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Improving the Lifting Capacity of Drilled Cuttings Using Henna Leaf Extracts and Lignite in Bentonite Water-based Drilling Mud

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Abstract. One of the basic functions of drilling fluids is to transport drilled cuttings to the surface. Bentonite with low solids content is preferred in carrying out this task. However, a low amount of bentonite in the drilling mud is incapable of effective cuttings lifting and suspension. In this study, a new, green, low-cost henna leaf extract and lignite in bentonite water-based drilling mud was used to transport cuttings to the surface. The effects of three hole angles (0°, 45° and 90°) were examined at different cuttings size diameters (0.5 mm, 1.0 mm, 2.0 mm and 2.4 mm) for the mud systems. The average cuttings transport efficiencies were found to be in the following order: 52-94% for 0.5 mm diameter, 45-93% for 1.0 mm diameter, 38-90% for 2.0 mm diameter, and 33-83% for 2.4 mm diameter. Viscosity and hole angle are directly related to cuttings transport efficiency. A plastic viscosity of 16 cP and yield point of 12.5 lb/100ft² were the most effective mud properties for a 45° hole angle, which needs attention while preparing the drilling mud. Addition of henna and lignite can be used to improve the rheological and filtration properties of bentonite water-based drilling mud.

Keywords: *cuttings size diameter; cuttings transport efficiency; henna; hole angle; lignite, rheological properties.*

1 Introduction

Achieving effective drilled cuttings removal to the surface is one of the major challenges in drilling operations [1]. This problem appears to have been well examined in the case of straight hole angles [2], but in the case of highly deviated and horizontal well drilling, removal of drilled cuttings is still a major problem [3]. Also, drilling in highly deviated and horizontal wells is more complicated when the well depth and hole deviation are larger [4]. Application of this form of drilling system is in most cases connected with serious drilling

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problems, which often affect the performance of the drilling mud. High torque and drag, barite sag, formation damage, lost circulation, low penetration rate, increased equivalent circulating density, kick leading to blowout if not properly controlled, hole instability, and in bad situations, differential stuck pipe, are some of the problems faced while drilling in high angle wells [1-6]. If these problems are not properly addressed, they can get worse and lead to well-side tracking or even loss of the entire well [7]. Thus, an appropriate design of the drilled cuttings transport strategy, such as incorporating optimum drilling fluid properties and using the best drilling practices, is crucial to obtaining successful drilling operations.

The transportation of drilled cuttings by drilling mud is much easier if suitable additives are used to formulate the drilling mud. Selecting suitable additives to meet the desired goal of drilling a well is a determining factor of the performance efficiency of such a well [6-7]. Drilling muds are indispensable and play a crucial role in drilling operations. This includes, but is not limited to, maintaining wellbore integrity, lifting rock cuttings from the subsurface to the surface, cooling and lubricating the drill-bit, suspending drilled cuttings when the pump is off, controlling the loss of filtrates into the formation by forming a mud cake on the wall of the wellbore, and controlling the formation pressure of the well [7-10]. Bentonite clay is commonly used to formulate water-based mud (WBM) in order to improve cuttings transport performance and reduce loss of filtrates into the drilled formation [11]. However, the solids content of WBM is increased if a high amount of bentonite clay is added, and these high clay solids have numerous adverse effects: (1) they reduce the drilling rate, (2) promote pipe sticking, and (3) cause undue torque and drag. Therefore, it is more appropriate to use a low amount of bentonite clay in order to control the overall amount of solids in the mud [11]. However, a low amount of bentonite clay in the mud makes the mud incapable of providing adequate rheological properties needed for effective transportation of drilled cuttings and other debris to the surface. To remedy this issue, polymeric viscosifiers are either added as substitutes for bentonite or used together with bentonite in conventional WBM in order to achieve the desired result.

Bio-based henna from the hina tree (*Lawsonia inermis L.*) is a low-cost, ecofriendly, naturally occurring material that is readily available to formulate drilling fluids for drilling operations [12-14]. Henna leaf extracts (HLE) have been utilized with great success as shale swelling inhibitor, viscosifier, lubricity enhancer [12-13]. However, the application of henna alone as viscosifier for cuttings transport has not yet been proven owing to its appreciably low gel strength for effective drilled cuttings suspension. It has been suggested that thinners such as lignite could help to improve the weak gelling nature of henna mud [15-16]. Thinners also have the capacity to control viscosity and stabilize drilling muds, especially at temperatures above 350 °F in order to avoid mud gelation [16]. Lignite as thinner decreases the flocculation tendency of the mud and makes the positive charges located on the bentonite clay platelets less effective. It can also help to prevent the clay platelets from bonding together [16]. It is mainly introduced to muds containing high flocculation caused by bentonites and excessive solids to lower the gel strength and the yield point [16].

