100 °C and 500 psi, respectively. The filtrate test was carried out both under normal conditions and elevated conditions. The filtrate loss and mud cake were measured after the test was run for 30 mins. Figure 7 shows a comparative analysis of the performance of different mud samples under elevated temperature and pressure.

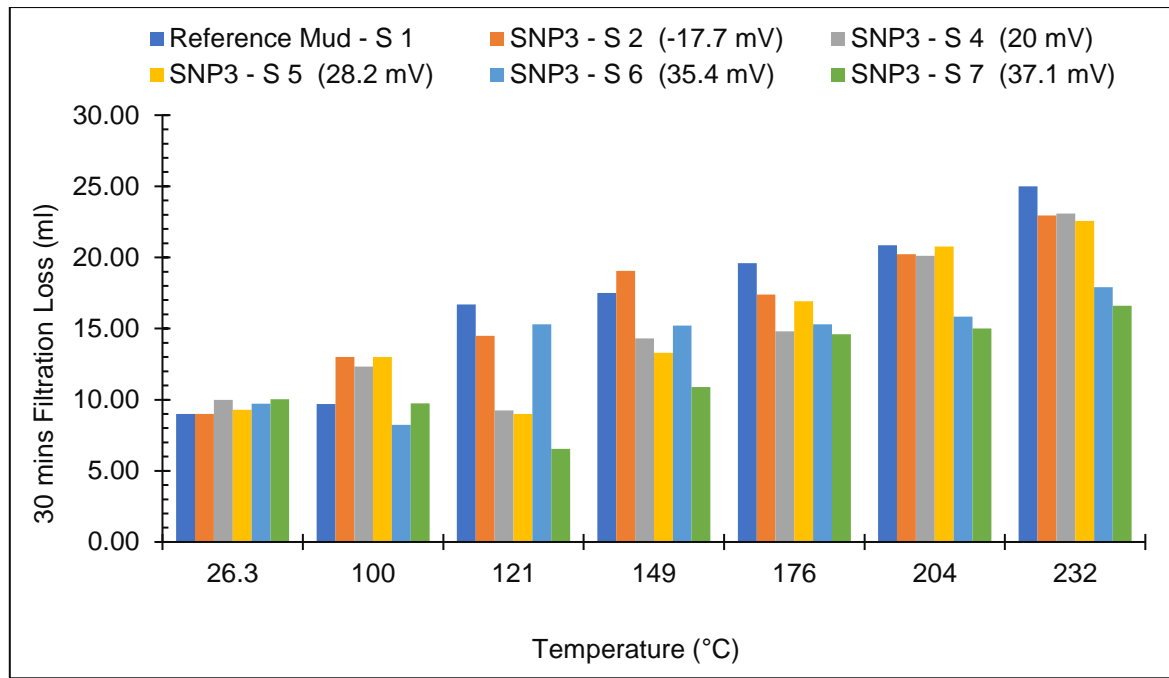


Figure 7: Comparative analysis of filtrate loss at different aging temperatures at 25 psi, 50 psi, 100 psi, 150 psi, 250 psi, 300 psi.

From Figure 7 above, filtration loss at LPLP up to 100 °C for the reference mud showed no major, or statistically significant variation in the fluid loss across the samples, with the reference mud performing similarly or better than the nanoparticle muds. The nanoparticle muds generally exhibited a higher filtrate loss at LPLP conditions until a temperature of 100 °C. There was an increase in filtrate loss with increase in temperature for most samples. As temperature increased, the filtrate loss from the reference mud and mud with unmodified silica was higher than the filtrate loss from the muds with modified silica. From the temperature of 121 °C, the reference mud lost the highest filtrate. This was because bentonite is sensitive to temperature and in HPHT conditions, the polymers degrade leading to increasing fluid loss and poor upward cuttings carrying abilities ([Bourgoyne Adam, Chenevert et al. 1986](#), [Kelessidis, Tsamantaki et al. 2007](#)). From the study of ([Smith, Rafati et al. 2018](#)), the authors stated that the stability of bentonite WBMs can be maintained up to a temperature of 121 °C and thereafter, degradation occurs. This is because, at temperatures above 121 °C, WBMs exhibit a shear thickening behaviour resulting to gelling and filtration problems. On the other side, the addition of unmodified silica NPs did not solve the problem as filtration loss was similarly or greater than the reference mud. The high volume of filtrate loss was because of the deflocculation of bentonite particles due to the electrostatic repulsion between silica NPs and bentonite particles via face-to-face interaction which resulted in failure to form a linked structure as seen in Figure 4 (a) ([Elochukwu, Gholami et al. 2017](#)). Poor structure formation network of silica NPs and bentonite resulted to deflocculation. Modified silica performed better than unmodified silica as the volume of filtrate loss was less compared to other mud samples especially muds with a higher value of zeta potential. The performance of modified silica was due to the face-to-face electrostatic attraction between (modified silica and bentonite) and the edge-to-face (positive edge bentonite - negative face bentonite) seen in Figure 4 (b). This configuration traps modified silica between the clay particles forming clusters known as heterocoagulated formation ([Elochukwu, Gholami et al. 2017](#), [Guan, Gholami et al. 2020](#)). This formed structure holds and retains the fluid within the formation hence reducing the filtrate volume loss. ([Daswani and Van Herk 2014](#)) stated that when two particles of distinct

characteristics e.g. size, chemical composition or charge interact, it will lead to forming clusters, and lastly result in the formation of a gel like structure termed as heterocoagulation.

