QATAR UNIVERSITY

COLLEGE OF ENGINEERING

DEVELOPMENT AND EVALUATION OF FIBROUS FLUID FORMULATIONS FOR HORIZONTAL GAS AND OIL WELL CLEANOUT

BY

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ABSTRACT

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Title: Development and Evaluation of Fibrous Fluid Formulations for Horizontal Gas and Oil Well Cleanout

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Cuttings substantial buildup on the downside of the wellbore is a challenging problem that encounters oil and gas drilling operations. Field reports indicate that inefficient hole cleaning increases the nonproductive time (NPT) by 30 percent. Good cuttings transportation within the wellbore is essential for efficient drilling operations. Inadequate hole cleaning can jeopardize the drilling process and lead to many problems, including reduced penetration rate, increased torque, bit wearing, and lost circulation. The addition of fiber enhances the cleaning properties of the drilling sweep with minor changes in the fluid rheology. However, maintaining stable uniform dispersion is essential to enable fibers' functionality for the intended purposes, which is challenging under wellbore harsh conditions. Furthermore, surface charge type and density (anionicity) of base polymers used in drilling fluids can contribute to the improvement of cutting suspension and hole cleaning properties. Therefore, the development of stable Fibrous Cleanout Fluids (FCFs) using different anionic polymeric formulations provide bases for efficient utilization of these materials toward successful hole cleaning. As a result, the main aim of this thesis is to provide fundamentals for cuttings, fiber, and polymer interactions, focusing on the development of stable fibrous water-based fluids for horizontal and vertical drilling hole cleaning applications. This thesis starts with an intensive literature review on different types of drilling fluids, experimentally tested and utilized in the drilling field; also, the vast majority of hole cleaning parameters are reported (Chapter 2). Following the materials and methods (Chapter 3), the results and discussion (Chapter 4) are split into two sections. The first part (Section 4.1) examines the influence of fibers concentration and aspect ratio, base polymer concentration, and solution temperature on FCFs stability; Fibers of higher aspect ratio showed better stability properties for FCF; formation of fiber's structured network decreases the fiber's sensitivity to destabilization under various conditions. The second part (Section 4.2) explored the impact of different base polymers anionicity and fibers addition on fine cuttings suspension and transportation. Zeta potential readings incorporated with total suspended solids (TSS) spectrometric measurements have highlighted the electrokinetic role in cuttings suspension. Solutions with high anionicity exhibit higher TSS concentrations. Particle-particle and particle-polymer electrostatic repulsive forces create a situation that prevents the settling of fine particles and preserves their suspension. Fiber addition improves the base fluid carrying capacity due to physical and hydrodynamic interfaces. Structured networks are formed in the medium of drilling fluid by fiber-fiber networking. Subsequently, the fiber network intercepts the trajectory of free-falling particles (cuttings); this fiber-particle interaction merges particle into the bulk of the network as a plug, which moves upward or remains suspended due to the fiber network high bouncy. Overall, the application of polyanionic polymer and fibers for hole cleaning application shall provide an environmentally friendly alternative to toxic oil-based muds. Outcomes of this thesis include one published article and two under review manuscripts.

Key Words**:** Water-based drilling fluid; Hole cleaning; Fibers; Electrokinetic; Fine cuttings transportation; Suspension.

DEDICATION

To my father Abdelhameed Feriri, my mother Razaz Hamour, and my brothers

To my academic advisors, Dr. Mustafa Nasser and Prof. Ibnelwaleed Hussein

for their continuous support and motivation.

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Chapter 1: Introduction

1.1. Research Overview

Oil and natural gas consumption worldwide is expected to increase annually, along with global economic growth. According to the BP Statistical Review of World Energy 2020, oil and natural gas accounts for 57.3% of the world's primary energy share, and the increase in global consumption in 2019 was 0.9% for oil and 2% for natural gas (BP, 2020). Drilling technologies have been developing to meet high market energy demands. Drilling fluids are considered as the core of the drilling operations; these fluids are used to achieve several sophisticated requirements, such as cooling and lubricating the drill bit, filter cake formation, wellbore stability, and cuttings transportation (Akpan et al., 2019; Bloys et al., 1994; Caenn & Chillingar, 1996; Xiaofeng et al., 2013). Cuttings transportation is defined as uplifting cuttings from downside of the wellbore to the surface.

Among many drilling operations challenges, hole cleaning is considered a common problem in inclined and horizontal wells (Costa, Stuckenbruck, Fontoura, & Martins, 2008; I. Ismail et al., 2017). Inadequate hole cleaning leads to operational difficulties such as bit wearing, increased drag and torque of drill pipe, reduced rate of penetration (ROP), and stuck pipe (Fink, 2012; Hopkins & Leicksenring, 1995; Lake et al., 2006; Sayindla, Lund, Ytrehus, & Saasen, 2017). Moreover, gradual hole blockage might create fractures and cause lost circulation during pipe tripping operation (J. Li & Walker, 2001). Furthermore, difficulties in other operations such as casing and cementing jobs as well as wireline logging operations, might also increase (Nazari, Hareland, & Azar, 2010). Studies showed

(Massie, Castle-Smith, Lee, & Ramsey, 1995; Patel, Thakar, Pandian, Shah, & Sircar, 2019) that a significant amount of nonproductive time (NPT) is associated with drilling problems that are caused by poor hole cleaning.

Selection of suitable mud and developing efficient drilling fluid management techniques are vital in the success of vertical, horizontal, and deviated well drilling. The main challenges in such operations include narrow mud window between the pore pressure and formation fracturing pressure, barite sag, and inadequate hole cleanout. Thus, equivalent circulating density (ECD) should be well managed. Currently, different methods such as jetting, reverse circulation, downhole tools, enhanced cleanout fluids, and gel sweeps are utilized to remove sand, rock cuttings, and other solids from a wellbore. Even though these new methods predominantly provide efficient cleanout, their effectiveness diminishes as the wellbore geometry becomes complicated; thus, sophisticated completion methods are required. In complex trajectory wells, modern and cost-effective ways are necessary to improve the efficiency of wellbore cleaning operations because conventional procedures cannot be economical when the cost of a cleanout job offsets the production gain.

Drilling Sweeps and drilling fluids are commonly used in the petroleum industry to enhance wellbore cleaning performance throughout the drilling operations. A drilling sweep is a specialized drilling fluid that is used to perform specific task such as cuttings transportation. Drilling sweeps are formulated by modifying the properties of the ordinary drilling fluid (base fluid) by additives in order to enhance the cuttings removal efficiency. Optimizing the sweep fluid design significantly cuts down the cost of the drilling program by reducing the number of wiper trips and reducing the NPT (Power, Hight, Weisinger, &

Rimer, 2000). Drilling fluids are classified according to their base fluid type into water-based muds (WBMs), oil-based muds(OBMs), and the recent foam-based muds (Jones & Hughes, 1996; Mahmoud et al., 2020). Water-based muds encounter instability problems in shale formations and in extreme conditions of high-temperature and high-pressure. Although oil-based muds exhibit good thermal stability compared to WBMs (Fornasier, Campo, Djuric, & Obando, 2017; Sinha et al., 2017), they are relatively expensive. Also, oil-based muds are not environmentally friendly fluids, and their use is strictly controlled (Christiansen, 1991). Hence, there is a great motive toward improving the properties of WBMs to meet the field requirements.

