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Transports of Different Cuttings Sizes in A Wellbore using Henna and Lignite Materials

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Abstract: *Knowledge gained in the field has revealed that ineffective transports of cuttings are the major contributing factors for undue torque and drag problem during wellbore drilling operations; however, only little information is known about cuttings transports behaviour with different cuttings sizes owing to availability of limited field data on flow pattern of different cuttings sizes. In this study, cuttings transports experiment at a constant flowrate of 380.52 bbl/D with four different cuttings sizes (0.5, 1.0, 2.0 and 2.4 mm) was conducted in a laboratory-scale flow loop of dimensions (3.0 in. × 2.0 in., 11 ft.-long) annular test section with no pipe rotation. The effects of these cuttings sizes at three hole-angles (0°, 45°, and 90°) were investigated. The findings revealed that the larger cuttings sizes (2.0 mm and 2.4 mm) shows a lower degree of cuttings transportation compared with the smaller cuttings sizes (0.5 mm and 1.0 mm). Accordingly, the smallest cuttings size of 0.5 mm has higher cuttings recovery to the surface. The fluid viscosity and hole-angles were found to have direct contributions to cuttings transports, while cuttings size have minimal contributions. Viscosity at 8 cP and other muds properties at this viscosity, such as yield point (5 lb/100ft²), 10-sec gel strength (7.0 lb/100ft²), and 10-mins gel strength (8 lb/100ft²) achieved the optimum cuttings transports efficiency by producing the highest contribution to the cleaning of the wellbore compared to the overall performance of the mud at other viscosities (2.5, 4.5, 5.5, 12, 13 and 17 cP). Hole-angle of 45° was found to be the most challenging for effective cuttings transports owing to its lower cuttings transferring efficiency, and they need greater attention while designing the drilling mud. The outcomes of these study could lead to a new approach in improving cuttings transportation using henna and lignite materials.*

Keywords: *Cuttings Transports Efficiency, Cuttings Sizes, Henna, Lignite, Bentonite Clay.*

1. INTRODUCTION

Efficient drilled cuttings transports from the wellbore to the surface has been found to be a major challenge in drilling operations [1]. In rotary drilling operation, drilled cuttings can be crushed to finer particles when they are being circulated out of the wellbore. Drilling in such a wellbore may not be able to continue if cuttings removal is not efficient. Due to the problem of undue torque and drag caused by the settling of drilled cuttings at the lower side of the deviated or horizontal sections, it may be difficult to run casing in the hole even if drilling to the targeted depth can be attained. Field practice, experience gained and observations from experimental data showed that it is more difficult to transport smaller cuttings under certain conditions when compared with other cuttings sizes [1 - 4]. Besides, smaller cuttings size is more incline to easily adhere a drill-pipe owing to its cohesive effects [4]. It is often very difficult to pull out the pipe once it gets trapped by drilled cuttings. By estimating the total concentrations of drilled cuttings within the annulus, it was observed that it is easier to transport smaller cuttings in vertical wellbore, but they are difficult to transport in deviated or highly deviated wellbores [1]. This finding was in agreement with the report of [5]. They observed that at high holes-inclination, smaller particles are harder to transport. These smaller particles require a higher fluid flowrate to keep on moving forward continuously. The smallest of the cuttings used was of diameter 2.3 mm.

However, it was reported that the size of cuttings only contributes little to cuttings transports, but its impact on the effects of other variables is significant [6]. In the same way, it was observed that the contributions of cuttings size on cuttings accumulation in a deviated and horizontal wellbores are rather contingent on other variables [3]. According to the works of [3], that used mud of low viscosity, larger size cuttings are easier to transports than smaller ones at all flow velocities and pipe rotation speed. Nevertheless, with mud of high viscosity, the trend may inverse, reliant on different flow velocities. However, all the cuttings sizes previously mentioned falls within the sizes of 1.3-7 mm in diameter. In fact, the lifting mechanism of small cuttings size is more complex than that of medium or larger ones due to stronger particle-mud interphase interaction and particle-particle intraphase interaction [2].

It was reported that particle size range of 2-6 mm are harder to clean and has great influence on the cuttings bed height development [2]. They also pointed out that for equal hydraulic power rate, bigger particles lead to greater bed height formation than smaller particles. Another report has it that, it is easier to transport smaller cuttings provided the rotation speed of the pipe and mud velocity is high [8]. Their investigation was based on average particle size of 2-7 mm. It was reported that 0.76 mm size of average particles are very difficult to transport using water-based mud [4]. However, reports by [9] agreed to those reported by [8], in that smaller size cuttings transports is more effective at all hole-angles with a low mud viscosity, whereas between 0-50°, larger cuttings size is easier to transport with high mud viscosity**.** This is because cuttings transports worsened with increasing hole angles due to variation in fluid velocities in the wellbore. The cuttings slip velocity increases with the diameter of the cuttings, but the rate of this increase varies according to the different cuttings sizes range. For smaller cuttings size, slip velocity of cuttings increases approximately proportionally to the square diameter of the cuttings at all hole-angles. For larger cuttings size, the slip velocity increases proportionally to the square root of the cuttings diameter. As the hole starts to deviate from vertical, the fluid velocity component reduces and larger cuttings size tend to easily slip out of the drilling mud and settle. Thus, high mud viscosity will induce higher buoyancy force needed to keep the large drilled cuttings moving upward and to overcome the gravity effects acting on the large drilled cuttings [9]**.** It can be suggested from the above cuttings behaviour that there were divergent views on the actual size of cuttings that will be easier or more difficult to transport. Thus, based on these divergent views, these cuttings characteristics deserves more attention in this study. However, the mechanism of drilled cuttings transports will be much easier if suitable additives are used to design the drilling mud.

Various additives of polymers are used to formulate drilling mud in order to meet the different requirements of the mud, such as rheological properties, density, fluid loss control properties and shale swelling inhibition. The formation of selecting water-based mud (WBM) over pneumatic-based mud (PNM), synthetic-based mud (SBM) and oil-based mud (OBM) was stick to owing to their unique attributes, such as eco-friendliness, lower costs, no health, safety and disposal issues [10]. Another remarkable attribute of WBM formulated with polymer-based additives is the ease at which their characteristics can be modified and tailored for specific purposes [10, 11]. Henna extracts and lignite are among the polymers befitting with these attributes, and they can be used to enhance mud rheological properties and control the amount of filtrates entering into the formation.

A bio-based Henna or Hina (Lawsonia inermis L.) plant is a proven environmentally benign and low cost polymer [12]. It is an odoriferous plant of Lythraceae family. It is a small tree or shrub with spine tipped branches and 200-600 cm height. It has a smooth leaf often described to be opposite sub-sessile, shaped elliptically and approximately lanceolate, with depressed veins that can be seen clearly from the dorsal surface [13 - 15]. Henna plants are mostly cultivated in Egypt, Iran, India, Yemen, Algeria, Nigeria, Afghanistan and Pakistan, etc. [16]. The leaf extracts of Henna have been proven to contain lawsone, gallic acid, glucose, resins, mucilage, tannic acid, fats and traces of alkaloids [17]. It was indicated that the main constituents of Henna powder are gallic acid (3,4,5-trihydroxy benzoic acid, $C_7H_6O_5$), Lawsone (2-hydroxy-1,4 naphthoquinone, $C_{10}H_6O_3$), tannic acid, and dextrose (α-D-Glucose, $C_6H_{12}O_6$) [18].

