Effect of silica nano particles on the rheological and HTHP filtration properties of environment friendly additive in water-based drilling fluid

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Abstract

Rheological and filtration properties of drilling fluid contribute a vital role in successful drilling operations. Rheological parameters such as apparent viscosity (AV), plastic viscosity (PV), yield point (YP) and gel strength of drilling fluids are very essential for hydraulic calculations and lifting of drill cuttings during the drilling operation. Control of filtration loss volume is also very important for cost effective and successful drilling operations. Therefore, the main goal of this research is to improve the rheological and filtration properties of Grewia Optiva fibre powder (GOFP) by using 30–50 nm size of silica nano particles (SNP) in water-based drilling fluid. The experimental outcomes revealed that after hot rolling of mud samples at 100 °C for 16 h, the low pressure-low temperature (LPLT) and high pressure-high temperature (HPHT) filtration loss of GOFP additives was improved, after the addition of SNP on it. The mixture of 5% GOFP + 4% SNP has reduced the LPLT and HPHT filtration loss of drilling fluid by 74.03 and 78.12%, respectively, as compared to base mud. Thus, it was concluded that after the addition of 0.4% SNP, the LPLT and HPHT filtration control ability of GOFP additive in WBM were increased by 17.6 and 15%, respectively. The rheological parameters such as AV, PV, YP and gelation of drilling fluids were also improved by the addition of GOFP + SNP mixture in the base mud. Therefore, the implementation of GOFP + SNP mixture in water-based mud showed auspicious results which reaffirm the feasibility of using them in the successful drilling operations.

Keywords Drilling fluid · Grewia Optiva fibre · HPHT filtration property · Rheology · Silica nano particles

Introduction

Drilling in deeper wells is very challenging and costly due to high pressure and high temperature (HPHT) conditions (Caenn and Darley 2017a). Water-based mud (WBM) has a number of advantages over the oil-based drilling fluid (ODF), including low cost, easily available, superior cooling, cutting removal ability, rapid formation penetration rate, and environment friendly nature. Water acts as dispersion medium in the WBM due to the presence of the excess

amount; as a result, the filtrate generated due to temperature and pressure during the drilling enter in the porous rock formations and causes swelling of shale, caving, stuck up, bore hole instability and formation damage problems (Caenn and Darley 2017b; Fink et al. 2012). Beyond the temperature 250 °F, bentonite starts deteriorating, which leads to decrease in viscosity and increase the filtration loss volume of drilling fluid (Caenn and Darley 2017a). To design a suitable and efficient drilling fluid, the rheological and filtration properties are the key parameters (Caenn and Darley 2017c, d). Hot rolling of drilling fluids in roller oven at particular temperature is very essential because it correlate the behaviour of drilling mud when drilling is resumed in the well bore. Drilling fluid samples are kept in a stainless-steel ageing cell and rolled inside the hot roller oven at a particular temperature for minimum of 16 h to predict the effect of temperature on parameters of the drilling fluid after the long hot rolling (Liu et al. 2016).

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Recently, various polymeric additives like polyanionic cellulose (PAC) (Kafashi et al. 2017; Villada et al. 2017), hydroxyethyl cellulose (HEC) (Chaouf et al. 2019; Lian et al. 2019), carboxymethyl cellulose (Menezes et al. 2010; Zhang et al. 2016), acrylamide-styrene copolymer (SBASC) (Davoodi et al. 2019), Partially hydrolysed polyacrylamide (PHPA) (Jain et al. 2015), polyethylene glycol (Mech and Sangwai 2016), low and high density polythene (Yi et al. 2017), etc. have been used in water-based drilling fluid to ameliorate the rheological and filtration properties of the drilling fluids. While polyacrylamide (Magzoub 2021) has been used as lost circulation material in WBM. But, in deeper wells, these polymers are deteriorated at high temperature after a period of time. Therefore, various nanoparticles are used in drilling fluid for improving its performance (Zakaria et al. 2012; Abbas et al. 2021; Akhtarmanesh et al. 2013).