Although there have been some studies in the past indicating the application of lignite in controlling the viscosity of WBM [15-16] and HLE in reducing the intrusion of filtrates into the drilled formation [12-13], there are almost no studies on the use of these two materials together in a bentonite water-based drilling mud. Therefore, the objective of this study was to evaluate the cuttings lifting performance of these two products in a bentonite water-based drilling mud.

2 Experimental Section

2.1 Materials

Bentonite, henna powder, caustic soda (NaOH), high viscosity polyanionic cellulose (PAC HV), lignite, potassium chloride (KCl) and barite. These additives were obtained from Sigma-Aldrich (Merck, Sdn. Bhd. Malaysia). Tables 1 and 2 show the properties of the HLE and lignite used in this study. Aquarium sands were used as drilled cuttings. The sands were irregularly shaped and sieved into different size diameters of 0.5 mm, 1.0 mm, 2.0 mm, and 2.4 mm. The sands were stored in plastic bags of 200 g each. The density of the sands measured was 2.40 g/cm^3 and the total eight of the sieved sands was 8 kg.

Table 1 HLE properties.

Product	**Dry HLE**
Used part	Leaf
Color	Brown
Odor	Specific odor
Solubility in water	Soluble
Solubility in alcohol	Soluble
pH (30 g/L)	4.6 - 5.0
Total ash (550 °C/4 h)	14.36%
Description	Fine powder
Application	Hair dye, body paint, tattoo, dye, special shampoo, anti-corrosion

Table 2 Lignite properties.

Product	Air dried lignite
Moisture content	18.60%
Volatile matter	35.09%
Ash content	11.83%
Solubility in water	Soluble
Carbon	50.77%
Hydrogen	3.57%
Nitrogen	0.79%
Oxygen	14.19%
Sulphur	0.26%
Appearance (form)	Powder
Appearance (color)	Brown
Compatibility	Compatible with anionic and nonionic surfactants and wetting agents

2.2 Cuttings Transport Flow Loop Set-Up Descriptions

The research was accomplished through the design of a cuttings transport flow loop at the Heavy Duty Laboratory, Universiti Teknologi Malaysia (UTM) (Figure 1). Prior to the investigations, 80 L of drilling mud was prepared in a mud tank with different compositions, as shown in Table 3, and mixed thoroughly for 6 h until an homogeneous state was achieved. The dimensions of the flow loop were: 11 ft long transparent acrylic outer pipe with a diameter of 3.0 in OD and 2.0 in ID. The transparency of the outer pipe was required to allow a smooth observation of the cuttings as they were transported and also to identify the type of transport mechanism under different operating conditions. The inner pipe did not contain a centralizer, but was supported at the ends of the pipe in order to allow it to assume several types of motion while rotating. Both ends of the inner pipe were sealed to prevent mud from flowing through them.

The annulus test section was connected to a flexible tube on both ends so that different required hole angles could be attained i.e. 0° (vertical), 45° (deviation) and 90° (horizontal). In order to trap the cuttings, a separation tank was mounted after the annulus section, fitted with a wire mesh of 0.2 mm diameter. The wire mesh was much smaller than the cuttings size in order to achieve efficient separation. The mud tank used to prepare the drilling muds had a maximum capacity of 142 L, installed with a 1-hp mixing pump at the top, and at the outlet of the tank, a 2-hp centrifugal pump with a flowrate range between 20 and 42 L/min. The flow loop was provided with supporting systems that supported the pipe vertically and a pressure gauge to determine the pressure inside the loop. Also, a supplying and cooling system was attached to the flow loop.