Henna is mainly known for tattooing applications [16]. Its usage has also been extended for treatment purposes, such as antimicrobial agents [14], drug and dyes [19]. Henna have been proven to be a low cost, eco-friendly, a naturally occurring material, and readily available to formulate drilling fluids for drilling operations [17, 20, 21]. Henna leaf extracts have been utilized with certain success as a shale swelling inhibitor, viscosifier, and lubricity enhancer [20]. [17] hinged on their remarkable features, such as environmental acceptability, a naturally occurring material, low cost imprint, and readily available to formulate drilling fluids for drilling operations. They used some concentrations of henna powder extracted from its leaf in WBMs to inhibit shale swelling. In doing this, they carried out different series of tests ranging from compatibility test (rheological properties examinations), lubricity test, shale tests via adsorption measurements, dynamic linear swelling test, cuttings dispersion test, and contact angle measurements. For the compatibility test result, they reported that bio-based henna leaf extracts are compatible with WBM with improved viscosity, and the lubricity of WBM increases for the lubricity test. This lubricity test result is highly important in deviated, highly deviated or horizontal drilling often characterized with constant drill-string in contact with the wall of the wellbore. Results from different shale inhibition tests revealed that Henna extracts has the potential to inhibit shale swelling. This was achieved when Henna via hydrogen bonding between its component hydroxyl groups and presence of oxygen atoms on the surface of silica of montmorillonite absorbs on shale (coating of the shale particles surface) which resulted to the shale hydrophobicity and stability.

It was pointed out that henna extracts acted as corrosion inhibitor in metallic medium and improved the resistance of cement slurry against acid attack [21]. Synthesis and characterization studies carried out on Henna leaf extracts powder for thermal stability and solubility in water indicated that the coloured henna (*Lawsonia inermis L.*) leaf extracts displayed high degree of thermal stability and solubility in water [15]. These characteristics of Henna leaf extracts coupled with their earlier mentioned features could be vital for stability in rheological properties of drilling muds, and a good candidate for cuttings transports in harsh conditions, such as deep water offshore fields. However, the usage of Henna alone as a viscosifier for cuttings transports have not yet been proven owing to its appreciably low gelling strength for effective drilled cuttings suspension. It was suggested that thinners, such as lignite could help to improve and control the weak gelling nature of henna mud [22]. Thinners also has the capacity to stabilize drilling muds especially at temperatures above 350 °F in order to avoid muds gelling [23].

Lignite sometimes described as polymeric soluble brown coal is at the bottom in the coal ranking classification [22]. It is mainly used in power production as fuel [24]. For the period between 1976-2003, there were about 337 US Patents with the keywords 'lignite drilling'. This indicates the interest and patented information associated to the application of lignite in petroleum industry [24]. Lignite or reformed lignite have been widely used as thinners and filtrates loss control agent in drilling mud [22]. The key active constituents of lignite are the humic acid; it is a blend of polymers of high molecular weight containing heterocyclic structure and aromatics with carboxylic acid groups as the major functional groups [22]. These humic acid acts as a deflocculants in drilling muds [25]. Lignite as thinners decreases the flocculation tendency of the mud and makes the positive charges located on the bentonite clay platelets to be less effective, and also terminate the ability of the platelets to bond together [23]. These action helps to control excessive viscosity from bentonite based mud.

Lignites are also introduced into muds containing excessive solids caused by high flocculation to lower the gel strength and the yield point [24]. Normally, the mud pH is a determining factor on how effective thinners can be. Lignite unlike henna which is soluble at low pH is not soluble at low pH. For lignite to be effective in the mud, the mud's pH should be designed within the alkaline range or pre-solubilization of the lignite should be performed in high pH environment prior to its addition in the mud. Numerous studies have been carried out to investigate lignite as a fuel and its properties have been well reported under numerous disciplines, but it has not fully been proven as a drilling mud additive in drilling industry. However, bentonite clay is a basic viscosity modifier and filtrates loss reducer, and the need to address its limitations in WBMs especially for cuttings transports, is of great importance.

Bentonite clay is commonly used to formulate WBM in order to improve cuttings transports performance and reduce loss of filtrates or water seepage into the formation [26, 27]. It can also form a low permeable and thin mud cake, overcome or prevent loss of circulation, support and enhance wellbore stability in ineffective cemented formations [27, 28]. The solids content of drilling mud is high due to the addition of bentonite clay, and these high clay solids has numerous adverse effects: (1) they significantly lessens the drilling rate (2) promotes the incidents of pipe sticking and (3) causes undue torque and drag. Consequently, low concentration of bentonite clay in the mud is preferred in controlling the overall amount of solids in the mud [26]. At low concentration of bentonite clay in the drilling mud, the mud becomes incapable to offer adequate rheological properties needed for effective carrying capacity of drilled cuttings to the surface and suspension ability of drilled cuttings when there is no flow. Therefore, polymers are either added as a substitute to bentonite clay or used together with low concentration of bentonite in WBM in order to achieve the desired result. Polymeric viscosifiers or thinners generally in WBM improves the mud's viscosity and provides good cuttings transports and suspension performance [11, 29]. To solve these problem, various types of polymeric viscosifiers and thinners are added to improve the muds viscosities and to stabilize and enhance the gelling property of the muds. These functions can either be performed with a polymer of bio-based or synthetic origin or in combination of both, such as henna and lignite.

Therefore, the objective of this study is to look into the material properties of henna and lignite and examine the suitability of combining them in order to establish if their rheological properties in WBM formulated with bentonite clay can enhance the lifting of different drilled cuttings sizes from downhole to the surface and to suspend such cuttings when there is no flow.

2. MATERIALS, EQUIPMENT AND METHODS

2.1 Water-based mud materials

Bentonite, caustic soda (NaOH), polyanionic cellulose (PAC), lignite and barite. These additives were obtained from Sigma Aldrich (Merck), Sdn. Bhd. Malaysia. Henna powder from leaf extracts was provided by Saeed Ghani pharmaceutical company, Islamabad, Pakistan.

2.2 Cuttings particles

Aquarium sands were used in this study as drilled cuttings. Aquarium sand is natural and easy to clean. It absorbs water and its carbonates are usually fine chips of sea shell and corel. It is readily available and is the cheapest form of aggregate. It contains freshwater and small portions of salt water. Its contact with saltwater mud can increase the filtration of the mud especially that of the WBM. Adding surfactant will minimize the filtrates loss in salt contaminated drilling mud. The aquarium sands consist of irregular shape and size. The size range of the cuttings used in this study was between 0.5-2.4 mm. The sands were sieved with sieved shaker, washed, cleaned, weighed, and stored in plastic bags of 200 g each. The density of the sands measured was 2.40 g/cm^3 and the total sieved sands were 8 kg. Drilled cuttings are usually identified, described, and classified by touch and sight. Typical oil field particle sizes and range is shown in Table 1 based on Geotechnical investigation and testing (ISO 14688-1) [30]. Soft silt and clay may dissolve into the drilling mud, while hard clay may seem like small cuttings. Very fine to fine sand will be entrained in the drilling mud. Coarse sand and gravel sand can be broken into smaller parts. A typical oil filed drilling mud samples for WBM may consist of the following; the based fluid (water), soda ash (hardness control agent), caustic soda (pH control), bentonite or xanthan gum (viscosifiers), starch or PAC (filtrates loss reducer), potassium chloride (water activity control and shale inhibitor) and barite (weighting material). Any drilling fluid sample will be built by the addition of the needed amounts of materials (reliant on their function) into the base fluid (water) to obtain 1 lab. bbl (350 cm³ final volume) with specific parameters, such as mud weight, pH, plastic viscosity, yield point, gel strength, filtrates loss volumes and filter cake thickness, etc.

Table 1: Typical oil field particle sizes and range [30]

Particle sizes				**Size range (mm)**
Very coarse		Large boulder	LBo	> 630
		Boulder	Bo	200 - 630
		Cobble	Co	63 - 200
Coarse soil	Gravel	Coarse gravel	CGR	20 - 63
		Medium gravel	MGr	6.3 - 20
		Fine gravel	FGr	2.0 – 6.3
	Sand	Coarse sand	CSa	0.63 – 2.0
		Medium sand	MSa	0.2 – 0.63
		Fine sand	FSa	0.063 – 0.2
Fine soil	Silt	Coarse slit	CSi	0.02 – 0.063
		Medium slit	MSi	0.0063 – 0.02
		Fine slit	FSi	0.002 – 0.0063
	Clay		Cl	≤ 0.002

2.3 Drilling muds formulation

The formulation of WBM with different additives was carried out according to the recommended American Petroleum Institute (1997) with the use of mud formulator. Seven (7) types of drilling mud systems were formulated (see Table 2). The formulation follows in ascending order according to Table 2. Electronic mixer was used to properly stir each of the additives at least for 5 mins when added. Five samples of muds were prepared with different concentrations of lignite. Water was used as the base fluid, bentonite and henna as viscosifiers, NaOH for pH control, PAC as filtrates loss control agent, barite as weight control agent and lignite to enhance the gel strength. The Henna powder obtained was of pH 5.0 for 30 g.