In contrast to vertical wells, drilling a deviated well with an inclination angle more than 30° from vertical has more problems in cuttings removal. The drill cuttings form a stationary bed that cannot be cleaned out at flow rates less than the critical flow rate (i.e., the minimum flow rate that is required to agitate stationary bed particles). Thus, cuttings removal mechanisms in deviated wells can be classified into three modes of transport based on the inclination angle. When the hole deviation is less than 30° from vertical, the cleaning process is simply accomplished in a similar manner as in vertical wells. When the inclination angle is between 30° to 60°, cuttings may accumulate on the low-side of a wellbore and even slip back down the hole when the mud circulation rate is low, causing stuck pipe. In this range of inclinations, turbulent flow is required to clean the wellbore with an annular fluid velocity of 200 – 250 ft/min. In highly deviated with inclination greater than 60°, cuttings accumulate on the low side of the hole, forming a stable stationary bed (Lake et al., 2006; Ramsey, 2019; Xiaofeng, 2013).

Once the drill pipe progresses, it slides through the well, and cuttings are generated at the drill bit. Rock cuttings mix with the mud and flow as a solid-liquid system. The distribution of cuttings in the system during the flow depends on several parameters, including flow rate, angle of inclination, wellbore geometry, and solids and liquid properties. Experimental observations showed that a mixture of cuttings and mud flowing in horizontal wells could exhibit four types of flow patterns (Figure 1.1): fully suspended symmetric (a), fully suspended asymmetric (b), fully suspended layer with a moving bed (c), and fully suspended layer with stationary and moving beds (d) (Kelessidis & Mpandelis, 2003). The fully suspended symmetric flow patterns occur at extremely high velocities. Fine solid particles (d < 1 mm) become thoroughly and uniformly distributed in the liquid when particle settling is prevented by vigorous turbulent mixing. This flow pattern normally does not occur during drilling. Asymmetric flow patterns occur when the velocity is reduced, and the majority of solid particles tend to flow near the bottom, yet some cuttings are fully suspended, which creates asymmetric solid concentrations. Moving bed patterns are observed once the flow rate is further reduced (low flow rates), resulting in sedimentation of particles at the bottom of the hole that forms a moving solid bed and suspension layer above the bed with non-uniform distribution of solid particles.

The minimum bed moving velocity is usually referred to as the critical or suspension velocity. Reducing the velocity below the critical velocity results in the formation of three layers, which is the most realistic case scenario. The three layers include a stationary bed as the bottom layer, a moving bed as the middle layer, and the suspension layer, which is a heterogeneous solid-liquid mixture moving as the upper layer. The middle and upper layers have strong interaction; both layers exchange solid particles by rolling or jumping until an equilibrium condition establishes. Nevertheless, as the bed height increases, it leaves less area for the flow; thus, it increases the upper layer velocity, which enhances the erosion of the bed by the heterogeneous mixture (Kelessidis and Mpandelis, 2003; Yeu et al., 2019; Cho et al., 2000; Shu et al., 2014; Mohammadsalehi and Malekzadeh, 2012).

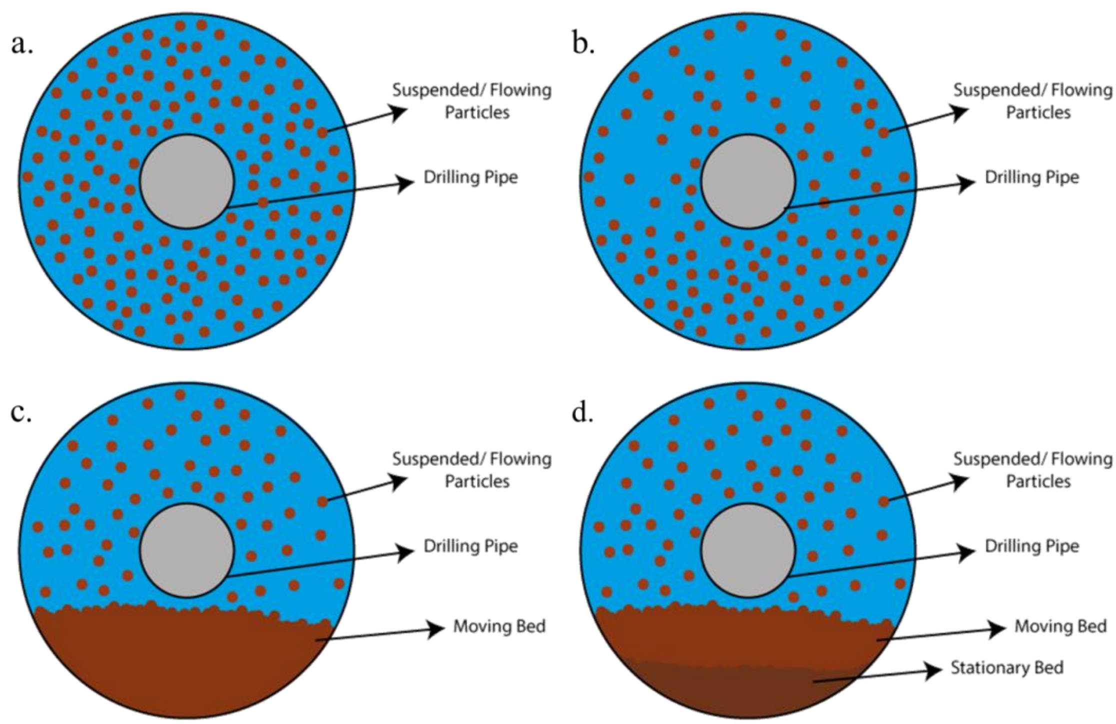


Figure 1.1 Cuttings flow patterns a) fully suspended symmetric b) fully suspended asymmetric c) moving bed d) stationary moving bed.

Different forces act on a particle suspended in flowing fluid.

Figure 1.2 shows the major forces acting on drill cuttings, which affect the hole cleaning process. The hydrodynamic drag and lift forces act on cutting particles; the drag force is a function of the particle projection area, drag coefficient, and the relative velocity between the particle and the surrounding fluid. Gravity force is related to the mass of the particle and the gravitational acceleration. The buoyancy force depends on fluid density, particle size, and gravitational acceleration.