Gel strength 10 sec. This property is vital as it facilitates the holding of drilled cuttings when the pump is off. A drilling mud must be able to carry drilled cuttings during a drilling operation and support the suspension of drilled cuttings when drilling is stopped e.g., for reasons of workover operations or tripping. After shearing for 10 seconds at 600 rpm, the gel strength was measured. Prior to testing, the samples were agitated for 5 minutes at 11,500 rpm, giving them the same preshearing history.

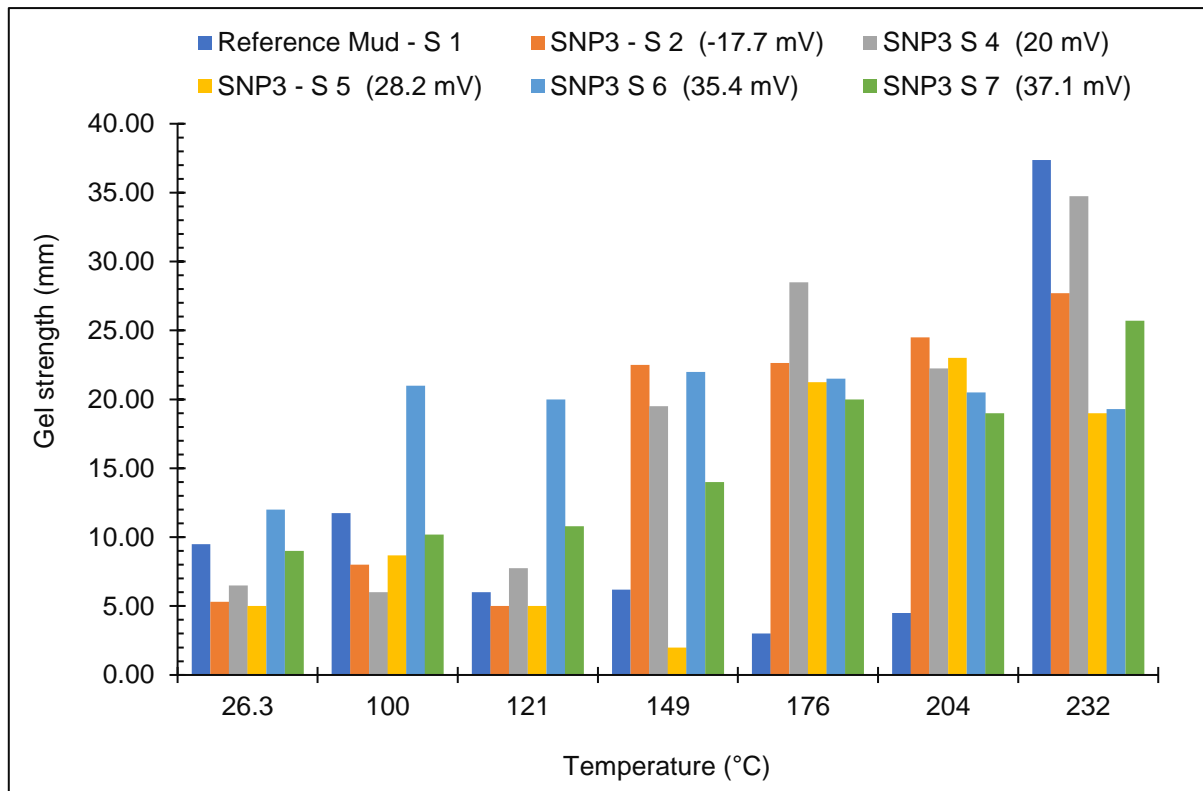


Figure 8: Comparative analysis of gel strength at different aging temperatures at 25 psi, 50 psi, 100 psi, 150 psi, 250 psi, 300 psi.