Table 2: Drilling muds composition

Mud types	**Composition**
Mud1 (Base mud)	Tap water (350 ml) + Bentonite (10 g) + NaOH (0.15 g) + PAC (0.25 g) + Barite (10 g)
Mud 2	Mud 1 + Henna (10 g)
Mud 3	Mud 1+ Henna (10 g) + Lignite (5 g)
Mud 4	Mud 1 + Henna (10 g) + Lignite (8 g)
Mud 5	Mud 1 + Henna (10 g) + Lignite (10 g)
Mud 6	Mud 1 + Henna (10 g) + Lignite (12 g)
Mud 7	Mud 1 + Henna (10 g) + Lignite (15 g)

2.4 Experimental test facility

Experiments with different cuttings sizes were conducted at the Universiti Teknologi Malaysia (UTM) low-pressure room temperature (LPRT) flow loop, as shown in Figure 1. It was made up of cuttings inlet system, annular test section, mud circulation system, cuttings separation system, hoisting and control systems. The annular test section was 11 ft. long, consisting of 3.0 in. ID transparent outer-pipe and inner drill-pipe of 2.0 in. The outer diameter of the outer pipe was 3.2 in. The inner pipe did not contain centralizer but was supported at the end of the pipe having dimensions of 13 ft. long and 3 ft. width in order to allow it assume several types of motion while rotating. Both ends of the inner pipe were sealed to prevent mud from flowing through it. The annulus test section was connected to flexible tube on both ends of the inner pipe of dimensions 2.9 in. and 2.8 in. outer and inner diameters, respectively so that different required angles could be attained i.e. 0° (vertical), 45° (deviation) and 90° (horizontal). In order to trap the cuttings, separation tank with dimensions of 2.0 ft. length and 1.0 ft. width was mounted after the annulus section, and was fitted with wire mesh of 0.2 mm. The wire mesh was much smaller than the cuttings sizes in order to achieve efficient separation. The mud tank used to prepare the drilling muds was of a cylindrical shape with dimensions 2.4 ft. height and 1.8 ft. diameter. It was installed with 1 hp mixing pump at the top and at the outlet of the tank with 2 hp centrifugal pump. The pump flowrates were between 181.20-380.52 bbl/D. The capacity of the mud tank was 142 litres. The flow loop was provided with supporting systems that supports the pipe at vertical and a pressure gauge to determine the pressure inside the loop. Attached to the flow loop also was supplying and cooling system. Prior to the investigations, 80 litres of drilling mud were prepared in the mud tank with different composition and mixed until it achieves homogeneous state. It took about 6-8 hr for the additives to mix completely together.

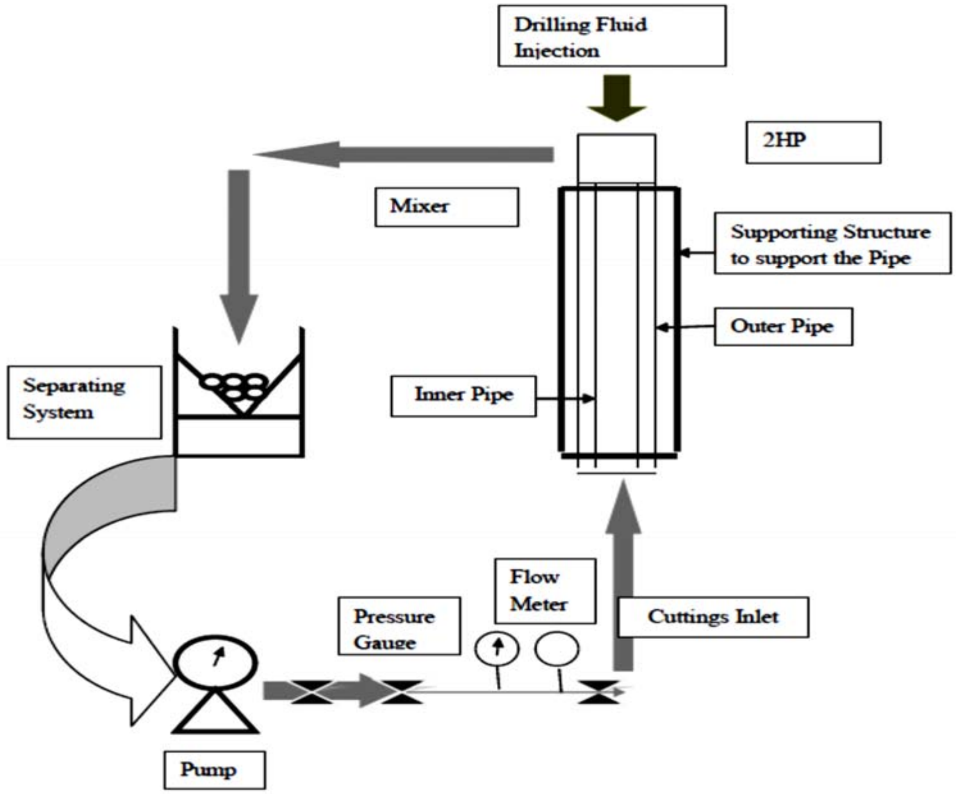

Figure 1: Representation of the LPRT flow loop.

2.5 Experimental method

2.5.1 Mud balance calibration

Baroid mud balance was used with sufficient accuracy to allow the measurement within ± 0.1 lbm/gal or ± 0.5, lbm/ft^3 (± 0.01 g/cm^3). Before initiating the experiment with drilling mud, the instrument was calibrated with freshwater. Freshwater has a reading of 8.3 ppg or 62.3 lbm/ft^3 (1 g/cm^3) at 70 °F (21 °C). The mud balance was cleaned and inspected. The cap was filled with freshwater and the cover was replaced. The cover was tightened and the cup was dried. The balance was checked at the slider at the water line. The instrument was calibrated when it balances.

2.5.2 Fann model 35 viscometer fluid calibration

Certified Newtonian calibration fluid check was used to calibrate the mud viscosities. The sample cup was filled with calibration fluid to the scribe line and was placed on the Fann Model 35 Viscometer stage. The stage was elevated until the rotor is at proper immersion depth as observed by the scribe line. Thermometer was placed into the sample cup and was allowed to touch the bottom. It was secured to the side of the viscometer to prevent breakage. The instrument was operated at 100 rpm for about 3 mins to equalize the temperature of the rotor, bob and the fluid. The temperature and dial readings at 300 rpm and 600 rpm was recorded to the nearest 1 °C. The results were within ± 1.5 cP when it was compared with the fluid chart. To do this, the 600 rpm reading was divided by 1.98 prior to comparing the results to the fluid chart. Readings outside this specified limit are indication that the instrument should be calibrated or repaired. After the calibration check, the rotor set pieces, bob including the inner and outer portions as well as the bob, thermometer, sample cup and work area were wiped clean, and the tests for rheological properties determination were conducted.

2.6 Rheological properties measurement

The pH, density and rheological properties were estimated. The pH was measured with pH meter. The densities of the different mud samples were measured with mud balance. A Fann viscometer was used to measure the rheological properties of the 7 mud samples according to the recommendations of American Petroleum Institute (13B-1, 1997) at different dial readings of 3, 6, 100, 200, 300, and 600 revolutions per min (rpm). The viscometer produces the viscosity values in unit of cP or mPa.s. Dial readings were performed thrice to make certain for consistency in the results. The Bingham plastic fluid model described by the equations (1-3) below were used to determine the plastic viscosity (PV), apparent viscosity (AV), yield point (YP), and gel strength (GS). The PV, YP, and AV were then calculated from the 300 rpm to 600 rpm viscometer dial readings. The gel strength (GS) for 10-sec and 10-min were measured according to API recommendations (13B-1, 1997). Filtrates loss volume (Fl) determination was measured using a filter press at 100 psi and room temperature. The volumes of filtrates were collected for each sample for every 5-mins and the filter cake thickness (Fc) was measured.