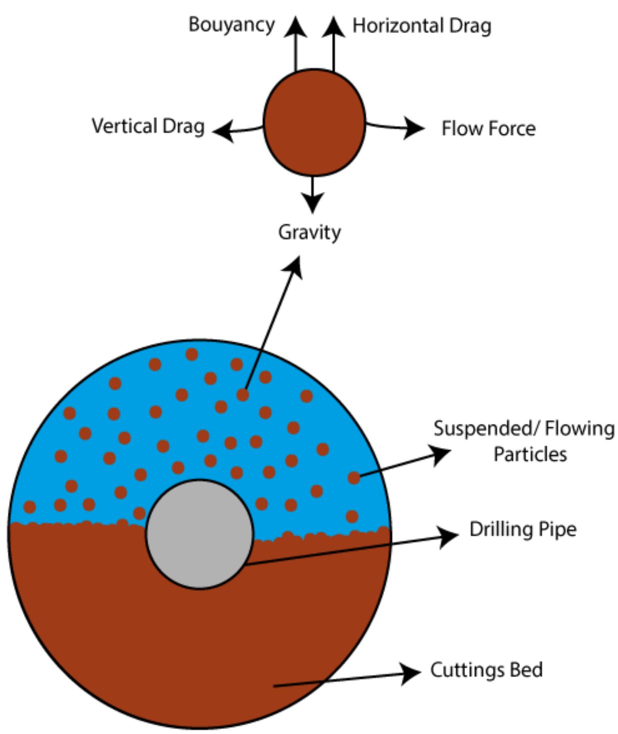


Figure 1.2 Forces affecting cuttings transportation.

1.2. Tangible Objectives

The ultimate objective of this thesis is to develop and test the performance of fibrous-containing water-based mud as an alternative to the conventional toxic OBM for horizontal drilling and cleanout application; this can be achieved through the enhancement and better understanding of the WBM properties in terms of cuttings suspension and transportation. Consequently, three sub-objectives are drawn:

I. Development of stable Fibrous Cleanout Fluids (FCFs) used for horizontal drilling cleanout, utilizing different base polymeric suspensions —including Carboxy Methyl Cellulose (CMC), Polyacrylamide (PAM), and Xanthan Gum (XG) — with fibers of two aspect ratio at ambient and elevated temperatures. This can be achieved through laboratory graduated cylinders settling studies and fluid rheology tests.

II. Optimize fiber stability under different conditions. Outcomes of the first objectives will be exploited for fibers stability models. Regression models for the stability of polymeric-base fibrous suspensions are produced, the stability measurements are analyzed using Minitab ® to evaluate the impact and interaction of factors (fiber and polymer concentration, fibers' aspect ratio, and temperature) affecting fibers' stability and determine optimum conditions for the stability of the FCFs.

III. Evaluate the performance of stabilized FCFs on different cuttings size suspension and transportation. In addition to the mechanical reinforcement that fiber provides toward cuttings suspension, highlighting factors that diminish fiber's impact. This objective can be accomplished through Total Suspended Solids (TSSs), Zeta Potential (ZP), and rheological measurements.

IV. Explore the influence of surface charge and molecular structure of the polymeric suspensions on fine cuttings carrying capacity. The assessment is achieved through measurements of TSSs and ZP.

1.3. Research Contributions

Standard procedures reported in the literature to improve hole cleaning performance are to operate with higher flow rates or modify the rheological properties of the drilling fluids. Increasing the flow rate is not always a feasible option due to increased annular friction pressure limited by the pumping capacity, also the increased operational costs such as wellbore erosions, and lost circulations (Allahvirdizadeh, Kuru, & Parlaktuna, 2016). Viscosity and density of drilling fluid, flow rate, wellbore geometry, inclination angle, annular velocity, cuttings/particles shape, size, and weight are among crucial factors affecting cuttings transportation (S. G. Valluri, Miska, Ahmed, Yu, & Takach, 2006). Incongruous usage of drilling fluid can jeopardize the whole drilling process reducing the penetration rate, and consequently, causes fluid loss, lost circulation, stuck pipe, or even catastrophic downhole blow out (Wei et al., 2020). OBMs have been extensively used in many drilling operations; characteristics such as good thermal stability, effective cuttings transportation, good lubricity, salt-resistance, and stability in shale formation nominate them as the superior option (Fornasier et al., 2017; Hermoso, Martinez-Boza, & Gallegos, 2014; Hermoso, Martínez-Boza, & Gallegos, 2014; Sinha et al., 2017). Nevertheless, the current global communities' perspectives are into sustainability and protection of the environment beforehand the oil/ gas exploration and production (Wajheeuddin & Hossain, 2018). The literature is abundant of publications on toxicity and severe effects of OBMs on the environment and human health (Almudhhi, 2016; Christiansen, 1991; Jerry et al., 1987; Okoro et al., 2020; Seyedmohammadi, 2017); thus, the use OBMs is restricted and faces a lot of governmental and non-governmental regulations and challenges. These concerns have redirected the drilling industry toward the utilization and exploration of eco-friendly drilling fluids. WBMs are considered inexpensive and environmentally friendly drilling fluids (Aftab et al., 2020; Christiansen, 1991; Tehrani, Young, Gerrard, & Fernandez, 2009), yet they encounter instability issues in shale formation or under extreme wellbore conditions; also, they lack in suspension properties that facilitate cuttings transportation. Therefore, improvement of WBMs characteristics is crucial to replace the toxic OBM with a viable alternative and subsequently achieving sustainability.

In recent years, various studies were conducted to improve the hole cleaning performance of WBMs by altering rheological properties. Studies utilize polypropylene (PP) and polyethylene (PE) beads have reported (Natalie V Boyou, Ismail, Hamzah, & Uche, 2018; Hadyan Hakim, Katende, Sagala, Ismail, & Nsamba, 2018; Onuoha, Ismail, Piroozian, Mamat, & Ismail, 2015; Wong Jenn Yeu et al., 2019; T. Ti. Yi, Ismail, Katende, Sagala, & Mugisa, 2017) an increase of cuttings transportation efficiency up to 15% in a vertical and horizontal configuration. The addition of polymer beads aids the reduction of cuttings slipping velocity attributed to their hydrodynamic interaction. Moreover, several studies have proposed the utilization of fibrous materials for hole cleaning, herbal fibers extracted from basil seeds showed effective hindering to particles settling velocity under static and dynamic conditions (Movahedi, Farahani, & Jamshidi, 2017). Furthermore, results of nano cellulose fibers and crystals showed better rheological properties for filter cake with low permeability in addition to the suspension and resuspension properties (Song et al., 2016a). To the best of our knowledge, no study was conducted on fine particles (d ≤ 0.5 mm) suspension and transportation. In addition, very limited studies were conducted on the electrokinetic behavior of fine and coarse particles in different base polymeric fibrous formulations (see section 2.6). This work shall provide foundations for the development of stable FCF using four different base polymeric suspensions and elaborate on insights of particle-polymer surface forces.