From Figure 8 above, all mud samples maintained gel strength up to 121°C. Bentonite WBM exhibited the lowest gel strength compared to all other mud sample after 149 °C. This gel increased to maximum thereafter at a temperature of 232 °C. This behaviour indicates the complex effects of temperature resulting to high temperature thickening and high temperature solidification hence failure of the mud system. The degradation of bentonite mud led to the fluid content of the mud to be lost. Progressive gels are undesirable as a high pump pressure may be required to initiate circulation which is an additional cost. The mud with unmodified silica also showed a slightly higher gel strength from a temperature of 149 °C. SNP3 – S4 exhibited higher increasing trend at 176 °C and 232 °C indicating the effects of temperature explained previously. SNP3 – S4 showed the least gel strength at 149 °C which instantly increased thereafter away from the previous trend indicating start of failure due to temperature increase. Temperature decreases the ability of NP to protect the clay particles. Muds with modified silica gel strength increased steadily with temperature especially the muds with the highest absolute value of zeta potential. This could be attributed to the formation of the heterocoagulation structure which facilitates the retentivity of water within the drilling mud system hence reducing the temperature effects of high temperature thickening and high temperature solidification which would have led to gelling and filtration problems.

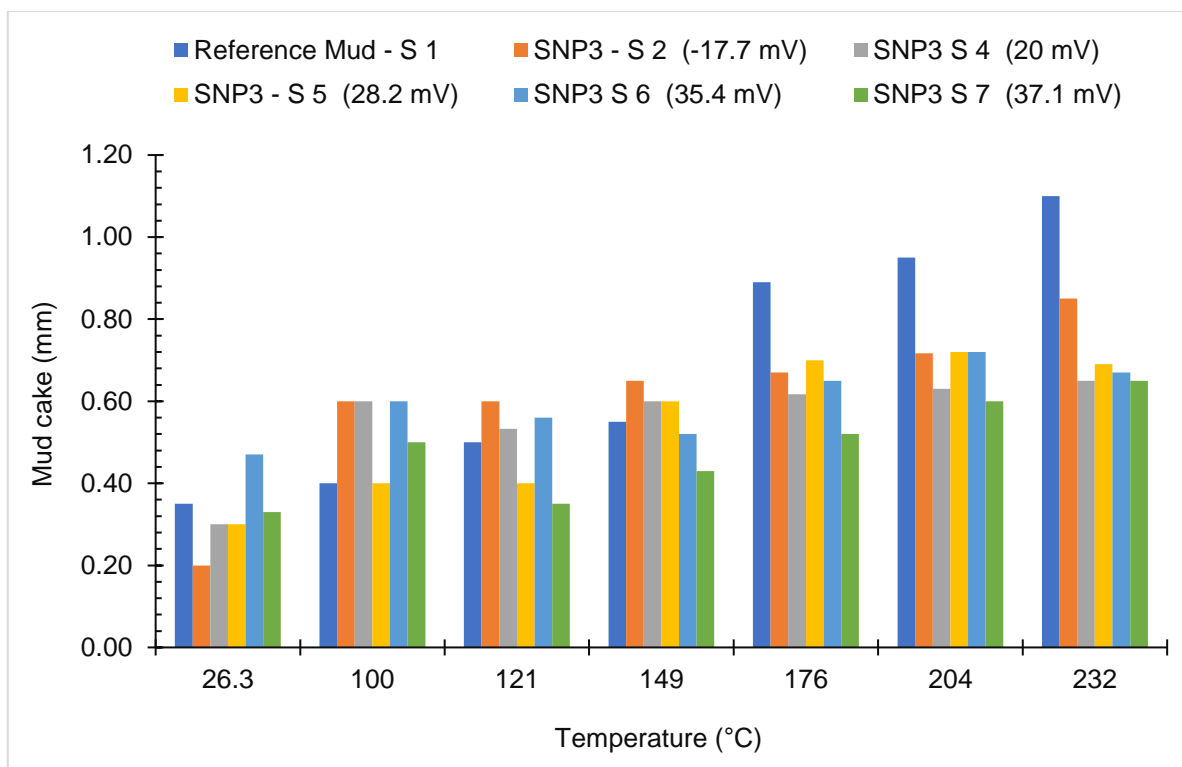


Figure 9: Comparative analysis of Mud cake at different aging temperatures at 25 psi, 50 psi, 100 psi, 150 psi, 250 psi, 300 psi

Mud cake. A mud fluid that forms a thin, less permeable mud cake is always desirable. It is evident that the reference mud had a thicker mud cake as temperature increased from 176 °C onwards which explains the volume of filtrate loss from the mud system. At temperature lesser than 121 °C, the reference mud cake was thinner than some silica mud samples. It's also evident that mud cake thickness of all the mud samples increased with increase in temperature though the reference mud and the mud with unmodified silica formed unwanted poor compaction mud cakes resulting in thicker permeable mud cakes as temperature increased. The mud with the highest absolute zeta potential value performed better than other muds with modified silica at all temperature changes. A mud that produces a thin mud cake acts as a barrier on the borehole wall preventing loss of mud fluid to the formation which might have caused borehole problems like a kick, increased pressure surges, excessive drag etc. Therefore, as mentioned earlier, the filter cake of the mud with unmodified silica was thicker, soft, and permeable while that of the mud with modified silica NPs was thinner, and unerodable. This confirms the theory about the formation of the heterocoagulation structure between modified silica NPs and bentonite as a result of the electrostatic attractive forces which result in formation of thinner mud cakes. It can therefore be concluded that modified silica NPs when used would enhance the filtration properties of the mud fluid hence leading to a thinner mud cake as it has been shown above from Figure 9.