PV (cp) = rotor speed value (600 rpm-300 rpm) (1)

YP (lb/100^2) = rotor speed value at 300 rpm – PV (2)

AV (cP) = rotor speed at 600 rpm /2 (3)

2.7 Experimental investigations of drilled cuttings

After formulating the drilling mud and mixing it thoroughly in the mud tank, cuttings transports experiment was conducted with a laboratory scale LPRT flow loop and the simplified procedure was provided in Figure 2.

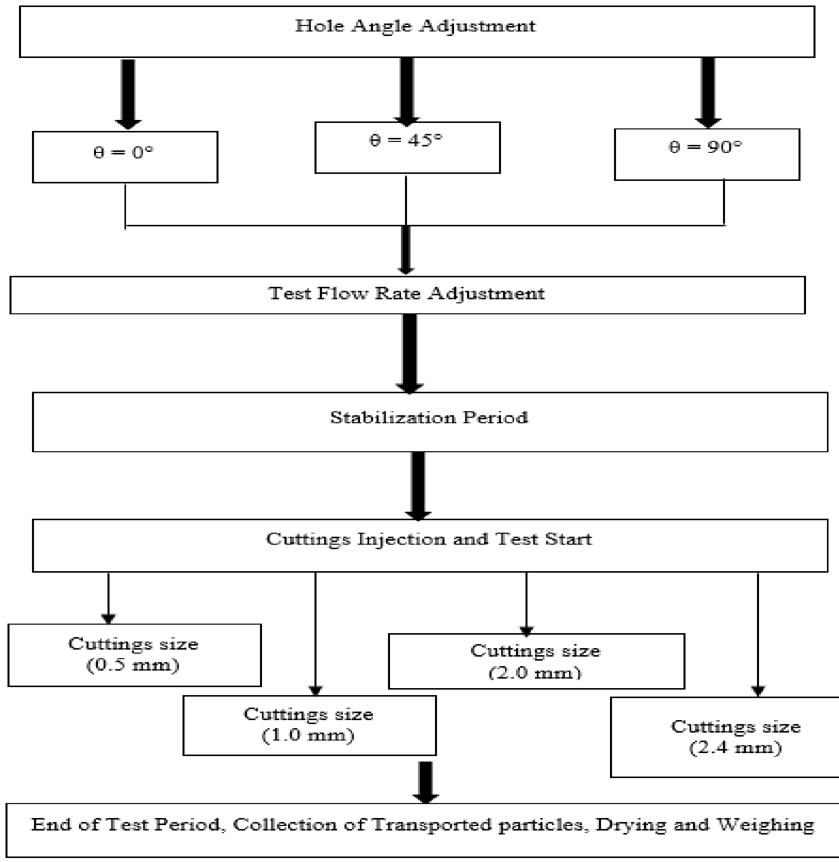

Figure 2: Cuttings transports experimental flowchart.

The experiment 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 it was allowed to flow at stabilized flowrate for 7 min. 200 g of cuttings was injected through cuttings inlet and valves were opened to divert the flow so that the cuttings could be carried along. The flow was maintained for 5 min and cuttings were then collected from the wire mesh at the shale shaker after turning off the pump. The collected cuttings were then washed, cleaned, dried, weighed and stored in a separated plastic bag for each run. The investigations were continued with a constant flowrate of 380.52 bbl/D at varying hole-angles (0º, 45º and 90º). This process was repeated until all the stages of the experiments were fully executed using the 7 mud systems and the three hole-angles with different cuttings sizes (0.5 mm, 1.0 mm, 2.0 mm and 2.4 mm). The performance of each mud system after being tested where compared with the cuttings transports efficiency (CTE) given in equation 4 below.

$$\text{CTE (\%)} = \frac{\text{Weight of recovered cuttings in gram}}{\text{Weight of total injected cuttings in gram}} \times \frac{100}{1} \qquad (4)$$

3. RESULTS

Table 3 shows the obtained results of mud properties measurements from viscometer dial readings for the 7 mud systems.

Table 3: Drilling mud properties

Mud		**Rheological Properties**							
	pH	**Density (ppg)**	**PV (cP)**	**YP (lb/100 ft^2)**	**YP /PV**	**GS (lb/100 ft²)**		**Fl (ml)**	**Fc (mm)**
						10-sec	**10-min**		
Mud 1 (Base mud)	9.8	8.6	2.5	1.1	0.44	5.0	6.5	16.0	4.9
Mud 2	8.6	8.5	4.5	2.4	0.53	3.5	5.0	8.5	3.5
Mud 3	8.2	8.2	5.5	3.0	0.55	4.0	5.0	11.0	4.9
Mud 4	8.3	8.2	8.0	5.0	0.55	7.0	8.0	8.5	3.7
Mud 5	8.5	8.4	12	8.0	0.67	9.5	9.5	5.5	3.5
Mud 6	8.5	8.4	13	10	0.77	10.5	11.5	5.3	3.2
Mud 7	8.7	8.5	17	15	0.88	12	13	5.0	2.4

YP/PV indicates yield point to plastic viscosity ratio.

Figure 3 indicates the effect of different cuttings sizes on CTE using Mud 1, which is the Base mud. The rheological properties of this mud system are: plastic viscosity (2.5 cP), yield point (1.1 lb/100 ft^2), 10-sec gel strength (5.0 lb/100 ft^2) and 10-min gel strength (6.5 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 1 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

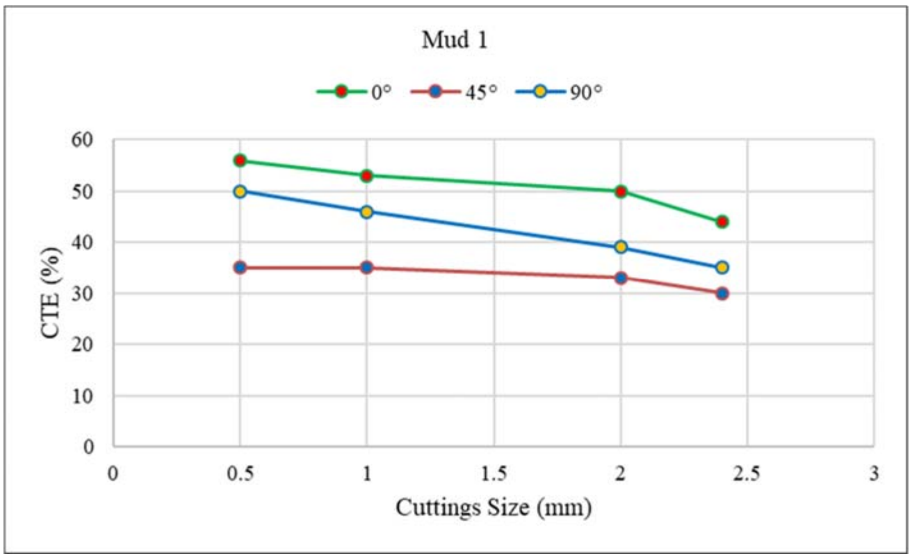

Figure 3: Effect of different cuttings sizes on CTE using Mud 1 (Base mud).