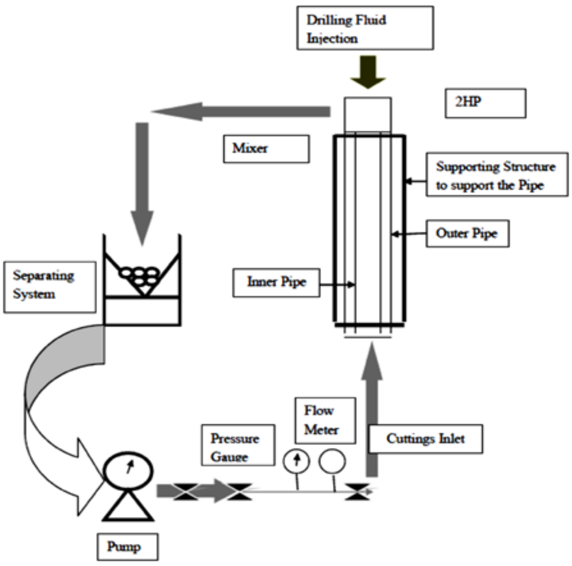

Figure 1 Representation of the cuttings transport flow loop.

2.3 Methods

2.3.1 Drilling Mud Formulation

The formulation of WBM with different additives was carried out according to the API recommendations (17). Seven types of drilling mud systems were formulated as shown in Table 3.

Table 3 Drilling mud compositions.

Mud types	Composition
Mud #1 (WBM)	Tap water (350 ml) + Bentonite (15 g) + NaOH (0.15 g) + PAC HV (0.25 g) + KCl (15 g) + Barite (10 g)
Mud #2	Mud #1 + Henna (10 g)
Mud #3	Mud #1+ Henna (10g) + Lignite (5g)
Mud #4	Mud #1 + Henna (10g) + Lignite (8g)
Mud #5	Mud #1 + Henna (10g) + Lignite (10g)
Mud #6	Mud #1 + Henna (10g) + Lignite (12g)
Mud #7	Mud #1 + Henna (10g) + Lignite (15g)

2.3.2 Rheological Properties Measurement

The densities of the different mud samples were measured with a mud balance. A Fann viscometer, model 35 (Houston, Texas, USA), was used to measure the rheological properties of all the mud samples at different dial readings of 3, 6, 100, 200, 300, and 600 revolutions per min (rpm) according to the API recommendations (17). The viscometer produces the viscosity values in cP or mPa.s. The Bingham plastic fluid model described by Equations (3)-(6) below was used to determine the plastic viscosity (PV), apparent viscosity (AV), yield point (YP), and gel strength (GS). The PV, YP, and AV were calculated from 300 rpm and 600 rpm viscometer dial readings. The gel strength (GS) for 10 sec and 10 min were also measured [17]. Filtrate loss volume (FL) was measured using a Fann API filter press, series 300 (Houston, Texas, USA), at 100 psi and room temperature. The volume of the filtrate for each mud sample was obtained after a 30-min period and the filter cake thickness (FCT) was also measured.

$$\text{PV (cP)} = \theta_{600} - \theta_{300} \tag{1}$$

$$\text{YP (lb/100ft}^2\text{)} = \theta_{300} - \text{PV} \tag{2}$$

$$\text{AV (cP)} = \theta_{600}/2 \tag{3}$$

2.3.3 Drilled Cuttings Investigation

A simulation of the drilled cuttings in the flow loop was first conducted with water in order to check and fix any leakage in the flow loop. Before injecting the drilled cuttings, the flow was stabilized using the pump controller and was allowed to flow at a stabilized flowrate for 7 min. Through the cuttings inlet, 200 g of cuttings was injected and the valves were opened to divert the flow so that the cuttings could be carried along. The flow was maintained for a further 5 min and the cuttings were then collected from the wire mesh at the shale shaker after turning off the mud pump. The collected cuttings were washed, dried, weighed and stored in a separate plastic bag for another run. The investigations were continued with a constant flowrate of 42 L/min at varying hole angles (0°, 45° and 90°). This process was repeated using the seven mud systems and the three hole angles with different cuttings diameters (0.5 mm, 1.0 mm, 2.0 mm and 2.4 mm). The performance of each mud system was evaluated using the cuttings transferring efficiency (CTE) given in Eq.(4) below.

$$\text{CTE} = \frac{\text{Weight of recovered cuttings in gram}}{\text{Weight of total injected cuttings in gram}} = \frac{M_r\ (g)}{M_i\ (g)} \tag{4}$$

3 Results and Discussions

Figures 2 and 3 show the obtained results of mud properties and average control sample measurements for the seven drilling mud systems, respectively.