5. Conclusion

This experimental analysis was performed to establish the effectiveness of modified nano silica in improving WBM fluids used in geothermal wells. Silica NPs were modified by grafting a cationic surfactant around the surface of silica NPs. Different amounts of CTAB were added to silica NPs dispersion to establish the optimum amount of CTAB that would efficiently alter the surface of silica NPs. According to the results, this was a successful strategy for reducing agglomeration in silica NPs, resulting in improved mud system properties. In the experimental work, stability was crucial, it will be advantageous to use CTAB modified silica NPs in geothermal drilling mud systems when silica is in a good, dispersed state. This will result in a

stable mud system as it has been seen from the results achieved from this experimental work. The main findings of this study can be listed as follows.

1. The optimum CTAB amount that resulted to better enhancement was 2.0 wt.% CTAB followed by 1.0 wt.% CTAB. These amounts resulted in effective surface modification leading to higher values of absolute zeta potential of 37.4 mV and 35.4 mV respectively.
2. Modified NPs with a high absolute value of zeta potential in mud samples maintained a stable viscosity profiles with increase in temperature especially at temperatures above 121 °C.
3. The reference mud and mud with unmodified silica NPs displayed the highest values of plastic viscosity with increasing temperatures from 149 °C to 232°C. Mud with unmodified silica had the highest viscosity Increase.
4. The reference mud had a higher YP compared to the mud with unmodified NPs and muds with modified NPs at low temperatures up to 100 °C. Above that temperature, reference mud YP decreased. Mud with a higher absolute value of zeta potential exhibited a higher YP at HPHT conditions.
5. Modified silica improved the filtration properties of the samples. Increase in temperature from 100 °C led to higher filtration loss from the reference mud and mud with unmodified NPs compared to muds with modified NPs at every temperature. Filtration loss was improved by 17.6 and 29.5 % on average by SNP3 – S6 and SNP3 – S7 respectively compared to other mud samples.
6. Above 149 °C, the reference sample mud cake thickness increased with temperature increase more than other mud samples. Samples with modified silica, SNP3- S4, SNP3- S5, SNP3- S6, SNP3- S7 mud cake thickness reduced by 17.1, 10.6, 11.6 and 28.7 % on average respectively.

Acknowledgments

The petroleum lab at the University of Salford was used for this study. The authors would like to thank Alan Mappin the petroleum lab technician and support as well as Michael Greenwood in the NanoLab for his advice.

Nomenclature

WBMs	Water based muds
OBMs	Oil based muds
DLS	Dynamic light scattering
Pac	Polyanionic-Cellulose
HPHT	Hight pressure/High temperature
LPLT	Low pressure/Low temperature
SiO ₂	Silica dioxide
SNPs	Silica nanoparticles
NPs	Nanoparticles
API	American Petroleum Institute
YP	Yield point (100 lb/ft ²)
PV	Plastic viscosity (cP)
BHR	Before hot rolling
AHR	After hot rolling
R	Reference bentonite mud
ABDACI	Alkylbenzyldimethylammonium
TEOS	Tetraethyl orthosilicate