Nano particles are surface-charged particles, which have been used widely in the drilling fluid since last couple of decades to improve the efficacy of drilling fluid at high temperature as compared to polymeric additive (Aftab et al. 2017; Rafati et al. 2018). The heat stability, filtration and rheological properties of drilling fluid have been improved by nano particles in water-based drilling fluid; therefore, suitable size of nano particle is the explication of drilling under the drastic conditions like HPHT and water-sensitive shale formations. (Cheraghian et al. 2021. Hoelscher et al. 2012, Katenda et al. 2019). Recently, various nano particles like bismuth ferrite (Perween et al. 2019), hydrophilic gilsonite (Pakdaman et al. 2019), cupric oxide and zinc oxide (Beg et al. 2019; Dejtaradon 2019), zinc titanate (Perween et al. 2018) and magnesium aluminium silicate (Wang et al. 2018), barite nano particle (Caldarola, 2016. Loggins et al. 2017) titanium dioxide (Bayat et al. 2019), TiO_2 /Polyacrylamide nanocomposite (Sadeghalvaad et al. 2015), etc. as additives have been used in water-based drilling fluid to improve its efficiency. Cellulose nanoparticles (CNPs), microfibrillar cellulose (MFC) and cellulose nanocrystal have been improved the rheological and filtration property of bentonite-based drilling fluid (Li et al. 2015). The salt contamination of bentonite water-based drilling fluid with cellulose nanocrystal reveal that cellulose nanocrystal stabilized rheology and filtration property of bentonite water-based mud (Li et al. 2020a, b, c). Water-based drilling fluids (WDFs) with thermo controllable rheological properties are developed using bentonite (BT) and dual-functionalized cellulose nanocrystals (fCNCs). This work demonstrated a new concept of formulating smart drilling fluid based on BT and biomass-derived CNCs via rational surface fictionalization and interface design, paving the way for the development of next generation of drilling fluids with low toxicity, sustainability, in situ rheology controllability, and thermal tolerance. (Li et al. 2020a,b, c). Cellulose nanofibres

(CNFs) and polyanionic cellulose (PAC) hybrid have been used as rheological and filtration loss modifiers in the high performance water-based mud. The outcomes of this study revealed that CNFs and PAC hybrid potentially improved the rheological and filtration property of bentonite-based drilling fluid (Li et al. 2020a, b, c). Silica nano particle with xanthan gum has been used for enhancing rheological, filtration and lubrication properties of a water-based drilling fluid system (Al- Yasiri et al. 2019). Clay/ SiO_2 nanocomposite was synthesized and analysed by conventional characterization methods. This novel system of drilling fluid containing nanoparticles has shown improvement in rheological properties as well as filtration control. It has been found that the clay/silica nanocomposites have a tendency to improve the rheological stability of drilling mud at higher temperature (Cheraghian et al. 2018). A novel hydrophobic associated polymer-based silica nanoparticles composite with core-shell structure has been provided the thermal stability of water-based mud system. It has improved the rheology, lubricity and filtration properties of water-based mud system. The HPHT filtration loss at 200°C /16 h with silica nanoparticle was 20.5 ml (Mao et al. 2015). Silica and graphene nanoparticles used in water-based mud system to improve the shale stability during the drilling operations. These nanoparticle reduced the Woodford shale cutting dispersion by 35.61% as compared to base fluid, which showing its effectiveness in water-based drilling fluid in illitic shales (Aramendiz, et al. 2019). In another study, it was observed that with varying the concentration of silica nano particles from 0.001 to 1.5 wt% in the WBM, the viscosity of drilling mud was increased (Gbadamosi et al. 2019).

In the recent years, several natural products have been studied in water-based drilling fluid. These additives are Corn cob and sugar cane as viscosifying agent (Iranwan et al. 2009), Banana peel ash as pH enhancer (Adebowale and Raji 2015), However, rice husk (Okon et al. 2014), extracted cashew and mango leaves (Omotioma et al. 2014), extracted potato starch from potato tubers (Nyeche et al. 2015), grass (Hossain and Wajheuddin 2016), date seed powder (Amanullah and Ramasamy 2016), corn cob and coconut shell (Onuh et al. 2017), rice husk and saw dust (Agwu, Okorie. et al. 2019), potato peels powder (Al-Hameedi 2019), etc. all these additives have been used as filtration loss control agent in the water-based mud. Various lost circulation materials (LCM's) have been used in water-based drilling fluid to stop losses (Alsaba et al. 2014). Recently, used LCM in WBM is Durian rind (Fatihah Majid 2019). Beyond these, other additives like, pomelo peels powder as effective shale inhibitor (Zhang et al. 2020), and stem peels powder of *Grewia Optiva* fibres (particle size $250\ \mu\text{m}$) as non-invasive fluid additive (Prakash et al. 2020), etc. have been studied in water-based drilling fluid.

Above references are suggesting for the use of nano particles with natural additive in WBM so that the performance of natural product may be improved at high temperature and high pressure conditions. Therefore, in the present work, 30–50 nm size of silica nano particles (99.9% purity) are used with the natural product *Grewia optiva* fibre (particle size 125 μm) to improve the rheology, LPLT and HPHT filtration properties of WBM.