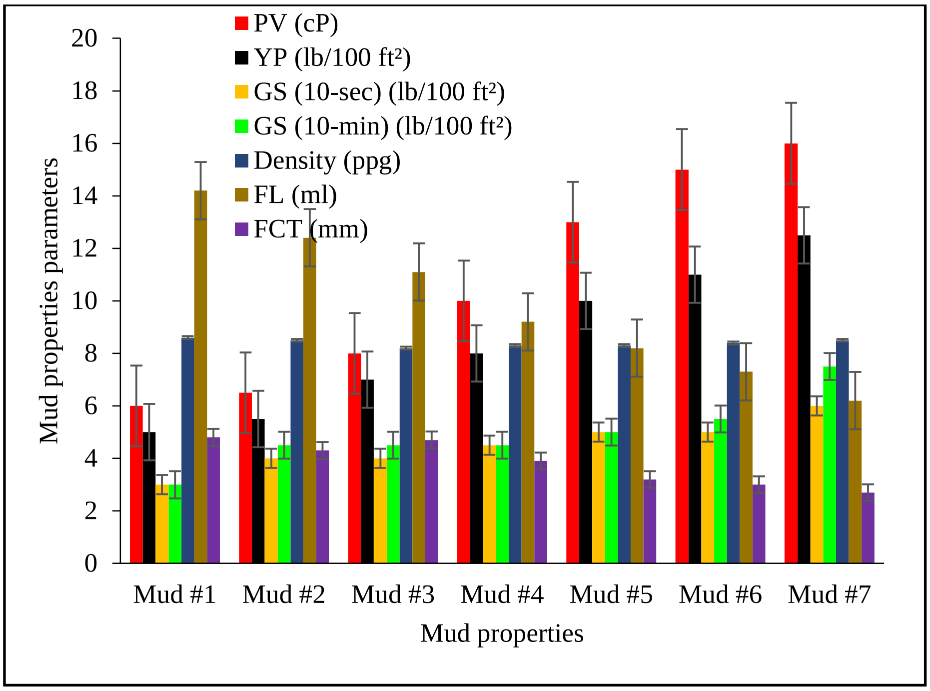

Figure 2 Mud rheological and filtration properties.

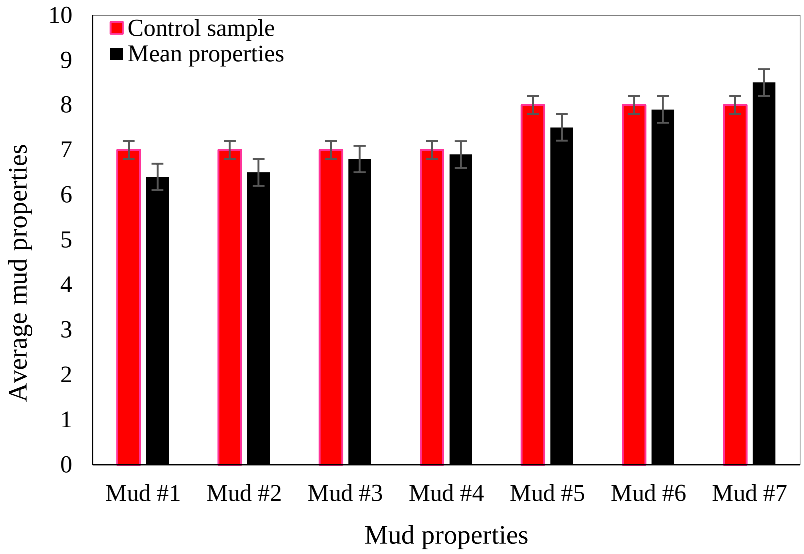

Figure 3 Average mud properties with control samples.

3.1 Mud Density

Mud density controls hydrostatic pressure in a wellbore and prevents unwanted flow into the well. The data for the mud density are shown in Figure 2. It can be seen that there was no considerable variation in mud weight after addition of henna and lignite to Mud #1.

3.2 Rheological Behavior of Mud Systems

Figure 2 shows that the PV, YP, 10-sec GS and 10-min GS of the based mud (Mud #1) increased with the addition of HLE and lignite. The PV is an indication of high shear rate viscosity and is a function of the viscosity of the liquid phase and the volume of solids present in the drilling mud. The addition of solids, such as clays, which swell due to adsorption of water, will increase the PV. On the other hand, anything that causes changes in the low shear rate viscosities will be reflected in the YP. In other words, the YP denotes the tendency of clay layers to link together and form a flocculate structure and indicates the ability of the drilling mud to carry cuttings to the surface in dynamic conditions [18-20].