References

- Abdo, J. and M. Haneef (2013). "Clay nanoparticles modified drilling fluids for drilling of deep hydrocarbon wells." *Applied Clay Science* **86**: 76-82. <https://doi.org/10.1016/j.clay.2013.10.017>.
- Abu-Jdayil, B., M. Ghannam and M. S. Nasser (2016). "The modification of rheological properties of bentonite-water dispersions with cationic and anionic surfactants." *International Journal of Chemical Engineering and Applications* **7**(2): 75-80. [https://doi.org/10.1016/S0167-577X\(99\)00230-X](https://doi.org/10.1016/S0167-577X(99)00230-X).
- Al-Risheq, D. I., S. M. Shaikh, M. S. Nasser, F. Almomani, I. A. Hussein and M. K. Hassan (2022). "Enhancing the flocculation of stable bentonite suspension using hybrid system of polyelectrolytes and NADES." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **638**: 128305. <https://doi.org/10.1016/j.colsurfa.2022.128305>
- Alford, S., A. Asko, M. Campbell, M. Aston and E. Kvalvaag (2005). Silicate-based fluid, mud recovery system combine to stabilize surface formations of Azeri Wells. SPE/IADC Drilling Conference, OnePetro. <https://doi.org/10.2118/92769-MS>
- Allahvirdizadeh, P. (2020). "A review on geothermal wells: Well integrity issues." *Journal of Cleaner Production* **275**: 124009. <https://doi.org/10.1016/j.jclepro.2020.124009>
- Archer, R. (2020). Geothermal energy. *Future Energy*, Elsevier: 431-445. <https://doi.org/10.1016/B978-0-08-102886-5.00020-7>
- Barry, M. M., Y. Jung, J.-K. Lee, T. X. Phuoc and M. K. Chyu (2015). "Fluid filtration and rheological properties of nanoparticle additive and intercalated clay hybrid bentonite drilling fluids." *Journal of Petroleum Science and Engineering* **127**: 338-346. <https://doi.org/10.1016/j.petrol.2015.01.012>.
- Bavadiya, V., S. Srivastava, S. Salehi and C. Teodoriu (2019). Geothermal Drilling Training and Certification: Should It Be Different? The 44th Workshop on Geotherma I Reservoir Engineering. Stanford, California, USA. [online] Available at: <<https://pangea.stanford.edu/ERE/pdf/IGASTandard/SGW/2019/Bavadiya.pdf>> [Accessed 15 September 2022].
- Bavadiya, V. A., Z. Alsaihati, R. Ahmed and K. Gustafson (2017). Experimental investigation of the effects of rotational speed and weight on bit on drillstring vibrations, torque and rate of penetration. Abu Dhabi International Petroleum Exhibition & Conference, OnePetro. <https://doi.org/10.2118/188427-MS>
- Bhagat, S. D., Y.-H. Kim, K.-H. Suh, Y.-S. Ahn, J.-G. Yeo and J.-H. Han (2008). "Superhydrophobic silica aerogel powders with simultaneous surface modification, solvent exchange and sodium ion removal from hydrogels." *Microporous and Mesoporous Materials* **112**(1-3): 504-509. <https://doi.org/10.1016/j.micromeso.2007.10.030>.

Bland, R. G., G. A. Mullen, Y. N. Gonzalez, F. E. Harvey and M. L. Pless (2006). HPHT drilling fluid challenges. IADC/SPE Asia Pacific drilling technology conference and exhibition, Society of Petroleum Engineers. <https://doi.org/10.2118/103731-MS>

Bourgoyne Adam, T., M. Chenevert, K. Millheim and F. Yong (1986). "Applied Drilling Engineering, SPE Textbook Series." [https://doi.org/10.1016/0148-9062\(87\)90345-7](https://doi.org/10.1016/0148-9062(87)90345-7)

Capuano Jr, L. (2016). Geothermal well drilling. Geothermal Power Generation, Elsevier: 107-139. <https://doi.org/10.1016/B978-0-08-100337-4.00005-X>

Castellano, M., L. Conzatti, G. Costa, L. Falqui, A. Turturro, B. Valenti and F. Negroni (2005). "Surface modification of silica: 1. Thermodynamic aspects and effect on elastomer reinforcement." *Polymer* **46**(3): 695-703. <https://doi.org/10.1016/j.polymer.2004.11.010>.

Cedric, H. (2010). "Geothermal drilling costs." Drilling Today, Jaipur, India, website: http://dthrotarydrilling.com/News/9-October-2010/geothermal_drilling.html.

Chemwotei, S. C. (2011). "Geothermal drilling fluids." *Report 10*: 149-177. [online] Available at: <<https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2011-10.pdf>> [Accessed 15 September 2022].

Daswani, P. and A. Van Herk (2014). "Hetero-coagulation." Encyclopedia of Polymeric Nanomaterials. Springer, Berlin, Heidelberg. DOI **10**: 978-973. https://doi.org/10.1007/978-3-642-36199-9_348-1

Edalatfar, M., F. Yazdani and M. B. Salehi (2021). "Synthesis and identification of ZnTiO₃ nanoparticles as a rheology modifier additive in water-based drilling mud." *Journal of Petroleum Science and Engineering* **201**: 108415. <https://doi.org/10.1016/j.petrol.2021.108415>

EIA, U. (2016). "Trends in US oil and natural gas upstream costs." US Energy Information Administration. Available: <https://www.eia.gov/analysis/studies/drilling/pdf/upstream.pdf> (2016), Accessed 14th Mar 2022.

Elochukwu, H., R. Gholami and S. S. Dol (2017). "An approach to improve the cuttings carrying capacity of nanosilica based muds." *Journal of Petroleum Science and Engineering* **152**: 309-316. <https://doi.org/10.1016/j.petrol.2017.03.008>.