1.4. Research Outcomes

Journal Papers

1. **Mahmoud, H.**, Hamza, A., Nasser, M.S., Hussein, I.A., Ahmed, R., Karami, H., 2020. Hole cleaning and drilling fluid sweeps in horizontal and deviated wells: Comprehensive review. J. Pet. Sci. Eng. https://doi.org/10.1016/j.petrol.2019.106748
2. Alhajabdalla, M., **Mahmoud, H.**, Nasser, M.S., Hussein, I.A., Ahmed, R., Karami, H., 2021. Application of Response Surface Methodology and Box-Behnken Design for the Optimization of the Stability of Fibrous Dispersion Used in Drilling and Completion Operations. American Chemical Society Omega. Accepted
3. **Mahmoud, H.**, Alhajabdalla, M., Nasser, M.S., Hussein, I.A., Ahmed, R., Karami, H., 2021. Settling Behavior of Fine Colloidal Particles in Fiber-Containing Drilling Fluids. J. Pet. Sci. Eng. https://doi.org/10.1016/j.petrol.2020.108337

4. **Mahmoud, H.**, Alhajabdalla, M., Nasser, M.S., Hussein, I.A., Ahmed, R., Karami, H., 2021. Rheology of Polyanionic Fiber-Containing Water-Based Mud Developed for Hole Cleaning and Lost Circulation Applications. Under Preparation

Chapter 2: Literature Review

2.1. Drilling fluids

Drilling muds can be classified according to their base fluid type: water, oil, synthetic, or gas-based fluids. The proper mud type selection depends on many criteria such as temperature, formation type, and well depth. For example, water-based muds (WBMs) are considered as the conventional fluid type; however, these muds display instability at high temperatures. Furthermore, the presence of shale, which is very sensitive to water, limits the use of this mud type. Oil-based muds (OBMs) can resolve many problems of the water-based mud in addition to good thermal stability and lubricity. Despite these benefits, its application often results in a lot of environmental concerns, which restrict the field implementation of oil-based drilling fluids due to their toxicity. Air and foam based muds are associated with underbalanced drilling in which a well is drilled by maintaining borehole pressure less than the pore pressure to minimize reservoir damage by mud invasion (JieNian et al., 2010; Lake et al., 2006; Wisniowski, 2017; Yan, Wang, Sun, Luan, & Shao, 2014).

Viscosifiers and weighting materials are added to the drilling fluid to improve its ability to carry drill cuttings to the surface. Cuttings can be re-suspended by increasing the flow rate to the maximum allowable pumping pressure. However, ECD must be considered as a limiting factor as well as avoiding excessive erosion of the filter cake and the wellbore when using turbulent flow. In highly deviated wellbores, the fluid velocity will be affected by the inclination, which decreases the ability of the mud to suspend and transport the cuttings. Cuttings beds are more likely to form on the low side of the hole as a result of limiting the flow rate to manage the ECD. Moreover, the resting of the drill pipe on the low side of the hole creates an eccentric annular geometry, which forces a considerable amount of mud to flow in the high side of the wellbore. Consequently, local fluid velocity decreases in the narrow annular gap, allowing the accommodation of cuttings and the formation of cuttings beds. The most preferred method is maintaining laminar flow conditions and applying mechanical agitation by rotating the drillstring to resuspend and transport the deposited particles. Unfortunately, this technique delays the formation of cuttings beds but will not prevent it completely.

Drilling fluids sweeps can work properly in deviated and horizontal wells (George, Ahmed, & Growcock, 2011). Sweeps are formulated by adjusting their properties either to suspend cuttings in stationary beds or transport particles on the top of the cuttings layer. They can be generally classified into: high density, high viscosity, low viscosity, high density/high viscosity, and tandem sweeps. Using sweeps along with drillstring rotation improves hole cleaning performance, which has been established as a rule of thumb in the hole cleaning practice. Drilling by coiled tubing is considered as the worst cleaning scenario because such a system has no drillstring rotating capability. In non-rotating drillstring scenarios, high-density sweeps are preferred. Moreover, the volume of sweep is essential for the success of the operation. High viscosity sweep fails to clean the bore properly because of the flow diversion effects and the lack of cuttings resuspension capability (Hemphill, 2010; Hemphill and Rojas, 2002; Ahmed and Takach, 2009).

2.2. Sweep fluids and their formulations

The selection of drilling fluid is one of the vital factors in the hole cleaning process of horizontal and deviated wells. Rheological properties such as viscosity and yield point determine the carrying capacity of mud. Although other parameters such as drill pipe rotation and flow rate can help in lifting and suspending drill cuttings, well-designed drilling mud improves the efficiency of the process. Moreover, understanding the working mechanism of each additive used can provide better insight into the designing of new formulations.

Conventional mud systems have been applied successfully to clean vertical wells. However, their efficiency decreases during drilling inclined and horizontal wells because of the effect of hole inclination. In deviated wells, the cuttings settle down laterally as the angle increases, causing cuttings to accumulate and deposit on the low side of the hole. Both cases illustrate the challenging situation where many factors are competing together, decreasing the wellbore cleanout efficiency. Many drilling sweeps have been developed to enhance the competency of cuttings transport in horizontal wells. Drilling fluid is one of the main factors that can be controlled by proper adjusting of its properties. Therefore, full analysis of the used systems with understanding the working mechanism can help in improving the mud design to improve the cutting transport in horizontal wells drilling. Many additives were mixed with conventional mud systems to develop new formulations in order to maximize the cuttings removal from the hole. The next section reveals the types of additives used, their working mechanisms that mainly contribute to the cleaning process, techniques used for testing the developed formulations, and the discrepancies between the lab-scale and field application. Figure 2.1 summarizes the reviewed types of additives as well as the base fluid of each sweep.

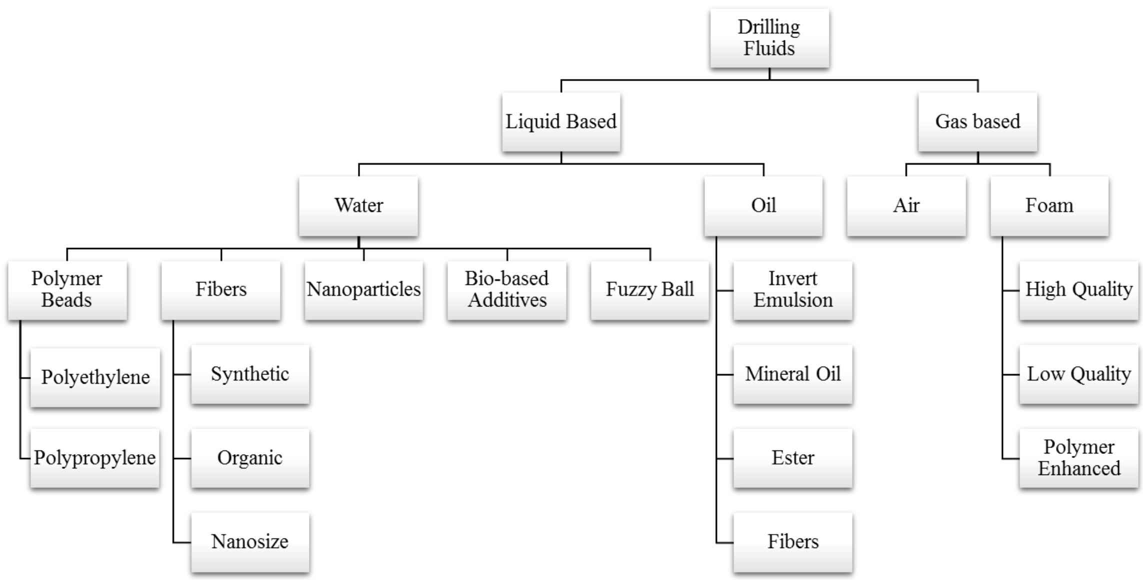


Figure 2.1 Classification of drilling fluids additives and sweeps.