Moreover, frictional pressure loss is directly related to the YP. A higher YP implies higher pressure loss while the mud is being circulated [18-20]. It is important to identify the gel strength of the drilling mud, else it could have the wrong value and cause problems while drilling. Gel strength is the shear stress measured at a low shear-rate after a mud has set quiescently for a period of time. The gel strength is a crucial drilling mud property because it shows the ability of the drilling mud to suspend drill solids and weighting material when circulation is ceased. A low gel strength will result in the cuttings dropping to the bottom of the annulus when the pump is off. With a high gel strength, the mud becomes static and blocks solids from flowing out of the annulus.

The PV of the base mud increased when 10 g of HLE was added. HLE is a deflocculant and can help to control the PV of the mud if the mud flocculates. This can be ascribed to the changes in the chemical structure of HLE in bentonite WBM [18]. When lignite was introduced to the mud systems, all the mud rheological properties increased with increasing concentration. The PV of the base mud increased from 6 cP to 16 cP when 15 g lignite was added. The improvement in the PV of the base mud with HLE and different concentrations of lignite suggest that the PV automatically increased when it was exposed to drilled cuttings and other solid particles, such as barite in the bentonite WBM.

The YP of the bentonite WBM increased from 5 lb/100ft^2 to 5.5 lb/100ft^2 when HLE was added, and further increased with increasing concentration of lignite. The YP of the base mud increased to 12.5 lb/100ft^2 with 15 g lignite. The YP was significant at low hole angles (vertical) and less effective at higher hole angles [18-19]. The obtained YP values ranged from (5-12.5 lb/100ft^2); these values could be more effective at lower hole angles. This is because low angle wells may need lower pumping power compared to high angle wells, which generally have larger hole diameters. In addition, if the YP is too high, it will make the mud difficult to be pumped out from the bit because more pressure is required to suppress the shear stress [19,20]. The 10-sec and 10-min GS showed similar rheological trends, which increased with an increasing amount of lignite in the base mud. The 10-sec GS and 10-min GS of the base mud increased from 3 lb/100ft^2 to 4 lb/100ft^2 and from 3 lb/100ft^2 to 4.5 lb/100ft^2, respectively, with the addition of HLE. HLE has a deflocculating property; deflocculants are generally used to control the YP and GS [18]. In addition, in the presence of deflocculants such as HLE, clay separated unit layers cannot be linked together due to neutralization of the positive edges of the bentonite clay unit layers. This may result in helping HLE to control the YP and GS of base mud [20]. More so, the obtained values of GS could improve the efficiency of the solids control apparatus. It is suggested that the gelling property of lignite contributed to improving the GS of the base mud from 3-6 lb/100ft^2 for 10-sec GS and 3-7.5 lb/100ft^2 for 10-min GS. When the mud sets to a gel, the GS will have the capacity to suspend drilled cuttings when circulation ceases and will break up easily to a thin mud when agitated again [10,18-20].

3.3 Filtration Properties

The obtained data on the filtrate loss volume and filter cake thickness are shown in Figure 2. The filtrates loss volume for Mud #1 showed the highest filtrates loss capability into the formation compared to the other mud samples containing HLE and lignite. The filtrate loss volume is dependent on the performance of the materials that make up the drilling fluid. HLE improved the filtration properties of the base mud (Mud #1) formulated with PAC HV, a filtrate loss control agent, by decreasing the filtrate volume from 14.2 ml to 12.4 ml. With increased addition of lignite, the filtrate volume of the base mud decreased from 14.2 ml to 6.2 ml after addition of 15 g lignite. Lignite contains a humic acid that makes it soluble in aqueous medium. The soluble lignite in WBM acts as a deflocculant by interacting with solid particles to enhance the seal of the filter cake on the wellbore [15].

The higher the filtrate loss into the formation, the higher the filter cake thickness. The base mud filter cake thickness was higher before addition of HLE and lignite as shown in Figure 2. The filter cake thickness of the base mud decreased from 4.8 mm to 4.3 mm when HLE was added and decreased further to 2.7 mm at 15 g lignite. It is suggested that addition of HLE and lignite improved the filtration control properties of the base mud and hence lowered the filter cake thickness. This value could be desirable in preventing stuck pipe incidents. The effect of a thick mud cake is that it reduces the effective diameter of the drilled wellbore, thereby increasing the area of contact between the drill pipe and the cake, leading to a greater risk of stuck pipe incidents [18-19].