Falcone, G., X. Liu, R. R. Okech, F. Seyidov and C. Teodoriu (2018). "Assessment of deep geothermal energy exploitation methods: The need for novel single-well solutions." *Energy* **160**: 54-63. <https://doi.org/10.1016/j.energy.2018.06.144>

Fallah, A., Q. Gu, D. Chen, P. Ashok, E. van Oort and M. Holmes (2021). "Globally scalable geothermal energy production through managed pressure operation control of deep closed-loop well systems." *Energy Conversion and Management* **236**: 114056. <https://doi.org/10.1016/j.enconman.2021.114056>

Finger, J. and D. Blankenship (2010). "Handbook of best practices for geothermal drilling." Sandia National Laboratories, Albuquerque. <https://doi.org/10.2172/1325261>

Fritz, B. and M. Jarrett (2012). Potassium silicate-treated water-based fluid: An effective barrier to instability in the Fayetteville shale. IADC/SPE Drilling Conference and Exhibition, OnePetro. <https://doi.org/10.2118/151491-MS>

Ghasemi, N., M. Mirzaee, R. Aghayari and H. Maddah (2018). "Investigating created properties of nanoparticles based drilling mud." Heat and Mass Transfer **54**(5): 1381-1393. <https://doi.org/10.1007/s00231-017-2229-7>

Guan, O. S., R. Gholami, A. Raza, M. Rabiei, N. Fakhari, V. Rasouli and O. Nabinezhad (2020). "A nano-particle based approach to improve filtration control of water based muds under high pressure high temperature conditions." Petroleum **6**(1): 43-52. <https://doi.org/10.1016/j.petlm.2018.10.006>

Gul, S. and V. Aslanoglu (2018). Drilling and well completion cost analysis of geothermal wells in Turkey. 43rd workshop on geothermal reservoir engineering. [online] Available at: <https://www.researchgate.net/profile/Sercan-Gul/publication/322941229_Drilling_and_Well_Completion_Cost_Analysis_of_Geothermal_Wells_in_Turkey/links/5a7f1c344585154d57d73da9/Drilling-and-Well-Completion-Cost-Analysis-of-Geothermal-Wells-in-Turkey.pdf> [Accessed 15 September 2022].

Howard, S. K. (1995). Formate brines for drilling and completion: state of the art. SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers. <https://doi.org/10.2118/30498-MS>

Hunter, R. J. (2013). Zeta potential in colloid science: principles and applications, Academic press. <https://doi.org/10.1016/C2013-0-07389-6>

Ibeh, C. S. (2010). Investigation on the effects of ultra-high pressure and temperature on the rheological properties of oil-based drilling fluids, Texas A & M University. [Online] Available from: [Online] Available from: <https://hdl.handle.net/1969.1/ETD-TAMU-2569>, 25th March 2022

Ibrahim, M. A., M. Z. Jaafar, M. A. M. Yusof and A. K. Idris (2022). "A review on the effect of nanoparticle in drilling fluid on filtration and formation damage." Journal of Petroleum Science and Engineering: 110922. <https://doi.org/10.1016/j.petrol.2022.110922>

Ismail, A., A. Aftab, Z. Ibupoto and N. Zolkifile (2016). "The novel approach for the enhancement of rheological properties of water-based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads." Journal of Petroleum Science and Engineering **139**: 264-275. <https://doi.org/10.1016/j.petrol.2016.01.036>.

Jung, Y., Y.-H. Son, J.-K. Lee, T. X. Phuoc, Y. Soong and M. K. Chyu (2011). "Rheological behavior of clay–nanoparticle hybrid-added bentonite suspensions: specific role of hybrid additives on the gelation of clay-based fluids." ACS applied materials & interfaces **3**(9): 3515-3522. <https://doi.org/10.1021/am200742b>.