2.2.1. Additives used with water-based fluids

Many additives have been used to improve the performance of WBMs by adjusting its rheological properties. At low flow rates, simple high-density sweeps such as KCl based fluids demonstrated better cuttings removal efficiency than the bentonite fluid, even though the bentonite had superior performance at high flow rates in horizontal configuration (Ytrehus et al., 2014).

Complicated fluid systems with polymer beads such as polyethylene (PE) and polypropylene (PP) with various densities, synthetic fibers, and naturally extracted types, as well as nanomaterials, have been used to enhance the solids transport efficiency of water-based fluids.

2.2.2. Polymer beads

Polymer beads such as PE and PP have been introduced in water-based mud to decrease the cuttings slipping velocity because of their hydrodynamic interference. Thus, the polymer beads improve the hydrodynamic drag within the drilling fluid which leads to an increase in the drag coefficient. In addition, the impulsive force due to the collisions between beads and drill cuttings enabled the cuttings to be suspended more efficiently. Among many types of polymer beads been proposed to assist in cutting removal in horizontal wellbores, PE and PP are the most used.

PE beads do not interact with water and have high thermal stability with a melting point of 450^{o}C. Because of their low specific gravity, the mud weight is expected to reduce. Yi et al. (2017) studied the effect of low and high-density polyethylene (LDPE and HDPE) beads with different concentrations (1 – 5 vol. %) on wellbore cleaning using WBMs at different hole angles (0°, 60°, and 90°) and flow loop with a fixed inner pipe. Sand used to simulate cuttings with a size range from 1.18 – 2.00 mm and a density of 2.65 g/cm^3. The densities of LDPE and HDPE beads were 0.92 g/cm^3 and 0.96 g/cm^3, respectively, while their diameter was 3 mm. The beads were spherical in shape. PE beads showed better performance in vertical and deviated wells with cuttings remove efficiency of more than 15 % and 10 %, respectively. This improvement is attributed to the addition of the drag force provided by the LDPE beads to counteract the gravity force and reduce the slip velocity of cuttings due to their hindering effect. However, both types of PE loss their efficiency at a 90^{o} deviation angle with a cutting transport ratio of only 2 %. A similar trend was observed when LDPE beads with a concentration between 1 to 5% (vol. /vol.) used to improve cutting transport in vertical and horizontal configurations at a flow rate range of 0.4 to 0.6 L/s. The best cleaning performance was achieved at high concentrations of PE in the mud. However, the efficiency decreased as the deviation angle increased (Wong Jenn Yeu et al., 2019). Comparing the performance of LDPE and HDPE beads showed that low-density beads are better than high-density beads (Wong Jenn Yeu et al., 2019; T. Ti. Yi et al., 2017).

Hakim et al. (2018) concluded that PP polymer beads are better as hole cleaning agent than PE to remove cuttings from horizontal wells with water-based mud at different concentrations (1 – 5 percent by volume) due to their low density. In terms of drill cuttings size effect, small cuttings were found to be easier to transport than large ones. The effect of cuttings size has been confirmed by Boyou et al. (2018), who investigated the performance of 1% by weight PP-based polymer beads in water-based mud. Cuttings used were in size range between 0.50 and 3.34 mm and tested at different hole angles (0° - 90°). Small cuttings in regular water-based mud improved by 6-8 % for hole angles less than 30° and 4% between angles of 60°-90°. Onuoha et al. (2015) presented spherical PP beads (density of 0.86 g/cm^3) as additive with water-based mud to improve the hole cleaning at different wellbore angles using fine sands with size between 1.0 and 1.2 mm and density 2.4 g/ cm^3. More than 10% of increment was achieved by using 1.5 wt. % of PP beads with water-based mud in a vertical orientation; however, as the hole angle increased from vertical, the cutting removal efficiency decreased. Table 2.1 reveals the cuttings removal efficiency of different types of polymer beads at various hole angles compared to the base fluid. Figure 2.2 depicts the cuttings transportation efficiency of PE and PP beads in horizontal wellbores.

Table 2.1 Cuttings transportation efficiency of different polymer beads at different hole angles.

Additive Type	Density, g/cm^3	Cuttings Transportation Efficiency, %			Cuttings Size, mm	Reference
		Vertical	Deviated	Horizontal		
1 – 5 Vol. % LDPE	0.92	15	10	2	1.18 - 2	Yi et al., 2017
1 – 5 Vol. % HDPE	0.96	10.5	8	1	1.18 - 2	
1-5 Vol. % HDPE	0.92	16.5	13	2	1.18 - 2	Yeu et al., 2019
1 – 5 Vol. % PE	0.952	-	-	10	0.5 - 4	Hakim et al., 2018
1 – 5 Vol. % PP	0.844	-	-	15	0.5 - 4	
1 wt. % PP	-	7	4	4	0.50 - 3.34	Boyou et al., 2018
1.5 wt. % PP	0.86	10	-	-	1 - 1.2	Onuoha et al., 2015

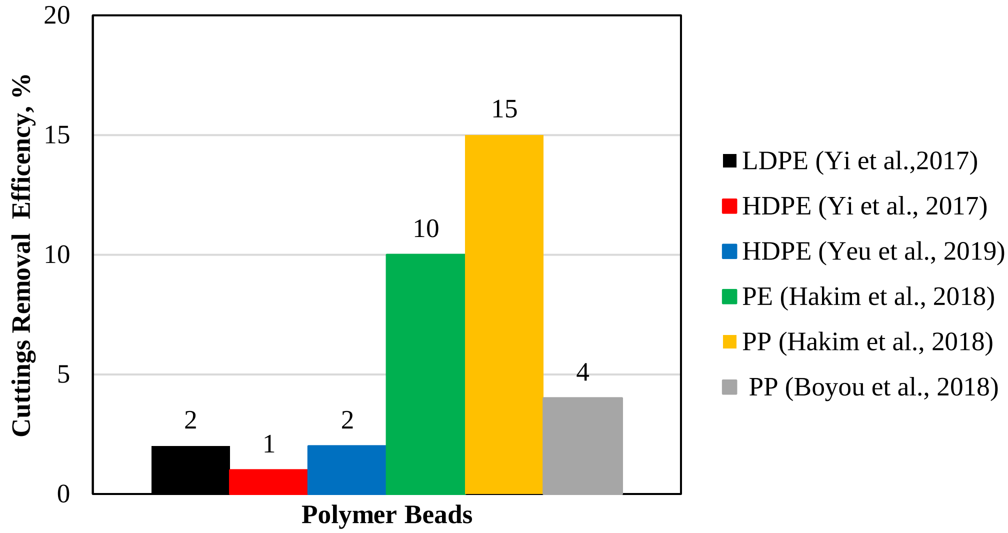


Figure 2.2 Comparison of cuttings removal efficiency of different polymer beads in horizontal flow loops.