3.4 Effects of Hole Angle on Cuttings Transportation

The results of cuttings transport efficiency with various cutting size diameters are shown in Figures 4(a)-(d). It can be seen that hole angles and mud viscosities have a direct contribution to the transportation of cuttings to the surface.

All the flow lines produced a downward behavior by deviating from a vertical (0°) to 45° hole angle (deviated), signifying that the CTE decreased. It gradually increased to a 90° hole angle (horizontal).

The hole angle of 45° showed the lowest CTE, indicating that it is the most challenging hole angle for cuttings transportation. This could be due to the recurrent sliding and tumbling down of the cuttings bed when the hole starts to deviate from vertical [3-5]. The stability of the cuttings started gaining strength as the deviation increased past a 60° hole angle.

The results shown in Figure 4 are consistent with previous researches [3-6]. They reported that cuttings transportation is more challenging at a hole angle range of 35-60°. It is suggested that in oil well drilling, the cuttings have a tendency to settle in the whole vertical portion of the annulus, while in the deviated, highly deviated or horizontal sections they only have a few portions to settle. These phenomena have been explained in several studies as being caused by fluid velocity variation in the annulus, which ranges from zero at the wall to maximum at a point between the pipe’s outer wall and the wall of the wellbore [3-6]. This behavior is the reason for achieving the highest cuttings transferring efficiency at a 0° hole angle and the poorest at a 45° hole angle in this study.

In terms of different cuttings sizes, the average cuttings transferring efficiency at various cuttings size diameters were found to be in the following range: 52-94% for 0.5 mm, 45-93% for 1.0 mm, 38-90% for 2.0 m and 33-83% for 2.4 mm. Among these variations, the cuttings size diameter of 0.5 mm showed the highest average transport performance for all the mud systems. Next was the 1.0-mm cuttings size diameter, followed by the 2.0 mm diameter and finally the 2.4 mm cuttings size diameter. These data show that the smaller the cuttings size diameter, the better the cuttings transport performance for all hole angles and viscosities.