- Karakosta, K., A. C. Mitropoulos and G. Z. Kyzas (2021). "A review in nanopolymers for drilling fluids applications." *Journal of Molecular Structure* **1227**: 129702. <https://doi.org/10.1016/j.molstruc.2020.129702>
- Karimi, M. A., M. A. Mozaheb, A. Hatefi-Mehrjardi, H. Tavallali, A. M. Attaran and R. Shamsi (2015). "A new simple method for determining the critical micelle concentration of surfactants using surface plasmon resonance of silver nanoparticles." *Journal of Analytical Science and Technology* **6**(1): 1-8. <https://doi.org/10.1186/s40543-015-0077-y>.
- Kelessidis, V., C. Tsamantaki, N. Pasadakis, E. Repouskou and E. Hamilaki (2007). "Permeability, porosity and surface characteristics of filter cakes from water–bentonite suspensions." *WIT Transactions on Engineering Sciences* **56**: 173-182. <https://doi.org/10.2495/MPF070171>.
- Kiran, R. and S. Salehi (2020). Assessing the Relation between Petrophysical and Operational Parameters in Geothermal Wells: A Machine Learning Approach. Proceedings of the 45th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA. [Online] Available from: <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Kiran.pdf>, Accessed 20th March 2022
- Kruszewski, M. and V. Wittig (2018). "Review of failure modes in supercritical geothermal drilling projects." *Geothermal Energy* **6**(1): 1-29. <https://doi.org/10.1186/s40517-018-0113-4>.
- Laribi, S., J.-M. Fleureau, J.-L. Grossiord and N. Kbir-Ariguib (2006). "Effect of pH on the rheological behavior of pure and interstratified smectite clays." *Clays and Clay Minerals* **54**(1): 29-37. <https://doi.org/10.1346/CCMN.2006.0540104>.
- Lee, Y.-L., Z.-C. Du, W.-X. Lin and Y.-M. Yang (2006). "Monolayer behavior of silica particles at air/water interface: a comparison between chemical and physical modifications of surface." *Journal of colloid and interface science* **296**(1): 233-241. <https://doi.org/10.1016/j.jcis.2005.08.070>.
- Liu, F., H. Yao, Q. Liu, X. Wang, X. Dai, M. Zhou, Y. Wang, C. Zhang, D. Wang and Y. Deng (2021). "Nano-silica/polymer composite as filtrate reducer in water-based drilling fluids." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **627**: 127168. <https://doi.org/10.1016/j.colsurfa.2021.127168>
- Ma, X.-k., N.-H. Lee, H.-J. Oh, J.-W. Kim, C.-K. Rhee, K.-S. Park and S.-J. Kim (2010). "Surface modification and characterization of highly dispersed silica nanoparticles by a cationic surfactant." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **358**(1-3): 172-176. <https://doi.org/10.1016/j.colsurfa.2010.01.051>.
- Mahmoud, O., H. A. Nasr-El-Din, Z. Vryzas and V. C. Kelessidis (2016). Nanoparticle-based drilling fluids for minimizing formation damage in HP/HT applications. SPE international conference and exhibition on formation damage control, Society of Petroleum Engineers. <https://doi.org/10.2118/178949-MS>

Mahmoud, O., H. A. Nasr-El-Din, Z. Vryzas and V. C. Kelessidis (2017). Characterization of filter cake generated by nanoparticle-based drilling fluid for HP/HT applications. SPE international conference on oilfield chemistry, Society of Petroleum Engineers. <https://doi.org/10.2118/184572-MS>

Mahmoud, O., H. A. Nasr-El-Din, Z. Vryzas and V. C. Kelessidis (2018). "Using ferric oxide and silica nanoparticles to develop modified calcium bentonite drilling fluids." SPE Drilling & Completion **33**(01): 12-26. <https://doi.org/10.2118/178949-PA>

Maiti, M., A. K. Bhaumik and A. Mandal (2021). "Performance of water-based drilling fluids for deepwater and hydrate reservoirs: Designing and modelling studies." Petroleum Science **18**(6): 1709-1728. <https://doi.org/10.1016/j.petsci.2021.09.001>

Martin, C., M. Babaie, A. Nourian and G. Nasr (2022). "Rheological Properties of the Water-Based Muds Composed of Silica Nanoparticle Under High Pressure and High Temperature." SPE Journal: 1-14. <https://doi.org/10.2118/209786-PA>

Martin, C., M. Babaie, A. Nourian and G. G. Nasr (2022). "Rheological Properties of the Water-Based Muds Composed of Silica Nanoparticle Under High Pressure and High Temperature." SPE Journal: 1-14. <https://doi.org/10.2118/209786-PA>

McDonald, M. J. (2007). The use of silicate-based drilling fluids to mitigate metal corrosion. International Symposium on Oilfield Chemistry, OnePetro. <https://doi.org/10.2118/100599-MS>

Mohamed, A., S. Salehi and R. Ahmed (2021). "Significance and complications of drilling fluid rheology in geothermal drilling: A review." Geothermics **93**: 102066. <https://doi.org/10.1016/j.geothermics.2021.102066>.

Moya, D., C. Aldás and P. Kaparaju (2018). "Geothermal energy: Power plant technology and direct heat applications." Renewable and Sustainable Energy Reviews **94**: 889-901. <https://doi.org/10.1016/j.rser.2018.06.047>

Paulillo, A., L. Cotton, R. Law, A. Striolo and P. Lettieri (2020). "Geothermal energy in the UK: The life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project." Journal of Cleaner Production **249**: 119410. <https://doi.org/10.1016/j.jclepro.2019.119410>

Rafati, R., S. R. Smith, A. S. Haddad, R. Novara and H. Hamidi (2018). "Effect of nanoparticles on the modifications of drilling fluids properties: A review of recent advances." Journal of Petroleum Science and Engineering **161**: 61-76. <https://doi.org/10.1016/j.petrol.2017.11.067>.

Rahman, I. A. and V. Padavettan (2012). "Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites—a review." Journal of Nanomaterials **2012**. <https://doi.org/10.1155/2012/132424>

Ramos-Tejada, M., F. Arroyo, R. Perea and J. Duran (2001). "Scaling behavior of the rheological properties of montmorillonite suspensions: correlation between interparticle

interaction and degree of flocculation." *Journal of Colloid and Interface Science* **235**(2): 251-259. <https://doi.org/10.1006/jcis.2000.7370>.