In summary, polymer beads added to water-based drilling fluids showed low efficiency in removing cuttings in horizontal wellbore compared to vertical and inclined holes because the lateral component of gravitational force increases in the horizontal section while the drag and impulsive forces remain the same. Moreover, the ability to suspend the cuttings depends on the cutting size, where small cutting particles are easier to be suspended.

2.2.3. Fibers

Fibers are dispersed in sweep fluids to form a stable network structure due to their entanglement. The fiber network prevents settling by mechanical contact and hydrodynamic interference between cutting particles and fibers. Consequently, fibers improve the carrying capacity of the fluid (Ahmed & Takach, 2009a). Different types of fibers such as monofilament synthetic, PP monofilament, cellulose nanofibers, and natural hydrated basil seeds have been used to enhance cuttings transport. Fibers generally have low density and various aspect ratios. Table 2.2 summarizes the sweep fluid formulations that contain fiber. Minor changes were observed in the flow behaviors of the base fluids after adding the fiber. However, the addition of fiber hinders the settling of the sphere particles. Settling velocity drops smoothly and monotonously with increasing fiber concentration. Due to the formation of a fiber network that provides additional support and enhances the net drag force acting on the settling particles, the deposition rate of cuttings reduces with fiber concentration.

Table 2.2 Hole cleaning performance of different fibrous fluids.

Base Fluid	Fiber Type	Aspect Ratio Length/Diameter	Findings	Reference
0.75 wt. % CMC	0.02 – 0.1 wt. % monofilament synthetic fiber	3.175 mm / NA	Fiber caused a minor change in the behavior of CMC fluid and hindered the settling velocity of the particles.	Qingling et al., 2018
0.47 w/w % XG	0.04 w/w % synthetic monofilament fiber	10 mm / 100 µm	Adding fiber enhanced the cleaning performance of the XG and decreased pressure losses under laminar flow conditions without applying pipe rotation at ambient conditions.	Ahmed and Takach, 2009

Base Fluid	Fiber Type	Aspect Ratio Length/Diameter	Findings	Reference
0.5 wt. % PAM	0.5 wt. % HBS	-	Low concentration of HBS increased the drag force and prevented cuttings from settling at static and dynamic conditions without affecting the rheological properties of the fluid.	Movahedi et al., 2017
Water with low bentonite content (1 - 6 wt. %)	0.05 – 0.3 wt. % CNF / CNC	CNC average aspect ratio of 42 ± 13 (6.9 ± 2.3 nm in width and 290 ± 31 nm in length). CNFs have an aspect ratio (11.4 ± 4.9 nm in width and up to several micrometers in length)	Addition of cellulose nanoparticles reduced the yield point, viscosity, and gel strength due to the repulsive forces with bentonite.	Song et al., 2016
Water/oil-based mud Polyanionic cellulose (PAC)	0.00 %-0.08 Synthetic Monofilament fiber.	10 mm / 100 µm.	Fibers reduced the settling velocity of the spherical particles (2 – 8 mm) due to the applied drag forces with or without rotation.	Elgaddafi et al., 2012
0.5% XG with barite	0.05% Synthetic Monofilament fiber.	-	Weighted fiber sweeps with barite (10 ppg) improved the cuttings removal (river sand with approximately 3 mm diameter) in horizontal section with an eccentric drill pipe as a result of mechanical agitation.	Majidi and Takach, 2011

Fiber length ranging from nanometers to 13 mm and fiber diameters up to 100 micrometers have been used. For all aspect ratios, there was a minor impact on fluid rheological properties. However, no study has investigated the effect of aspect ratio on the cuttings removal. Fibers are dispersed in various polymer suspensions such as carboxymethyl cellulose (CMC), polyanionic cellulose (PAC), xanthan gum (XG), and polyacrylamide (PAM).

Sweep fluids showed better performance in removing cuttings at low flow rates as the inclination angle is reduced toward vertical (Ahmed & Takach, 2009a). However, the experiments were conducted at ambient conditions and the performance of fiber sweep has not been studied at elevated temperatures. In another study, 0.87 lb/bbl XG suspension showed an increase in shear stress as fiber concentration was increased; however, at high concentration (1.75 lb/bbl), the mud showed a reduction in shear stress with the increase in fiber concentration (George et al., 2011).

The properties of solids also have some impact on the effectiveness of fiber network in hindering the settling. Spheres with a diameter between 1 to 10 mm made of steel, titanium, and aluminum were used to simulate drill cuttings with different densities (Qingling et al., 2018). Increasing the diameter of aluminum particles, which were the lightest among the other spheres, resulted in a significant change in the hindering effect of fiber network as the particle diameter was increased starting from 4 mm.

Commonly used hole cleaning fibers are made of virgin polypropylene monofilament material which has high-temperature tolerance, mixing ability, and strength with low reactivity. In a recent study (Movahedi, Farahani, et al., 2017), herbal fibers extracted from hydrated Basil seeds (HBS) were used with water-based mud containing 0.5% polyacrylamide by weight to suspend the fibers. The addition of HBS hinders the settling velocity of different particles in both dynamic and static conditions.

Song et al. (2016) developed low-solid content drilling fluid mixed with cellulose nanoparticles containing cellulose nanofibers (0.8 wt. %) and nanocrystals. The ecosystem friendly fluid showed shear thinning behavior. Moreover, its rheological properties are significantly affected by the morphology of the nanoparticles. Adding a small quantity of short cellulose nano-fibers on low bentonite mud reduced the yield point, viscosity, and gel strength resulting in an ideal filter cake with low permeability. Repulsion between negatively charged cellulose nanocrystals (CNC) and bentonite lead to a better distribution of bentonite contrary to cellulose nanofibers (CNF)/bentonite where no repulsive forces are present. Moreover, the entanglement of fiber was observed to cause an increase in viscosity. However, flow loop tests were not performed with these fibers.

In summary, adding fiber enhances hydrodynamic drag and subsequently reduces the settling tendency of suspended high-density solids (George, Elgaddafi, Ahmed, & Growcock, 2014).