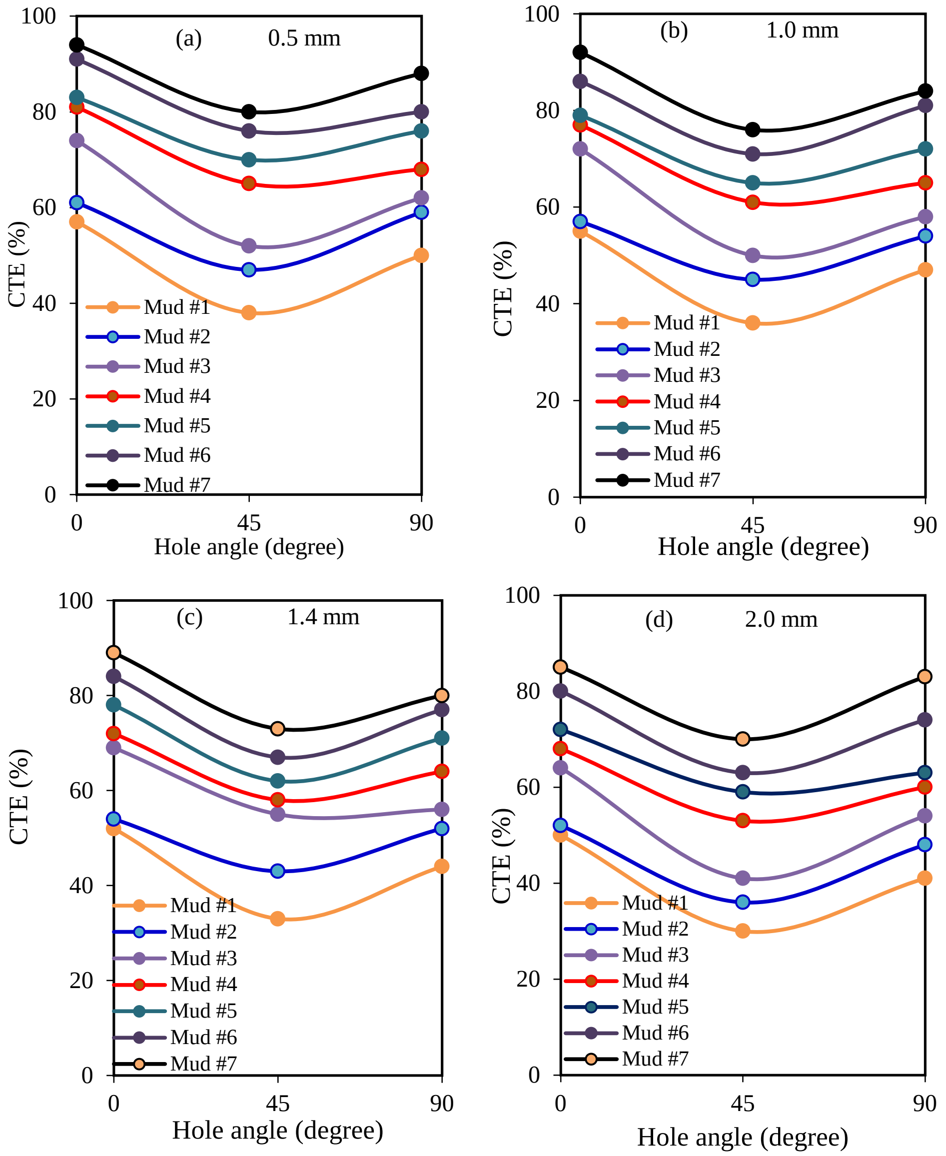

Figure 4 CTE versus hole angle for all mud systems and cuttings diameters.

3.5 Conclusions

This study examined the performance of bentonite water-based mud, HLE and lignite. The effects of three hole angles (0°, 45° and 90°) with different cuttings size diameters (0.5 mm, 1.0 mm, 2.0 mm and 2.4 mm) on cuttings transportation efficiency were carried out. The rheology and filtration properties of the base mud (Mud #1) enhanced with the addition of HLE and lignite, which contributed to an increase of the transport capacity of the base mud. As a result, more drilled cuttings were transported to the surface. A PV of 16 cP and a YP of 12.5 lb/100ft² were the most effective mud properties for the 45° hole angle, which needs attention while preparing the drilling mud. Transportation of drilled cuttings to the surface was easier with the use of smaller cuttings size diameters at all hole angles compared to bigger ones. The cuttings size diameter had a minimal impact on the performance of the muds, as an increase in viscosity leads to more cuttings being transported regardless of the size. The vertical portion of the well showed better cuttings transportation performance compared to the deviated and horizontal portions.

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Nomenclature

API	American Petroleum Institute
FCT	Filter cake thickness (mm)
FL	Filtrates loss (ml)
GS	Gel strength (lb/100ft²)
GS-10 min	10 min gel strength
GS-10 sec	10 sec gel strength
HLE	Henna leaf extracts
Hp	Horse power
ID	Inner diameter
KCl	Potassium chloride
Mi	Weight of injected cuttings in gram
Mr	Weight of recovered cuttings in gram
NaOH	Sodium hydroxide/caustic soda
OD	Outer diameter
PAC HV	High viscosity polyanionic cellulose
PV	Plastic viscosity (cP)
TE	Cuttings transport efficiency
UTM	Universiti Teknologi Malaysia
WBM	Bentonite water-based mud
YP	Yield point (lb/100ft²)

References

[1] Duan, M., Miska, S.Z., Yu, M., Takach, N.E. & Ahmed, R.M., *Transport of Small Cuttings in Extended Reach Drilling*, SPE Drilling Completion, **23**, pp. 258-265, 2008.

[2] Belavadi, M.N. & Chukwu, G.A., *Experimental Study of the Parameters Affecting Cutting Transportation in a Vertical Wellbore Annulus*, SPE paper presented at the Western Regional Meeting, 23-25 March, 1994, Long Beach, California, USA. Pp. 23-27.

[3] Ismail, I., Onuoha, M.D.U., Ismail, A.R., Piroozian, A., Sulaiman, W.R.W. & Abbda, S.M., *Improving Drilled Cuttings Lifting Using Polypropylene Beads in Water-Based Mud at Different Annular Mud Velocities*, International Journal of Engineering and Technology, **9**, pp. 1-10, 2016.