Grewia Optiva is an agro- forestry tree. It is commonly known as *Bhimal*. It is a tree of about 12 m height, and found in India, Srilanka, Pakistan, Thailand, China and Phillipines. Leaves are ovate and lanceolate, acuminate, base rounded with prominent nerves, margin serrate, and stallately hairy on both surfaces. The fibre is used in the manufacturing of ropes, nets, brooms and sticks. The advantage of this fibre over the other natural products is its tensile strength and thermal stability (Gaur et al. 1999). Raw *grewia optiva* fibre contained $68.9 \pm 1.5\%$ (w/w) cellulose, $16.8 \pm 0.5\%$ (w/w) hemicelluloses, $12.8 \pm 1.5\%$ (w/w) lignin and $1.5 \pm 0.5\%$ (w/w) pectin and wax (Karakoti et al. 2020), which motivated the use of *Grewia optiva* fibre with silica nano particles in the water-based mud.

Materials and methods

Materials used for the study are bentonite powder (Provided by Oil and Natural Gas Corporation Limited, Dehradun, India), soda ash (manufactured by Central drug house pvt. Ltd. New Delhi, India), caustic soda (manufactured by RFCL limited new Delhi, India), *Grewia Optiva* fibre (collected from Himalayan region of Garhwal Uttarakhand, India) and silica nano particles with 30–50 nm size and 99.9% purity

were purchased from the Parshwamani metals Pvt. Limited, Mumbai, India.

Sample preparation of *grewia optiva* fibre powder (GOFP)

Raw fibre was obtained from the branches of the *Grewia Optiva*, were collected during the month of November from the Garhwal region of Uttarakhand, India. These branches were first wetted with water for 3–4 weeks and then fibrous peels were separated from the sticks by dissolving gummy material. The fibrous peels thus obtained were thoroughly rinsed with 2% detergent solution and then placed in a dry oven at 70 °C for 24 h (Prakash et al. 2020). When these fibrous peels were completely oxidized, they were cooled and further cut into small pieces with the help of a sharp knife. Ground these fibrous peels (Fig. 1 a) into fine powder through a grinder machine and sieved to 125 (μm) (Fig. 1 b). The reason for using 125 μm particle size additive is to increase surface area and the area of extent for effective ability of any natural product to be a better filtration loss control additive (Ghazali et al. 2014).

Experimental procedures and laboratory measurements

Mud samples preparation

A fresh bentonite mud was prepared as per API (American Petroleum Institute) standards. About 7% Bentonite, 0.1% soda ash and 0.2% caustic soda were mixed in 350 ml of water, and the resulting mixture was kept at room temperature for 24 h (Table 1). Here, this mud was designated as base mud. Followed by it, four another mud samples were

Fig. 1 a Raw fibre of *Grewia Optiva*, b 125 μm *Grewia Optiva* fibre powder (GOFP)

Table 1 Materials used for the mud formulation

Mud material	Conc. % (w/v)	Mixing time (sec-ond)	Function of materials
Water	500 ml	–	Base liquid
Bentonite	7	900	Viscosifier
Soda ash	0.1	200	Softness of water
Caustic soda	0.1	300	pH enhancer
GOSP	1–4	500	Fluid loss control agent
Silica nano Particles	0.2–0.4	00	Filtration loss reducer and rheology modifier

also prepared. Out of these four mud samples, first sample contain 5% GOSP in base mud which was designated as GOSP-based mud. While second, third and fourth mud samples contain 5% GOSP + 0.2% SNP, 5% GOSP + 0.3% SNP, 5% GOSP + 0.4% SNP, respectively, in the base mud, which were designated as SNP-based drilling fluid. All these mud samples were mixed thoroughly in the Hamilton beach mixer at 1800 rpm for 30 min to obtain homogenous mixture. Upreti et al. (2017) also showed that at 5 wt% concentration, the tensile strength of Grewia optiva fibre was very high, while when the concentration of this fibre was increased to beyond 5%, its tensile strength began to decompose due to decrease in bonding between the fibre and matrix. Thereafter, the low pressure-low temperature (LPLT) filtration test, rheological properties and mud cake thickness, mud cake permeability, pH, and density test of all mud samples were performed (Table 2). After evaluating the required parameters, all mud samples were now put in ageing cells and hot rolled at 100 °C for 16 h. After hot rolling of mud samples, the various parameters of drilling fluids such as LPLT and HPHT filtration test and rheology, etc. were determined (Table 3).