2.2.4. New and emerging additives

2.2.4.1. Bio-based additives

Bio-based additives and organic oils have been proposed to reduce the environmental impacts of water and oil-based muds. Oseh et al. (2019) added henna leaf extracts as water-based fluid to remove aquarium sands (diameter 1 mm). Henna-water based mud presented better rheological and filtration characteristics as compared to bentonite and water-based mud, which provided higher cutting transport efficiency. 8.6 %, 6.7 %, and 8.1 % improvements in average cutting removal efficiency were achieved as compared to water-based mud in vertical, inclined, and horizontal configurations, respectively. In another study, an eco-friendly fiber extracted from hydrated basil seeds (HBS) was used with water-based mud (Movahedi, Farahani, et al., 2017). Synthetic ester-based mud derived from the palm pulp fruit was formulated to replace oil-based mud. Plastic viscosity of the fluid was the most critical parameter affecting hole cleaning efficiency without using barite and soda ash (Okon, Agwu, & Udoh, 2015).

2.2.4.2. Fuzzy ball

Fuzzy ball drilling fluid are low-density fluids 0.85-1 g/cm^3; this type of drilling fluid is developed through high stepless-frequency conversion-high speed blender utilizing water, sodium dodecyl sulfate, sodium dodecylbenzene sulfonate, hydroxyethyl starch, polyacrylamide in addition to other additives (Lihui et al., 2010).

Due to fluid loss and instability problems in the wellbores, fuzzy ball drilling fluids -fuzzy material containing air pocket core all surrounded by fuzzes- were innovated to provide adaptability and stability. The ability to change shape in order to match leak passages and the increased capability at high temperature and pressure (Lihui et al., 2010) reflects the wide range of applications such as conventional vertical wells, U-shaped wells, horizontal wells, and multi-branched horizontal wells. More than 1000 coal bed methane wells utilize this technique (Zheng et al., 2018).

Rheological experiments show that fuzzy ball fluids follow Bingham fluid model and are classified as plastic fluid (Lihui et al., 2010). The cuttings carrying capacity was found to be promising through the rheology characteristics; it promotes in comparison with polymer drilling fluid that the flowability of fuzzy fluids are stronger and better (Zheng et al., 2018). In addition, fuzzy-ball drilling fluids are environment-friendly mixtures, biodegradable, and protects the environment from drilling fluid leakages (Y. Zhang et al., 2019).

2.2.4.3. Nanoparticles

Recently, the focus in the petroleum industry has shifted to produce low-cost and environmentally friendly energy. Natural gas reservoirs have been explored and developed in conventional and unconventional formations. Shale gas is gaining more attention because the challenges associated with the shale formations at high-temperature conditions complicate the drilling process and raise the cost and non-productive drilling time dramatically. Horizontal wells have been used to develop such reservoirs, which resulted in complex technical problems where shale swelling and pore pressure transmission are combined with the hole cleanout issues in the long horizontal section of high-temperature wells.

Nanoparticles can improve the rheological properties and thermal stability of drilling mud. Moreover, nano-additives such as silica, aluminum oxide, and carbon nanotubes had shown potential in improving bit cooling, viscous behavior, and reductions in drag and torque as well as friction factors when they mixed with drilling fluids. Furthermore, the thermal stability of conventional muds has been upgraded to 160°C by using nanomaterial (N. V. Boyou et al., 2019; Xian-yu Yang, Yue, Cai, Liu, & Wu, 2015).

Recent advances in the drilling fluid research showed that WBMs formulated by nanoparticles had tackled the issues associated with shale gas drilling. Nanoparticles prevented pore pressure transmission in shale formations (Marcellus and Mancos) by physical plugging of nanopores (N. V. Boyou et al., 2019). Boyou et al. (2019) investigated the effect of 14 nm nanosilica on the efficiency of cutting removal in highly inclined flow loop system at rotational speed up to 150 rpm. Nanosilica enriched the performance of conventional WBMs in cutting removal by more than 38 % on average because of the increase in colloidal interactions between the drilling fluid and cuttings.

Large cuttings can be removed efficiently in horizontal well and small cuttings in vertical (Gbadamosi et al., 2019; 2018). The mechanism is interaction with cuttings and enhanced colloidal forces. Nano silica particles are tremendously light in weight with high surface area to volume ratio characteristics which increases drag and lift forces on cuttings to overcome gravitational and cohesion forces. Moreover, drillstring rotation increases the cutting removal efficiency under turbulent flow conditions. The addition of nanosilica was able to reduce the rheological properties such as yield point, apparent viscosity, plastic viscosity, and gel strength, especially for high mud weights. Maintaining the rheological properties of the mud, the nanoparticles considerably decreased the required pumping pressure without interrupting cuttings transport. This could be explained by the increase in colloidal interactions between the nanoparticles and cuttings when the mud is flowing.

Elochukwu et al. (2017) proposed using a cationic surfactant (2.5 % alkyl benzyl dimethyl ammonium chloride, ABDAC) by weight to enhance the filtration control without modifying the rheological properties of nanosilica-WBMs at low/high temperature and pressure environments. The cutting carrying capacity of the fluid was significantly affected by the repulsion between nanosilica and bentonite particles due to the presence of negative charges on their surfaces at different pH values, as indicated by zeta potential measurements.

Briefly, nanoparticles can improve the transport of cuttings in horizontal wellbores through colloidal interactions. Moreover, repulsion forces between nanoparticles and bentonite result in stable plate structure which can help suspend the cuttings without modifying the rheological properties of the mud.

2.2.5. Additives used with oil-based muds

OBMs have the advantage of high thermal stability at high temperatures and compatibility with shale formations. However, environmental concerns restrict the use of such mud types. Many additives and environmentally friendly oil types have been developed to minimize environmental footprint. Nevertheless, oil-based muds are now being less used due to environmental considerations and the focus is centered around water-based muds. As a result, recent studies on oil-based muds have been very limited, which reflects the limited references used in this section.

Gao and Young (1995) successfully used an organic pseudo-oil (Acetal) invert emulsion-based mud to drill a horizontal well in a reactive shale formation as an alternative to invert emulsion in a field trial. The cuttings removal mechanisms (lifting/suspension and rolling) of an inverted emulsion depends on the hole diameter. The suspension mechanism is dominant in small wellbores while rolling is the controlling mechanism in large holes. Both mechanisms are influential in the intermediate diameter holes. In a similar study (Kenny, 1996), natural ester oil from vegetables was used to replace mineral oil used in OBMs to decrease their environmental impact. The hole cleaning performance of ester-based mud depends on fluid velocity and the rheological properties at high temperature and pressure conditions. Ester based fluid rheological properties such as yield stress are not strongly affected by elevated pressure and temperature as compared to mineral oil and diesel-based muds. Moreover, at low-temperatures, ester-based fluid shows high yield stress and consistency index which are beneficial in offshore drilling using risers or large hole diameters at shallow depths.