Figure 4 shows the effect of different cuttings sizes on CTE using Mud 2, which is the Base mud containing 10 g of henna. The rheological properties of this mud system are: plastic viscosity (4.5 cP), yield point (2.4 lb/100 ft^2), 10-sec gel strength (3.5 lb/100 ft^2) and 10-min gel strength (5.0 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 2 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

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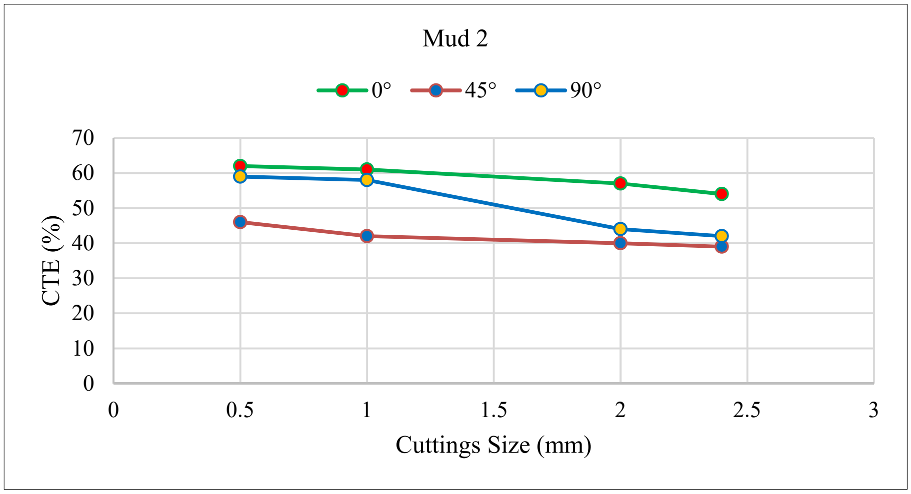

Figure 4: Effect of different cuttings sizes on CTE using Mud 2 (Mud 1 +10 g of Henna).

Figure 5 shows the effect of different cuttings sizes on CTE using Mud 3. The rheological properties of this mud system are: plastic viscosity (5.5 cP), yield point (3.0 lb/100 ft^2), 10-sec gel strength (4.0 lb/100 ft^2) and 10-min gel strength (5.0 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 3 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

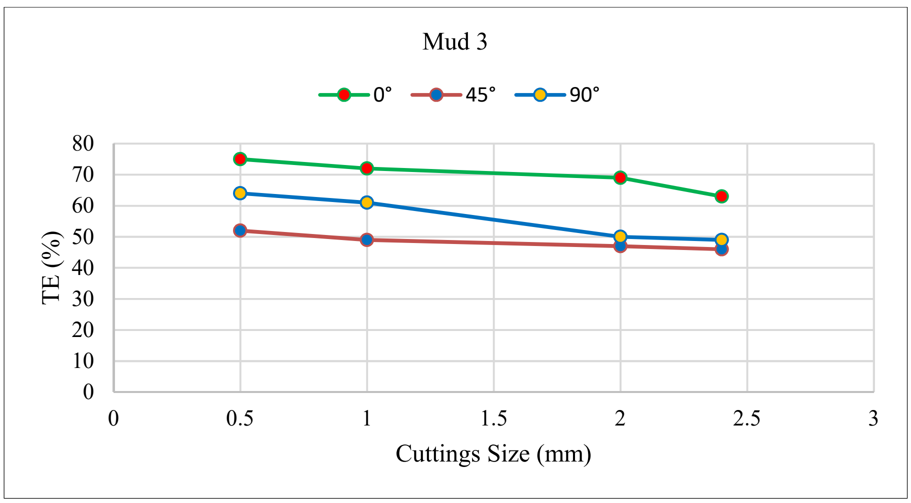

Figure 5: Effect of different cuttings sizes on CTE using Mud 3 (Mud 1+ 10 g of Henna + 5 g of Lignite).

Figure 6 shows the effect of different cuttings sizes on CTE using Mud 4. The rheological properties of this mud system are: plastic viscosity (8.0 cP), yield point (5.0 lb/100 ft^2), 10-sec gel strength (7.0 lb/100 ft^2) and 10-min gel strength (8.0 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 4 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

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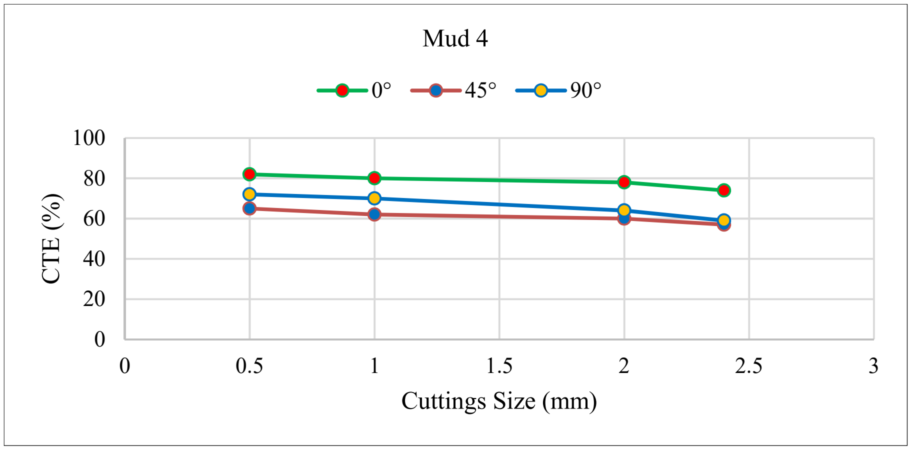

Figure 6: Effect of different cuttings sizes on CTE using Mud 4 (Mud 1+ 10 g of Henna + 8 g of Lignite).

Figure 7 shows the effect of different cuttings sizes on CTE using Mud 5. The rheological properties of this mud system are: plastic viscosity (12.0 cP), yield point (8.0 lb/100 ft^2), 10-sec gel strength (9.5 lb/100 ft^2) and 10-min gel strength (9.5 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 5 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

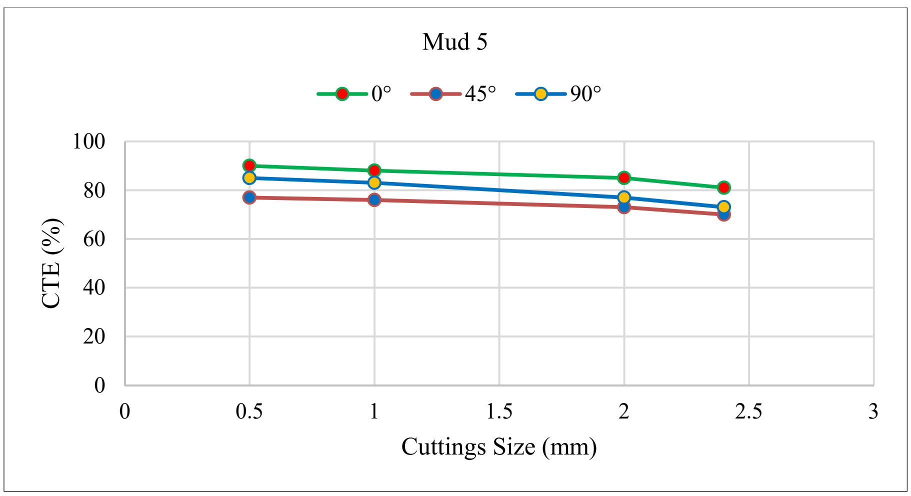

Figure 7: Effect of different cuttings sizes on CTE using Mud 5 (Mud 1+ 10 g of Henna + 10 g of Lignite).

Figure 8 indicates the effect of different cuttings sizes on CTE using Mud 6. The rheological properties of this mud are: plastic viscosity (13 cP), yield point (10 lb/100 ft^2), 10-sec gel strength (10.5 lb/100 ft^2) and 10-min gel strength (9.5 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 6 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

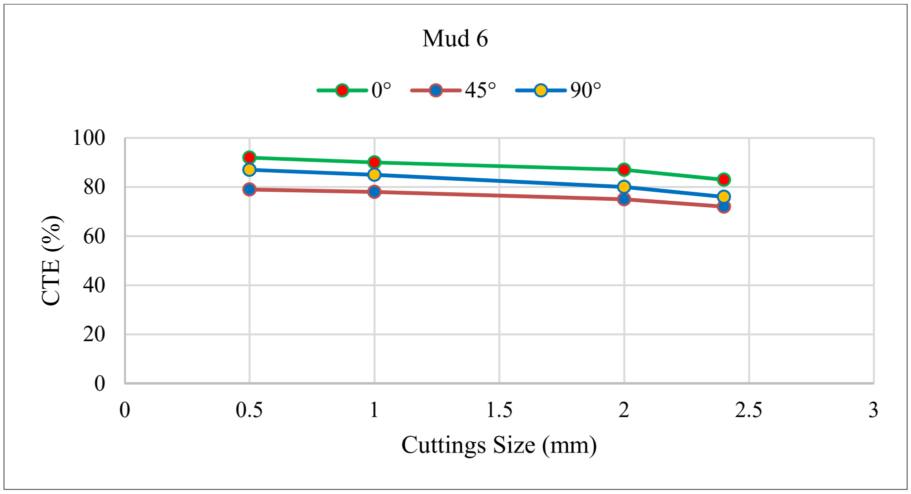

Figure 8: Effect of different cuttings sizes on CTE using Mud 6 (Mud 1+ 10 g of Henna + 12 g of Lignite).