Table 2 Properties of SET-1, SET-2 and SET-3 mud samples at before hot rolling (BHR)

Mud properties	Values				
	Base mud	5% GOSP	5% GOSP + 0.2% SNP	5% GOSP + 0.3% SNP	5% GOSP + 0.4% SNP
Mud weight (ppg)	8.68	8.70	8.70	8.70	8.70
pH	10.5	10.3	10.0	9.8	9.7
AV(cP)	18	31	34	36	38
PV (cP)	10	15	16	17	18
YP (lb/100ft ²)	22	30	34	36	38
Gel 0 (lb/100ft ²)	18	23	23	24	26
Gel 10 (lb/100ft ²)	27	34	38	40	42
LPLT, Filtration loss volume (cc)	27	6.4	6.1	5.7	5.3
Filter cake thickness (mm)	3.0	1.8	1.8	1.7	1.6

Rheological properties measurements

Fann viscometer model 35 was used to measure the rheological parameters of drilling fluid. A steady dial reading is noted at different RPM in viscometer to determine the apparent viscosity, plastic viscosity, yield point, and gel strength of the drilling fluid. The gel strength at 10 s and 10 min was determined at 3 rpm. Formulae: Rheological properties such as AV (Eq. 1), PV (Eq. 2) and YP (Eq. 3) of drilling mud are calculated by the following equations:

$$AV = \theta_{600}/2 \quad (1)$$

$$PV = \theta_{600} - \theta_{300} \quad (2)$$

$$YP = \theta_{300} - PV \quad (3)$$

where θ_{600} = Dial reading at 600 RPM, θ_{300} = Dial reading at 300 RPM

LPLT (low pressure-low temperature) filtration test

Mud was filled in a cell containing a Whatman 50 filter paper with a diameter 90 mm at bottom along with a filter screen. After the necessary connections, a 100 Psi pressure at room temperature was exerted on drilling mud by using nitrogen gas for a period of 30 min (American Petroleum Institute 2003).

HPHT (high Pressure-high temperature) filtration test

Ofite 171-00 series HPHT filter press was used to determine the HPHT filtration loss of drilling fluids. Mud was filled in the in the HPHT filter press cell containing filter paper with diameter of 2.5 inch. When mud acquired required temperature, 500 psi differential pressure (600 psi from the top of cell and 100 psi from the bottom of cell) was applied in the

Table 3 Properties of SET-1, SET-2 and SET-3 mud samples, After Hot Rolling (AHR) at 100 °C for 16 h

Mud properties	Values				
	Base mud	5% GOFP	5% GOFP + 0.2% SNP	5% GOFP + 0.3% SNP	5% GOFP + 0.4% SNP
Mud weight (ppg)	8.68	8.7	8.7	8.7	8.7
pH	9.5	9.0	9.0	8.8	8.6
AV(cP)	14	24	26	28	30
PV (cP)	7	11	11	12	14
YP (lb/100ft ²)	16	23	25	28	30
Gel 0 (lb/100ft ²)	11	19	20	21	23
Gel 10(lb/100ft ²)	19	25	26	30	34
LPLT, Filtration loss volume (cc)	32	8.5	8.0	7.3	7.0
LPLT, Filter cake thickness (mm)	3.5	2.0	2.0	1.8	1.8
HTHP, Filtration loss volume (cc)	52	16	15.2	14.2	13.6
HPHT, Filter cake thickness (mm)	7.7	5.0	4.6	4.3	4.2

HTHP filter press. After 30 min, the final volume of filtrate collected in a measuring cylinder was noted.

Results

Zeta Potential and particle size analysis of nano particles

Zeta potential is one of the most important parameters to estimate the stability of the nanoparticle as it gives the net electrostatic potential of any particle in suspension. Particles having zeta potential value more positive than + 30 mV or more negative than − 30 mV are generally treated as stable. For determining the Zeta potential, 5 mg/L of silica nano particles solution was prepared, stirred the solution by silverson mixture for 15 min. Maintained the pH of solution up to 10 by using 0.1 M NaOH solution. A similar methodology was applied for determining the zeta potential of GOFP and the mixture of GOFP + SNP samples. As per experimental data, it was observed that silica nano particles (SNP) possessed a zeta potential value of − 47.4 mV (Fig. 2a), which clearly indicates that nanoparticles are stables. Nanoparticles having high positive or high negative zeta potential value are never aggregate due to repulsive forces between the particles (Selvarajan et al. 2013). Similarly, the zeta potential of GOFP was − 24.1 mV (Fig. 3a), which indicates moderate stability of particles, while when the particles of GOFP and SNP were mixed, the zeta potential of these mixed particles was found to − 31.1 mV (Fig. 4a), which represents that these particles are stable and prevent aggregation due to repulsive forces among the particles. The average particles size (Z_{Avg}) of GOFP and SNP were found to 246 nm and 200 nm respectively (Fig. 2b and 3b, respectively). While the (Z_{Avg}) value of GOFP + SNP mixture was 229 nm (Fig. 4b). The particle size distribution

data indicates the agglomeration of nanoparticles in water, this agglomeration formed larger size nanoparticles. As a result, the average size of nano particles was found much larger than the size of nano particles used.