Rana, A., M. Murtaza, T. A. Saleh, M. S. Kamal and M. Mahmoud (2022). "An efficient, cost-effective, and green natural extract in water-based drilling muds for clay swelling inhibition." *Journal of Petroleum Science and Engineering* **214**: 110332. <https://doi.org/10.1016/j.petrol.2022.110332>

Randeberg, E., E. Ford, G. Nygaard, M. Eriksson, L. Gressgård and K. Hansen (2012). Potentials for cost reduction for geothermal well construction in view of various drilling technologies and automation opportunities. Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering. [Online] Available from: <https://pangea.stanford.edu/ERE/pdf/IGASstandard/SGW/2012/Randeberg.pdf>, Accessed 20th Febaury 2022

Scott, M. J. and M. N. Jones (2000). "The biodegradation of surfactants in the environment." *Biochimica et Biophysica Acta (BBA)-Biomembranes* **1508**(1-2): 235-251. [https://doi.org/10.1016/S0304-4157\(00\)00013-7](https://doi.org/10.1016/S0304-4157(00)00013-7).

Shadravan, A. and M. Amani (2012). "HPHT 101-what petroleum engineers and geoscientists should know about high pressure high temperature wells environment." *Energy Science and Technology* **4**(2): 36-60. <https://doi.org/10.2118/163376-MS>.

Shaughnessy, J. M., L. A. Romo and R. L. Soza (2003). Problems of ultra-deep high-temperature, high-pressure drilling. SPE Annual Technical Conference and Exhibition, OnePetro. <https://doi.org/10.2118/84555-MS>

Smith, J. R. (2001). "Energy demand creates new opportunities and challenges for drilling." *Journal of Canadian Petroleum Technology* **40**(05). <https://doi.org/10.2118/01-05-DAS>.

Smith, S. R., R. Rafati, A. S. Haddad, A. Cooper and H. Hamidi (2018). "Application of aluminium oxide nanoparticles to enhance rheological and filtration properties of water based muds at HPHT conditions." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **537**: 361-371. <https://doi.org/10.1016/j.colsurfa.2017.10.050>.

Soric, T., P. Marinescu and R. Huelke (2004). Silicate-based drilling fluids deliver optimum shale inhibition and wellbore stability. IADC/SPE Drilling Conference, OnePetro. <https://doi.org/10.2118/87133-MS>

Stöber, W., A. Fink and E. Bohn (1968). "Controlled growth of monodisperse silica spheres in the micron size range." *Journal of colloid and interface science* **26**(1): 62-69. [https://doi.org/10.1016/0021-9797\(68\)90272-5](https://doi.org/10.1016/0021-9797(68)90272-5)

Teodoriu, C. (2013). "Why and when does casing fail in geothermal wells." *Oil, Gas* **39**. [Online] Available from:

<https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/21041.pdf>

(2015) Accessed 20rd Feb 2022.

Teodoriu, C., M. C. Yi, A. Ichim and S. Salehi (2018). A novel view of cement failure with application to geothermal well construction. Proceedings of the 43rd Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA. <https://doi.org/10.3390/en12183426>

Vollmar, D., V. Wittig and R. Bracke (2013). "Geothermal Drilling Best Practices: The Geothermal translation of conventional drilling recommendations-main potential challenges." International Geothermal Association: Home. [online] Available at: <<https://www.semanticscholar.org/paper/Geothermal-Drilling-Best-Practices%3A-The-Geothermal-Wittig-Vollmar/c27442faab31bc83f4de81ab55278eb1b02b2990>> [Accessed 15 September 2022].

Vryzas, Z., O. Mahmoud, H. A. Nasr-El-Din and V. C. Kelessidis (2015). Development and testing of novel drilling fluids using Fe₂O₃ and SiO₂ nanoparticles for enhanced drilling operations. International petroleum technology conference, OnePetro. <https://doi.org/10.2523/IPTC-18381-MS>

Wang, C., R. Meng, F. Xiao and R. Wang (2016). "Use of nanoemulsion for effective removal of both oil-based drilling fluid and filter cake." Journal of Natural Gas Science and Engineering **36**: 328-338. <https://doi.org/10.1016/j.jngse.2016.10.035>.

Wu, Y., H. Patel and S. Salehi (2020). Thermal considerations of cement integrity in geothermal wells. The 45th Workshop on Geothermal Reservoir Engineering. Stanford, California, USA. [online]. Available from: <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Wu.pdf>, [Accessed 14th May, 2022].

Zhang, J. R., M. D. Xu, G. E. Christidis and C. H. Zhou (2020). "Clay minerals in drilling fluids: functions and challenges." *Clay Minerals* **55**(1): 1-11. <https://doi.org/10.1180/clm.2020.10>