Figure 9 indicates the effect of different cuttings sizes on CTE using Mud 7. The rheological properties of this mud system are: plastic viscosity (17 cP), yield point (15 lb/100 ft^2), 10-sec gel strength (12 lb/100 ft^2) and 10-min gel strength 13 lb/100 ft^2). Each line of the flow curve indicates the different cuttings sizes for the three hole-angles. The distance between a given line to another indicate the effects of mud viscosity of Mud 7 on the cuttings transports efficiency for the 3 hole-angles (0°, 45° and 90°).

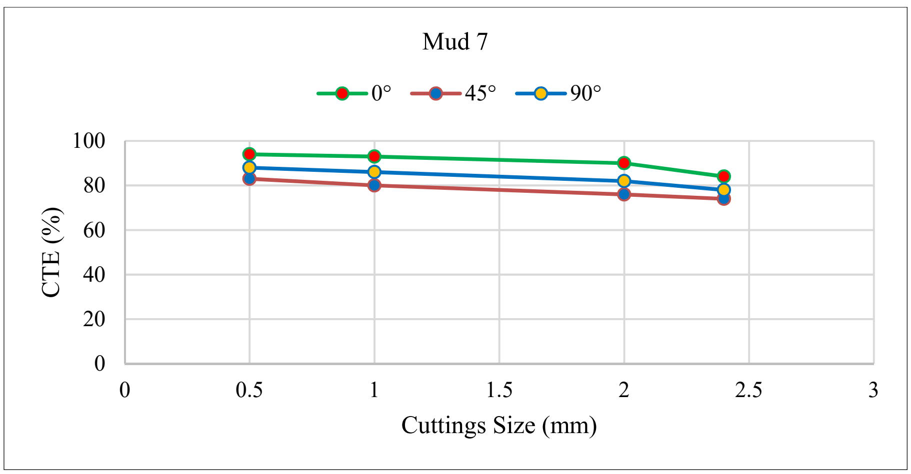

Figure 9: Effect of different cuttings sizes on CTE using Mud 7 (Mud 1+ 10 g of Henna + 15 g of Lignite).

Figure 10 indicates the percent increment of transported cuttings for different mud systems at 45º hole-angle. It indicates the contribution of each of the 7 mud systems in improving cuttings removal from the wellbore at 45º hole-angle. This angle was chosen above other angles (0° and 90°) considered in this study due to its low cleaning efficiency of drilled cuttings. This is the most difficult angle needing greater attention. At this angle, cuttings transports were less effective because cuttings tend to slide downward easily. It will also justify the overall performance of each mud compositions in terms of their rheological properties influence on cuttings transportation from downhole to the surface.

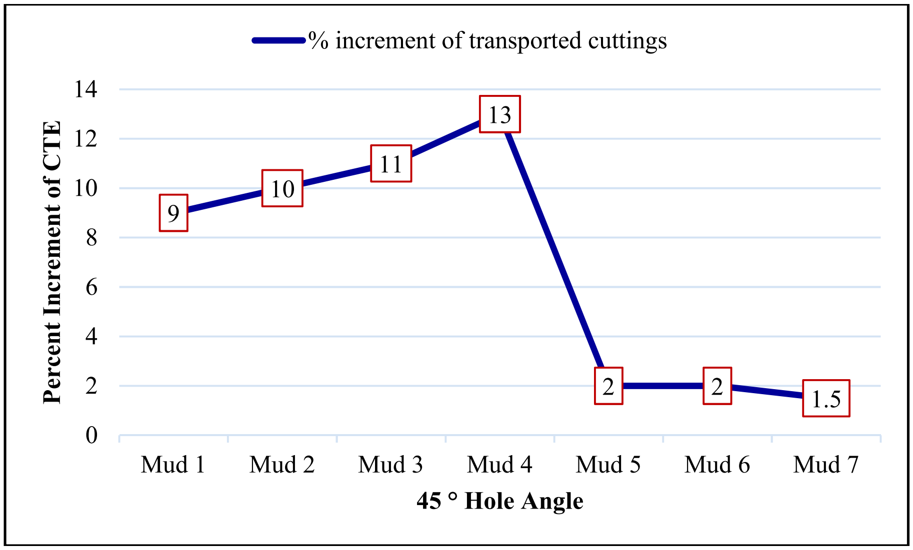

Figure 10: Percent increment of transported cuttings for different mud systems at 45º hole-angle.

4. DISCUSSIONS

4.1 Mud pH

With reference to the product pH value of 5.0/30 g of henna powder obtained, henna mud (Mud 2) in Table 3 has an improved pH level of 8.6. This is credited to the introduction of NaOH into the mud for pH modification. The pH of different concentrations of lignite also improved upon addition of NaOH. The NaOH modified the chemical arrangements of henna and lignite constituents when dissolving in water. However, the pH level of both muds are low compared to that of WBM (Mud 1) formulated with bentonite clay. Both the henna and lignite when in solution with water takes out their atoms of hydrogen from their constituent's chemical configuration leading to reduction in their pH level [20, 22].

4.2 Mud density

For the mud density result shown (see Table 3), the 7 mud system densities of 8.2-8.6 ppg were close with Mud 1 (WBM) having the highest density. Henna biopolymer and lignite brown coal are both lightweight materials, and as a result has low density compared to bentonite clay. It can be suggested that for mud containing henna and lignite to have improved density, higher amount of barite need to be added. Nevertheless, the 7 mud systems density values are appropriate for drilling mud.

4.3 Rheological properties

Table 3 revealed that the PV, YP and GS of the 7 mud systems increases as additives of Henna (Mud 2) and lignite (Mud 3-7) were added to the base mud (Mud 1). The improvement in the values of PV and AV when Henna and different concentrations of lignite were introduced into the mud systems suggest that the molecules of Henna and lignite dispersed and distributed homogenously in the water-based mud. It then indicates the viscous nature of henna and lignite materials. However, Mud 1-7 contains relatively low PV. A low PV signifies that the drilling fluid has the ability to drill the well very fast owing to less resistance to the flow of fluid at the bit. This is beneficial for flow of fluid because of lower exertions of equivalent circulating density downhole [29]. But, if the PV is too low (Mud 1-3), the cuttings transferring efficiency from downhole to the surface will be ineffective. This is because mud viscosity is a function of the base fluid viscosity, measurement and volumes of particles and the force existing between particles. For a low PV, it indicates that the materials used to formulate the mud has lower solids contents and higher water content in the mud. High water content drilling mud usually results in low PV, high friction and high mud filtrates loss volumes, and a great affinity of the mud with shale will result to in wellbore instability [17]. It is therefore suggested that a reasonably low PV (Mud 4-7) should be preferred for drilled cuttings removal as the PV of the mud automatically increases when exposed to drilled cuttings and other solids particles, such as barite. In addition, If the PV is too high, it will prompt excessive frictional pressure loss while being circulated. Therefore, optimal PV is needed to ensure effective cuttings removal to the surface without damaging the wellbore.