XRD Analysis

XRD tests of *grewia optiva* fibre were recorded within the range from 5 to 90° with an increment of 0.02 and a speed of 5°/min. The crystallinity index is calculated by using equation (4) (Segal et al. 1959)

$$\text{Crystallinity index} = I_{002} - I_{\text{amorph}} / I_{002} \times 100 \quad (4)$$

Where I_{002} = Intensity of (002) lattice diffraction, I_{amorph} = Intensity of diffraction (18°).

Three peaks are identified in the direction of 15.3, 22.5 and 24.4° and in raw *grewia optiva* fibre as shown in Fig. 5a. Crystalline index indicated that the crystalline phase of *grewia optiva* fibre is 60% and the remaining 40% is the amorphous phase due to the lignin, hemicellulose and pectin content. This peak is showing higher intensity in the direction of 16.5, 22.7 and 24.8° in SNP-treated fibbers (Fig. 5b). The crystallinity index is increased from 60% in the raw fibre to 80% with silica nano particles which is indicating an improvement in the order of regularity in constituent particles.

Fig. 2 a Zeta Potential of SNP, b Average particle size of SNP

Fig. 3 a Zeta Potential of GOFP, b Average particle size of GOFP

Fig. 4 **a** Zeta Potential of GOF+SNP Mix. **b** Average particle size of GOF+SNP Mix

Fig. 5 **a** XRD graph of GOF, **b** XRD graph of GOF+0.4% SNP particles

Fig. 6 Effect on apparent viscosity of different drilling fluid samples at BHR and AHR (100 °C)

Fig. 7 Effect on plastic viscosity of different drilling fluid samples at BHR and AHR (100 °C)

Mud samples analysis

Discussion

Effect on the rheological properties of drilling fluids

Apparent viscosity (AV)

AV represents the effective viscosity of the fluid, which depends on the ratio of shear stress and shear rate. Before hot rolling (Fig. 6), the AV of base mud and 5% GOFP mud were 18 cP, and 31 cP respectively. While with increasing the concentration of SNP from 0.2 to 0.4% (w/v) in GOFP mud, the AV of drilling mud was increased significantly from 34 to 38 cP respectively. After hot rolling of mud samples at 100 °C for 16 h, the AV of all mud samples were decreased as compared to the AV of drilling muds at before hot rolling (BHR), this is due to the thermal degradation of chemical after long hot rolling. As per experimental data, it was observed that even after long hot rolling, the AV of the drilling mud containing the mixture of 5% GOFP and 0.4% SNP was highly stable as comparison to other drilling fluid systems. Thus, we can say that the AV of GOFP base mud was increased drastically by 25% after the addition of 0.4% (w/v) SNP on it, which would be stabilized the viscosity of the mud during the drilling.

Plastic viscosity (PV)

It represents the frictional forces present in the drilling fluids. These frictional forces may be solid to solid, solid to liquid and liquid to liquid itself. PV of the drilling fluid is

generally increased by the addition of solid particles in the mud sample (Baker 2006). Data represented in Fig. 7 shows that after long hot rolling of various drilling fluid systems, the PV of all drilling fluids were decrease as compared to the before hot rolling, this is due to the thermal degradation of attractive forces among the mud particles. After hot rolling, the PV of base mud was 7 cP, while after the addition of 5% GOFP additive in base mud, the PV of resulting drilling fluid was increased to 11 cP. But, there was no change in PV was observed after the addition of 0.2% SNP (w/v) in the mud. However, the PV of mud was increased from 12 and 14 cP with increasing the concentration of SNP from 0.3 to 0.4%,

Fig. 8 Effect on yield point of different drilling fluid samples at BHR and AHR (100 °C)

respectively. Thus, overall results indicate that there is very less enhancement in PV after the addition of silica nano particles from 0.2 to 0.4% in 5% GOFP base mud, which is a good advantage of silica nano particles.

Yield point(YP)

Yield point (YP) of the drilling mud is a physical property that indicates the initial force in pound per sq. inch required to be applied to plastic or pseudo plastic, non-Newtonian fluids, in order to bring it to flowing state and it signifies the hole cleaning efficiency of the drilling fluid. Figure 8 shows that after hot rolling of mud samples for 16 h, the YP of drilling mud was increased by 8.6, 21.7 and 23.3% after the addition of 0.2, 0.3 and 0.4% SNP respectively in GOFP based mud. While after the addition of 0.4% SNP along with 5% GOFP in the base mud, the YP of resulting mud was increased by 87.5%. This is due to larger surface area and smaller size of SNP, the electrostatic force of attraction among the mud particles is also increased. This modified viscosity of drilling mud obtained after the use of 5% GOFP + 0.4% SNP in the base mud would be supported in the lifting of drilling cutting from the bottom hole to the surface during the drilling operations.