[4] Onuoha, M.D.U., Ismail, I., Piroozian, A., Mamat, N.S. & Ismail, A.S., *Improving the Cuttings Transport Performance of Water-Based Mud*, Sains Malaysian, **44**, pp. 629-634, 2015.

[5] Gavignet, A.A. & Sobey, I.J., *A Model for the Transport of Cuttings in Highly Deviated Wells. SPE 15417,* Presented at SPE Annual Technical Conference & Exhibition, 1-3 October, New Orleans, pp. 24-31, 1989.

[6] Ford, J.T., Peden, J.M., Oyeneyin, M.B., Gao, E. & Zarrough, R., *Experimental Investigation of Drilled Cuttings Transport in Inclined Boreholes*, SPE 20421, 65th SPE Annual Technical Conference and Exhibition, 23-26 September, New Orleans, LA, USA. pp. 197-206, 1990.

[7] Gatlin, C., *Petroleum Engineering: Drilling and Well Completions,* Prentice-Hall, Englewood Cliffs, New Jersey, pp. 125-129, 1960.

[8] Caenn, R., Darley, H.C.H. & Gray, G.R., *Introduction to Drilling Fluids*, in Composition and Properties of Drilling and Completion Fluids, 7th edition, Gulf Professional Publishing, USA, pp 1–748, 2017. ISBN: 978-0-12-804751-4.

[9] Caenn, R. & Chillingar, G.V., *Drilling Fluids: State of the Art*, Journal of Petroleum Science and Engineering, **14**, pp. 221-230, 1996.

[10] Darley, H.C.H. & Gray, G.R., *Composition and Properties of Oil Well Fluids*, Gulf Publishing Company, Houston, Texas, United States, **270**, pp. 495-498, 1981.

[11] Menezes, R.R., Marques, L.N., Campos, L.A., Ferreira, H.S, Santana, L. N.L. & Neves, G.A., *Use of Statistical Design to Study the Influence of CMC on the Rheological Properties of Bentonite Dispersions for Water-based Drilling Fluids*, Applied Clay Science, **49**, pp. 34-41, 2010.

[12] Moslemizadeh, A., Shadizadeh, S.R & Moomenie, M., *A Natural Dye in Water-based Drilling Fluid: Swelling Inhibitive Characteristics and Side Effects*, Petroleum, **3**, pp. 1-12, 2016.

[13] Moslemizadeh, A., Shadizadeh, S.R. & Moomenie, M., *Experimental Investigation of the Effect of Henna Extract on the Swelling of Sodium Bentonite In Aqueous Solution*, Applied Clay Science, **105**, pp. 78-88, 2015.

[14] Aghajafari, A.H., Shadizadeh, S.R., Shahbazi, K. & Tabandehjou, H., *Kinetic Modelling of Cement Slurry Synthesized with Henna Extract in Oil Well Acidizing Treatments*, Petroleum, **2**, pp. 96-207, 2016.

[15] Vassilios, C., Kelessidis, G.C., Pagona, M., Vassiliki, H., Christina, T., Athanasios, M., Cassiani, P. & Antonios, F., *Gelation of Water-based Bentonite Suspension at High Temperature and Rheological Control with Lignite Addition*, Applied Clay Science, **36**, pp. 221-231, 2007.

[16] Russell, J.A. & Patel, B.B., *Drilling Fluid*, US Patent, 4,704,214., 1987.

[17] American Petroleum Institute 13B-1, *Recommended Practice for Field Testing Water-based Drilling Fluids*, 5th edition, pp. 1-121, 2017.

[18] Annis, M.R., & Smith, V., *Drilling Fluids Technology*, Exxon Company, USA, 1996.

[19] Gbadamosi, A.O., Junin, R., Abdalla, Y., Agi, A. & Oseh, J.O., *Experimental Investigation of the Effects of Silica Nanoparticle on Hole Cleaning Efficiency of Water-Based Drilling Mud*, Journal of Petroleum Science and Engineering, **172**, pp. 1226-1230, 2018.

[20] Oseh, J.O., Norddin, M.N.A., Farooq, F., Ismail, A.R., Ismail, I., Gbadamosi, A.O. & Agi, A., *Experimental Investigation of the Effect of Henna Leaf Extracts on Cuttings Transportation in Highly Deviated and Horizontal Wells*, Journal of Petroleum Exploration and Production Technology, **5**, pp.1-18, 2019.