The YP could be described to be the minimum shear stress needed for a fluid to begin to flow. This parameter gives an indication of the pseudoplastic parameters of the fluid and its capacity to transport solids in solution or in suspension [5]. Mud systems with YP > PV denotes partial solids flocculation, which can result in increased filtrates loss volumes, drill string clogging and overwork of the pumping system. YP is significant at zero hole-angle (vertical) and less effective at inclined angles. The obtained YP results range of this study (8.0-15 lb/100 ft²) shown in Table 3 will be more effective at low-hole angles, and they are low enough to improve drilling operations without causing excessive mud flocculation. However, if the YP is too low (Mud 1-4), there will be reductions in the capacity of the mud to lift cuttings out of the hole, possibility for barite sagging or settling in the wellbore will increase [29]. On the other hand, too high of YP will make the mud difficult to be pumped out from the bit because more pressure will be required to suppress the shear-stress [29]. So, a suitable balance of YP that can avoid large solid particles or cuttings from settling down is needed, which is neither too low nor too high.

The 10-sec and 10-min GS showed similar trends of behaviour to that of YP (see Table 3), but at Mud 2 when Henna was added to Mud 1, both the 10-sec and 10-min GS dropped. The low value of Mud 2 (Henna mud) GS in comparison with those of other mud systems indicates its efficiency in improving solids control apparatus. Also, at Mud 3 containing 10 g of henna and 5.0 g of lignite, the 10-sec and 10-min experienced similar trend. However, the addition of lignite started having improved effect on the GS at Mud 4 when 8.0 g were added. From that point, more additions of lignite improved the GS owing to its gelling property. The mud systems GS increases with 58.3% from Mud 2-7 for 10 secs and 50% for 10 min, respectively. The low value of Mud 1 GS in comparison with Mud 4-7 indicates the efficiency of lignite in improving the gelling property of the mud. However, this lower trend of values of GS for the 7 mud systems for both 10 secs and 10 min indicates that the muds do not contain the progressive tendency to form gel. Muds having gelification behaviour attain high viscosities in short periods of time. The implication of this progressive gelification is the potential of the mud to induce high pressure (pressure at its peak) when mud circulation is restored after a pause, posing risks to the drilling process [31]. Nevertheless, the 10 min gel strength of Mud 1 with 6.5 lb/100 ft² and Mud 4-5 of 8.0-9.5 lb/100 ft² was within the specified range of 6-10 lb/100 ft² gel strength without NPs suggested by [9].

The increase in YP/PV ratio have been adjudged to increase the muds carrying capacity of drilled cuttings at all hole angles [32]. In terms of YP/PV ratios, though the ratios were appreciably low owing to the low values of YP in comparison with those of the PV, but the addition of Henna and different amounts of lignite into the base mud improved the ratios (see Table 3). This improvement is important for effective drilled cuttings lifting to the surface. When the mud sets to a gel, it will have the capacity to get drilled cuttings suspended when the pump is switch off and breaks up speedily to a thin mud when agitated as drilling is restored again [32]. In addition, the increasing values of the YP/PV indicates that the 7 mud systems are pseudoplastic, showing shear-thinning behaviour (i.e., as the shear-rate increases, the apparent viscosity decreases).

4.4 Fluid loss volume and mud cake thickness

For the filtrates loss volume and mud cake thickness results provided (see Table 3), the filtrates loss volume for Mud 1 showed the highest filtrates loss capabilities into the formation than those of the other mud systems. Mud filtrates is a measure of solid material ability in the mud to form a thinner mud cake with low permeability [17]. The filtrates loss volume is dependent on the performance of the materials that make up the drilling fluid. Mud 2 (Henna mud) has good filtration property in comparison with Mud 1. Addition of Henna into Mud 1 remarkable reduced the filtrates loss volume to half of its initial value before its addition. This is because henna can act as a deflocculants in drilling mud. It prevents high mud flocculation. High mud flocculation promotes excessive viscosity which leads to high intrusion of formation fluids into the formation [17]. In addition, henna via hydrogen bonding between its constituent's hydroxyl (OH) groups and presence of oxygen atoms on the surface of bentonite clay has the ability to bend or compress to seal the pores. Thus, reducing filtrates loss volumes [17]. Increased concentrations of lignite in the mud systems (Mud 3-7) starts to improve the filtrates loss volume reduction from Mud 5 more after addition of Henna at concentration of 10 g. Lignite contain a humic acid which makes it soluble in aqueous medium. This soluble lignite in water-based mud will act as clay deflocculants and enhance the quality of filter cake by controlling fluid loss into the formation [22].

The more filtrates loss into the formation, the more the filter cake thickness. The thicker mud cake indicates that more solid materials or debris settled at formation wall and more filtration lost to the formation. The WBM has a thick mud cake when compared to the remaining drilling mud systems (see Table 3). Based on this result, Henna mud (Mud 2) and lignite muds (Mud 5-7) can be considered to have good filtration control properties in comparison with WBM, and this property is desirable for drilling purposes as it could prevent stuck pipe incidents. The effect of a thick mud cake is that it can collapse easily and cause wellbore drilling problem, such as tighter hole (hole becomes smaller). It also reduces the effective diameter of the drilled wellbore, thereby increasing the area of contact between the drill pipe and the cake leading to greater risk of stuck pipe incidents [17, 23].

4.5 Effects of different cuttings sizes on cuttings transports efficiency

The percentage of drilled cuttings recovered indicates the mud ability to lift cuttings from downhole to the surface. The experimental findings obtained revealed that viscosity has positive influence on drilled cuttings removal. From Figure 3, the conventional WBM (Mud 1) with a PV of 2.5 cP gave the least transports efficiency of all the mud system. The smallest cuttings size of 0.5 mm at all hole-angles achieved the highest cuttings transports performance with values of 58 % for the vertical hole (0° angle), 50 % for horizontal hole-angle (90°) and 35 % for the deviated hole-angle (45°). It was followed successively with the 1.0 mm, 2.0 mm and least by 2.4 mm cuttings sizes. Of all the hole-angles, the 45° inclination achieved the lowest proportion of transported drilled cuttings, while the 0° and 90° hole-angles produced a better transports performance, in which the 0° hole-angle leads the 90° hole-angle. The same trend of results in Figure 3 was obtained for Figure 4. The Figure 4 formulated with conventional WBM additives and 10 g of henna (Mud 2) with a PV of 4.5 cP performed better than Mud 1 and fall behind Mud 3-7. The 45° hole-inclination also achieved the poorest percentage of transported drilled cuttings, and cuttings size of 0.5 mm was much easier to clean compared with other cuttings sizes. The vertical hole-angle (0° angle) for all cuttings sizes and viscosities exhibited the best cuttings transports performance. Addition of 8 g of lignite and 10 g of henna into Mud 1 improved the cuttings transferring efficiency of Mud 1 (see Figure 5). At all hole-angles and cuttings sizes, Mud 3 with a PV of 5.5 cP perform better than Mud 1 and 2, but recorded a lower transports efficiency in comparison to those of Mud 4-7. As usual, 0.5 mm cuttings size and 0° hole-angle achieved the best transports performance than other cuttings sizes and hole-angles, respectively. It can be suggested that the mud viscosity significantly influence drilled cuttings transports. An increased in mud viscosity led to higher cuttings transportation. Mud 4-7 shown in Figure 6-9, respectively followed the same trend highlighted for Mud 1-3 in a successive order of least cuttings transports performance to highest cuttings transports performance.