Gel strength

Gel strength of drilling fluid is mainly measured at 3 RPM with time interval of 10 s and 10 min by viscometer. It represents the strength of attractive forces in drilling mud under static conditions (Hakim, et al. 2018). The gel 0 and gel 10 value of various drilling fluids are plotted in Fig. 9, which are showing that the gelation of drilling fluids was increased gradually by the addition of GOFP and the various

Fig. 9 Effect on Gel Strength of different drilling fluid samples at BHR and AHR (100 °C)

concentration of SNP in the base mud. After hot rolling of mud samples, the Gel 0 values of base mud, GOFP mud and 5% GOFP + 0.4% SNP (optimized concentration) mud were 11, 20 and 25 respectively. While the Gel 10 values of these mud samples were 19, 25 and 34 respectively. The Gel 0 and Gel 10 values of SNP-based mud is showing fragile gelation, which is very essential for optimum drilling operation because this gelation ensure that no excess shear stress is required to break the gel again into the fluid when drilling operation would be resumed (Baker 2006). The optimum gelation value of SNP based mud would be helped in the holding of drill cuttings during the static condition.

Effect on the filtration properties of drilling fluid

LPLT filtration property

Filtration loss represents the ability of drilling fluid to plug permeable or producing formations by forming low filter cake. It occurs in two ways, i.e., static and dynamic (Hakim, et al. 2018). In the present study, the volume of filtration loss and the thickness of the filter cake was measured in the static conditions. Experimental data presented in Fig. 10 indicate that after hot rolling of mud sample at 100 °C for 16 h, the LPLT filtration loss volume of the base mud and 5% GOFP based mud were 32 ml and 8.5 ml, respectively. These data indicates that, after the addition of 5% GOFP in the base mud, the LPLT filtration loss volume was decrease by 73.4% (from 32 to 8.5 ml) which is showing better LPLT filtration loss control ability of grewia optiva fibre powder (GOFP) in the water-based drilling. Okon et al. (2014) showed that after addition of 10 gm CMC in 350 ml of base mud, the LPLT filtration loss volume of drilling mud was reduced by 62.77%

Fig. 10 Effect on LPLT filtration loss of different drilling fluid samples at BHR and AHR (100 °C)

Fig. 11 a SEM image of filter cake obtained from base mud, b SEM image of the filter cake obtained from 5% GOFP, c SEM image of the filter cake obtained from 5% GOFP + 0.4% SNP at 1000 KX magnification d SEM image of 5% GOFP + 0.4% SNP at 25 KX magnification showing effective plugging in filter paper

Fig. 12 Effect on LPLT filter cake thickness of different drilling fluid samples at BHR and AHR (100 °C)

(from 47 to 17.5 ml), while at the same concentration of PAC, the LPLT filtration loss volume of drilling mud was reduced by 59.57% (from 47 to 19 ml). These data are suggested that GOFP at 5% concentration is highly cost effective and better filtration control agent in water-based drilling fluid. The filtration loss property of GOFP was improved by the addition of silica nano particles (ranging from 0.2 to 0.4%) in the GOFP based mud. As per experimental results, it was observed that after the addition of SNP, the filtration control ability of GOFP was significantly increased. The LPLT filtration loss of drilling mud was decreased by 6.25%

(from 8.5 to 8.0 ml), 14.1% (from 8.5 to 7.3 ml) and 17.6% (from 8.5 to 7.0 ml) with addition of 0.2, 0.3 and 0.4% SNP, respectively, in the GOFP mud. This filtration loss reduction indicates that SNP introduced the cross linking among the mud particles which made filter cake impermeable and improved its mightiness. As per Boyou et al. (2019), nano-silica introduced a wide range of particles size distribution in the mud and increased colloidal interactions. SEM study was also carried out on the filter cake obtained from the different mud systems, which is predicting the cross-linking ability of silica nano particle in drilling mud (Fig. 11c). Figure 12 shows that after hot rolling of mud samples at 100 °C, 5% GOFP have reduced the filter cake thickness by 42.8% as compared to base mud (from 3.5 to 2.0 mm). While the thickness of the filter cake formed by 0.4% SNP along with 5% GOFP was reduced by 48.5% as compared to base mud (from 3.5 to 1.8 mm).

HPHT filtration property

Drilling fluid provide a hydrostatic pressure which should be greater than formation pressure or pore pressure to prevent the any unwanted flow from the wellbore (Bourgoyne et al. 1986; Stroud, 1922, 1926). The difference between the hydrostatic pressure and formation pressure is called over-balanced pressure. Since the recommended maximum over-balance pressure range between the formation pressure and hydrostatic pressure is 500 Psi (Rabia, 2002; Hossain and Al-Majed, 2015). Therefore, HTHP filtration test was conducted at 100 °C temperature under the differential pressure of 500 psi for 30 min. Experimental data plotted in Fig. 13 indicate that the after hot rolling of mud samples, the HPHT filtration loss volume of base mud was 52 ml while it was reduced from 52 to 16 ml by the addition of 5% GOPF in the base mud. It was observed that the HPHT filtration loss control ability of GOFP was increased by the addition silica nano particles (SNP) in the drilling fluid. Due to the smaller size and larger surface area of silica nano particles, they effectively reduced the invasion of water into shale and control filtration loss of drilling fluid (Fakoya and Shah, 2017).

After the addition of 0.2, 0.3 and 0.4% concentration of SNP, the HPHT filtration loss of GOFP was reduced by 5% (from 16 to 15.2 ml), 11.25% (from 16 to 14.2 ml) and 15% (from 16 to 13.6 ml), respectively, at 100 °C and 500 psi pressure. However, at optimum concentration of 0.4% SNP, the HPHT filtration loss volume of drilling mud was reduced by 73.84% (from 52 to 13.6 ml) as compared to base mud. This is due to high thermal stability of silica nano particles. However, in the absence of silica nano particle, the HPHT filtration loss volume of 5% GOFP base mud was reduced by 69.2% (from 52 to 16 ml) as compared to base mud. Results revealed that silica nano particles in the drilling fluid provided the thermal stability to the drilling fluid and form an

Fig. 13 Effect on HPHT filtration loss of different drilling fluid samples at BHR and AHR (100 °C)

impermeable bridge over the filter cake which reduced the filtration loss volume of the mud. Thus, in the deeper wells, 0.4% SNP is very effective to improve the HTHP filtration property of grewia optiva fibre during the drilling operations. This fluid loss reduction capability of SNP additive in drilling fluid may be mitigated different drilling problems like stuck up, shale hydration, tight pull, held up, well bore instability, etc. occurs during the drilling operation.

Recently, various studies have been done for improving the HPHT filtration property of WBM. Amanullah and Ramasamy, (2016) have used Date seed powder in water-based mud. The study of this research revealed that 6 gm date seed powder in 350 ml base mud has reduced the HPHT filtration loss volume by 59.4% as compared to base mud. Gbadamosi et al. (2019) have investigated that after the addition of 0.5% (w/v) silica nano particles in water-based mud, the HPHT filtration loss of drilling mud was reduced by 48% as compared to the base mud. Barry et al. (2015) used nano particle (3–30 nm size) in WBM. The HPHT filtration loss was reduced by 37% after the addition of 0.5% (w/v) Fe₂O₃ nano particles in the base mud. After long hot rolling of mud samples at 93 and 121 °C for 16 h, 0.5% (w/v) TiO₂ nano particles (particle size 250 nm) have reduced the HPHT filtration loss of WBM by 58% and 39.9%, respectively, as

compared to base mud (Beg et al. 2020). However, in the current study, 0.4% (w/v) silica nano particles (30–50 nm size) with 5% (w/v) GOFP have reduced the HPHT filtration loss of drilling mud by 73.84%, which make the mixture of 0.4% SNP and 5% GOFP more effective for designing of suitable drilling fluid. The thin and compact mud cake helps in decimating differential pipe sticking problems. The thickness of HPHT filter cake generated by base mud was 7.7 mm, while after the addition of 0.4% SNP and 5% GOFP in the base mud, the filter cake thickness was gradually decreased by 35.06% (from 7.7 to 5.0 mm) and 45.4% (from 7.7 to 4.2 mm), respectively, as compared to base mud (Table 3).

Scanning electron microscopy (SEM) characterization of filter cake

Scanning electron microscopy (SEM) was used to study the structure and the morphology of the filter cake. The SEM image was taken from the cross section of filter cake. This technique was used in this work to examine the effect of the different mud additives such as GOFP, silica nano particle (SiO₂), bentonite, etc. in the static filter cake formed during the fluid loss in WBM. The filter cake obtained from the

base mud, i.e., bentonite (Fig. 11a) was appearing like the compact, smooth and homogenous clay soil surface with the particle size less than 5 μm . Figure 13b is showing particle size less than 5 μm of GOF mud at 500kx magnification, which is showing the strong fibre of GOF on the surface of the cake. While Fig. 13c is showing particles size less than 200 nm at 100 KX magnification image of the SNP with GOF additive in the filter cake. Due to the very smaller size and larger surface area of nano particles, they were found to be discretely dispersed throughout the filter cake and helped in bridging the micro sized gaps. Fig. 13d is indicating the effective plugging of pores of filter cake, after the addition of SNP in GOF base mud. This effective plugging made an impermeable bridge over the filter cake and reduced the filtration loss volume of drilling mud.