In general, cuttings sizes of 0.5 mm and 1.0 mm were much easier to be transported compared to those of 2.0 mm and 2.4 mm at all hole-angles and viscosities. The overall cleaning efficiencies at various cuttings sizes were found to be in the following range: 35-94% for 0.5 mm, 34-93% for 1.0 mm, 33-90% for 2.0 m and 30-84% for 2.4 mm. With these variations, cuttings size of 0.5 mm recorded the highest cleaning efficiency in the wellbore. Next is the 1.0 mm cuttings size, and the 2.0 mm cuttings size performed better than the 2.4 mm cuttings size. The hole-angle at vertical (0°) for all mud compositions and cuttings sizes achieved the highest cleaning efficiency, followed by hole-angle 90° (horizontal). The least cleaning efficiency was observed at 45° (deviated) angle, which indicates that 45° hole-angle is the most challenging hole-angle for cuttings transports. This is due to the tendency of cuttings bed to slide recurrently and tumble down repeatedly at this hole-inclination. A possible reason why the smaller cuttings sizes (0.5 mm and 1.0 mm) are much easier to be transported than the larger cuttings sizes (2.0 mm and 2.4 mm) is that they are transported farther than larger ones before they can settle to form cuttings bed. Therefore, one can submit that the smaller the cuttings size, the easier for cuttings transports at all hole-angles with increasing mud viscosity. These finding is in agreement with the results of [9], in that smaller cuttings size is more effective to transport at all hole-angles with a low mud viscosity compared to other cuttings size. Also, it is easier to transport smaller cuttings size than larger ones using polymeric fluid. This is because the transportation of small cuttings size is mainly governed by the fluid viscosity and pipe rotation. The pipe rotation mechanically induces the smaller cuttings to the top portion of the annulus where high flowrates exist, while that of larger cuttings size is mainly dictated by the fluid flowrate [2]. Mud 7 containing the highest amount of lignite (15 g) in the solution of 17 cP gave the best cleaning efficiency in all the mud systems. This indicates that increase in the amounts of lignite in the solution favours cuttings transports. It is possible that higher concentrations of lignite in the mud caused Mud 7 to contain higher solids contents which increases the mud viscosity, thus leading to higher capacity of the mud to transport drilled cuttings to the surface.

However, the performance of the drilling muds in transporting cuttings to the surface are strongly dependent on the mud flowrate and viscosity, and less on cuttings size. It could be also suggested that in oil well drilling, the drilled cuttings irrespective of its size have the tendency to settle in the whole vertical portion of the annulus, while in the deviated, highly deviated or horizontal section, they only have a few areas to settle. These occurrence has been explained in many literatures to be caused by the effect of reduced fluid velocity component, which resists the cuttings slip velocity [5, 9, 33, 34]. Two velocity vectors acts on drilled cuttings in opposite direction in vertical annulus, and they are gravity force pulling them downward and annular fluid velocity pushing them upward. At any time, the fluid velocity is able to surpass the effects of gravity on the drilled cuttings owing to synergistic relationship between the fluid velocity and the drag and lift forces induced by difference in density, cuttings in the vertical sections have the tendency to transport out of the annulus. This explained phenomenon is responsible for achieving the highest cuttings transports efficiency at 0° hole-angle of this study for all cuttings sizes.

In the deviated, highly deviated and horizontal portion of the annulus, the cuttings slip velocity vector can be grouped into two components; one working contrary to the fluid velocity, in which it decreases with increasing hole-angles, and the other component driving the cuttings towards the low side-wall of the annulus. This force acting on drilled cuttings increases as hole-angle increases, as can be seen at 45° hole-angle. When this happens, the drilled cuttings are forced towards the low side-wall of the annulus. Appropriate hydraulic power is required for an effective cuttings transports at this angle. Furthermore, as the hole-angle increases beyond 60°, the declining nature of the cuttings transports reverses, and the fluids performance on cuttings transportation started to increase again. This is because drilled cuttings at 60° hole-angle and above are stable and have reduced effects of gravity, indicating reduced drilled cuttings avalanched (constant sliding downwards of drilled cuttings).

4.6 Incremental of cuttings transports efficiency

It can be observed from Figure 10 that CTE incremental was steadily increasing from base mud (Mud 1) to Mud 4, which was 9–13% increments. It recorded 1.0% increment from Mud 1-2 and Mud 2-3. The increment increases to 2.0% between Mud 3-4, in which the highest increments were achieved at Mud 4 formulated with 8 g of lignite and 10 g of henna added into the basic mud (Mud 1). Between Mud 4-5, the performance of the mud drastically dropped to 11.0%, and it remained constant between Mud 5-6. It also dropped between Mud 6-7 with 0.5%. The addition of 10 g, 12 g and 15 g amounts of lignite at a constant amount of 10 g of henna into the base mud (Mud 1) after 8.0 g have minimal contribution to the cleaning of the wellbore compared to the performance of the mud at Mud 4. Mud rheological properties has great impact in enhancing cuttings transportation since adequate viscosity can reduce the cuttings settling velocity. Mud rheological properties corresponding to 8 g of lignite and 10 g of henna in Mud 1 produced the optimum cuttings transports efficiency. It is suggested that the mud viscosity (PV of 8.0 cP) within this range under the same condition of this study, such as YP (5 lb/100ft^2), GS at 10-sec (7.0 lb/100ft^2), and GS at 10-mins (8 lb/100ft^2) should be designed for enhanced cuttings transports. These mud properties achieved the optimum cuttings transport efficiency.

4.7 Cost and environmental aspect

Different additives are added into the drilling mud to improve the performance of the mud. In addition to additive functionality in the drilling mud, several viabilities, such as toxicity, costs, and availability are major factors that are considered by drillers while preparing drilling mud. Henna powder extracted from henna leaf extracts is a bio-based polymer. The natural dye of henna which is readily available and conventionally used as skin and hair dye cannot have environmental problems which is beneficial for offshore drilling. It is commercially available and cannot increase the drilling cost owing to its eco-friendliness. Its effluents in the environment will not be a concern to human health and body of water. In southern Iran, henna trees can be found in abundance as vast area of farm lands are dedicated to cultivate it. In India, there are abundance agricultural lands dedicated for henna cultivation for both domestic usage and exports [35, 36]. In northern part of Nigeria, especially in Sokoto state, the farming of henna has gained increased awareness and are now commercially cultivated. Therefore, there is no concern on availability of henna for drilling operations. Besides, the powder obtained from extracted henna leaves is natural and has an average price of $1/kg, and is one of the major agricultural products within the Middle East region [35, 36]. On annual basis, significant amounts of henna leaf extracts are exported to other countries. Another attractive feature of henna extract is its anti-corrosion property. This property is desirable in drilling operations [35, 36]. Though lignite is mostly utilized as fuel in power plants, its application in drilling mud as lignite/lignosulphates mud has been very attractive [23 – 25]. It is easily weighted and provides good apparent viscosity and yield point control. It has good filtration loss control with low permeability filter cake. It is also economical to formulate and maintain up to 350 °F and offers good corrosion protection [23–25]. These attributes are beneficial for drilling operations especially in offshore regions.

5. CONCLUSIONS

This study examined the performance of basic water-based mud formulated with bentonite clay, contributions of henna in basic WBM, and the effects of different concentrations of lignite in the basic water-based mud for three hole-angles (0°, 45° and 90°) with different cuttings sizes of 0.5 mm, 1.0 mm, 2.0 mm and 2.4 mm on cuttings transports. The main conclusions are drawn as follows:

1. In terms of muds performance, addition of henna and different concentrations of lignite into the basic mud (Mud 1) enhances the performance of the mud, and subsequently more cuttings lifting from downhole to the surface. Thus, henna and lignite can function as a suitable drilling mud for effective cuttings transports.
2. In terms of cuttings size, it is easier to transports smaller cuttings at vertical section of the well than at increasing hole-angles. Cuttings size has less impact in the fluids performance as increase in viscosity leads to more cuttings being transported regardless of the cuttings size.
3. Hole-angle 45° was found to be the most challenging for cuttings transports, because at this angle, the sliding of cuttings bed tends to occur as the well starts to deviate from vertical. It is suggested that enough hydraulic power should be introduced at this inclination for an effective cuttings transports, and more attention should be given to this angle while preparing the drilling fluid for cuttings transports.
4. The additives formulated in this study are potential alternatives to the use of the commercially available bentonite clay. The major key challenge to mud engineers is on how to design drilling systems that are operationally safe, efficient, and that can meet the environmental requirements. It is suggested that the mud viscosity within the range of 8 cP under the same conditions of parameters and properties used in this study should be designed for enhanced cuttings transports. Other muds properties at this viscosity achieved the optimum cuttings transport efficiency.

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