Permeability of the filter cake

Among the various functions of the drilling mud, the most desired application is the minimum fluid loss volume by forming a low-permeable mud cake across the wall of the borehole. Drilling fluid with excessive filtration loss may influence the property of the well such as wellbore stability, differential sticking, and core recovery process, loss in mud volume and formation damage. Hence, an efficient drilling fluid is one which minimizes the filtrate loss in the formation by forming a thin filter cake with low permeability (Aston et al. 2002).

The permeability of filter cake is determined by Eq. (5) (Lomba, 2010):

$$K = Q_f \times \varepsilon \times \mu \times 8.95 \times 10^{-5} \quad (5)$$

Fig. 14 Effect on the filter cake permeability of various drilling fluids AHR at 100 °C for 16 h

Table 4 Cake permeability for water-based mud formulated after hot rolling of mud samples at 100 °C

Concentration	Filter cake permeability (mD)
Base mud	1.02×10^{-3}
5% GOF	0.155×10^{-3}
5% GOF + 0.2% SNP	0.147×10^{-3}
5% GOF + 0.3% SNP	0.121×10^{-3}
5% GOF + 0.4% SNP	0.117×10^{-3}

, where K = permeability of mud cake (mD). ε = thickness of mud cake (mm). μ = Viscosity of fluid in (cp).

After log hot rolling of drilling mud, the force of attraction among the particles are decomposed due to the effect of temperature. Therefore, permeability of filter cake obtained from the different drilling mud was measured after long hot rolling of mud samples at 100°C for 16 h. The permeability of various filter cake obtained after the LPLT filtration loss of drilling fluids are shown in Table 4. After the addition of 5% GOF in base mud, the permeability of filter cake was reduced from 1.02×10^{-3} to 0.155×10^{-3} mD (Fig. 14). However, after the addition of 5% GOF + 0.4% SNP mixture in the base mud, the permeability of cake was drastically reduced from 1.02×10^{-3} to 0.117×10^{-3} mD. This plugging tendency of SNP-GOF mixture in the drilling mud would be reduced the invasion of any solid and liquid particle into the permeable formations during the drilling operation.

Cost analysis

Grewia optiva fibre is an agro plant and easily available in nature. It is more cost effective and environment friendly than the conventional fluid loss control additives, e.g., CMC-LVG and PAC-LVG. The cost of different fluid loss control (Table 5).

Conclusion

As per experimental studies, it was observed that the filtration loss and rheological properties of GOF additives was effectively improved by using silica nano particles in the water-based drilling fluid. After hot rolling of mud samples

Table 5 Cost of fluid loss control material

Material	Cost/kg (USD)	Source
Carboxy methyl cellulose	4.96	Okoro et al. (2018)
Poly anionic cellulose	6.0	Okoro et al. (2018)
Grewia optiva fibre	0.3 (Approximately)	Shishir (2016)

at 100 °C for 16 h, 0.4% (optimum concentration) of SNP have reduced the LPLT and HPHT filtration loss of GOF additive by 17.6% (from 8.5 to 7.0 ml) and 15% (from 16 to 13.6 ml), respectively, in WBM. However, the mixture of 0.4% SNP + 5% GOF-based mud has reduced the LPLT and HPHT filtration loss by 78.1 and 74.03% respectively as compared to base mud. The LPLT and HPHT filtration control ability of GOF additive were increased by 17.6 and 15%, respectively, by using SNP in WBM. This reduction in filtration loss would be mitigated the various wellbore instability problems in high temperature and high pressure wells. Thickness of LPLT and HPHT filter cake produced by the mixture of 0.4% SNP + 5% GOF based mud was reduced by 48.5 and 45.4% respectively with respect to base mud. Reduction in the thickness of filter cake would be prevented of string stuck up problems. The YP of 0.4% SNP + 5% GOF mixture mud was increased by 87.5%, as compared to base mud. While the YP of drilling mud containing GOF was increased by 23.3% after the addition of 0.4% SNP on it. The 0.4% SNP + 5% GOF mixture has also increased the Gel 0 and Gel 10 of drilling mud by 21 and 36% respectively as compared to base mud.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflicts of interest.

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