The cuttings transportability of drilling fluids is considerably influenced by the drill pipe rotational speed. However, the impact of rotational speed on cuttings transport decreases after a critical value suggesting an optimum point. At low rotational speeds, the yield stress of the fluid keeps cuttings in suspension with minimal drillstring agitation. Adjusting the mud properties depends on the drilling objective and whether tripping activities are planned (Sayindla et al., 2016, 2017). When low viscosity OBM was used with 50 rpm pipe rotation, increasing the cutting rates to simulate the increase in penetration rate had a minor effect on the cuttings concentration (Ytrehus et al., 2018). Thus, suspended cuttings can be removed efficiently.

In a recent study (Werner, Myrseth, & Saasen, 2017), water in oil emulsion with an oil-water ratio of 95/5 was used to create mud with barite and organophilic clay as weighting material and viscosifier, respectively. Water in oil emulsion-based mud performed better in hole cleaning as compared to KCl based WBM due to the absence of yield stress in the brine mud and increase in viscoelasticity.

In a fiber sweep formulation study (Elgaddafi et al., 2012), synthetic monofilament fibers were suspended in mineral oil to reduce the settling velocity of solid particles. The fibers were added up to 0.08 % by weight, which slightly changed the fluid rheology and improved the total drag force, which comprises hydrodynamic and fiber drag forces.

Table 2.3 shows a summary of the oil-based sweep fluid studies and their main findings. Overall, cuttings removal efficiency using OBMs is affected by the hole size because lifting (suspension) and rolling are competing with each other as the hole size changes.

Table 2.3 Oil-based sweeps.

Formulation	Main Findings	Reference
Organic pseudo-oil (Acetal) invert emulsion-based mud	Lifting is dominant in small wellbores; rolling is the controlling mechanism in large holes whereas both are critical in the intermediate diameters.	Gao and Young, 1995
Vegetable Ester Based Oil	Pressure and temperature have a limited effect on the rheological properties of the base fluid compared to other types of oil such as mineral oil.	Kenny, 1996

Formulation	Main Findings	Reference
Water in oil emulsion based fluid with organophilic clay and viscofier	Better cuttings removal compared to brine based mud.	Werner et al., 2017
Synthetic monofilament fiber	The settling velocity of particles decreases due to the increase in the drag forces after adding 0.08 % of the fiber.	Elgaddafi et al., 2012

2.2.6. Foam based drilling fluids

Foam-based drilling fluids are regularly used in underbalanced drilling to minimize formation damage. Moreover, oil-based foams have been used instead of WBMs to drill water-sensitive shale formations. Nitrogen, air and carbon dioxide are mostly used to create foams in the field (Duan et al., 2010). Foam viscosity increases with increasing foam quality (gas volume fraction).

Naganawa et al. (2002) carried out tests in a field-scale flow loop to understand cuttings transport in highly inclined or horizontal sections using aerated mud. The cuttings carrying capacity of aerated mud depends on the gas-liquid flow pattern which can be bubbly, churn, slug, or stratified flow as the inclination angle increases. Air with a high flow rate can be used to disperse stationary cuttings beds formed at inclinations greater than 60^o. It was observed that in the horizontal section, liquid and air were separated and formed a wavy stratified flow pattern which resulted in the reduction of cuttings transport.

At different inclinations, numerous drilling parameters affect cuttings transport with foam. The vertical component of foam velocity in the annulus has to be larger than the deposition velocity of cuttings in order to properly clean the hole. Increasing the foam quality improves the cuttings transport; however, there is a critical velocity above which the foam quality has no influence (J. Zhang et al., 2018). Yan et al. (2014) reported that the cutting transport in wells with a complex trajectory was greatly affected by fluid rheology and flow rate— considered controllable parameters. Table 2.4 summarizes the effect of foam quality and foam velocity as well as the use of gasified sweeps on the cuttings transport in the horizontal section.

Table 2.4 Summary of foam and gas based sweeps used for horizontal wellbore cleaning.

Foam Quality, %	Foam Superficial Velocity	Main Findings	Reference
84 – 96	-	At laminar flow conditions, increasing foam quality enhanced solids transport.	Herzhaft et al., 2000
84 - 96	-	Cuttings transportation depends on specific volume ratio of foam to base fluid.	Saintpere et al., 2000
70 –90	2– 18 ft/s	Wall slip of high-quality foam.	Ozbayoglu et al., 2003
6 –95	-	The performance of foam in underbalanced drilling depends on foam stability.	Martins et al., 2001a
70 – 90	100-200 GPM	Addition of polymer with low concentration has a minor impact at elevated pressure and temperatures. Pipe rotation improves hole cleaning with low-quality foam at low flow rates.	Xu et al., 2013
80 – 90	1.8 -5.02 ft/s	For high foam quality, an increase in foam velocity decreases the cuttings transport efficiency while pipe rotation can improve the cleaning.	Gumati et al., 2013
70 – 90	2 – 6 ft/s	For high-quality foams, the critical superficial velocity to improve the movement of the cuttings is 5 ft/s whereas low-quality foams require higher values.	Chen et al., 2007

Foam Quality, %	Foam Superficial Velocity	Main Findings	Reference
70 – 90	2- 6 ft/s	Using polymer and increasing gas and liquid injection rate enhanced the cuttings transportation of foam based sweep.	Prasun and Ghalambor, 2018
60 – 90		Pipe rotation enhanced cuttings removal using low foam quality.	Duan et al., 2010
	2 – 5 ft/s	Foam velocity has a limited effect on the performance of low to medium foam quality.	
		The properties of foam based fluids are slightly affected by high-pressure high-temperature conditions.	
Gas /water	-	The liquid phase has a major impact on cuttings removal due to the increase in the local velocity when gas velocity is increased.	Ozbayoglu et al., 2012
Air-based	-	Cuttings transport depends on the flow pattern.	Naganawa et al., 2002

Duan et al. (2008) studied the effect of drill pipe rotation (up to 400 rpm) on the cleaning performance of high-quality foams (60 – 90%). The rotation of the pipe changed the cuttings bed profile resulting in high cuttings bed thickness on one side of the drillstring and low bed thickness on the other side. Moreover, the results assert the effect of pipe rotation on pressure drop and the rheological properties of the foam. Nevertheless, this effect decreased as the foam quality was increased. The impact of the pipe rotation depends on the eccentricity and the speed of rotation (Duan et al., 2010). Overall, increasing pipe rotation significantly enhances the hole cleaning process.

High-quality foams have the capability to erode cuttings beds (Martins et al., 2001). Nevertheless, the flow rate of liquid phase plays a critical role specifically when the foam quality decreases. Larger gas volume leads to mist or pure gas drilling. Transition to unstable foam and aerated fluid occur when the gas fraction reduces exceedingly. It is very difficult to maintain foam quality in the optimum range during drilling operations. The high compressibility of the fluid will allow the optimum values of gas volume to be reached very close to the surface.

Increasing foam quality and rotation speed improves hole cleaning in horizontal wellbores and decreases the frictional losses (Duan et al., 2010). However, wall slip was noticed at high foam quality (70 to 90 %) with increasing cuttings bed thickness (Evren M. Ozbayoglu et al., 2003). Moreover, the liquid phase has a major effect on the cutting transport behavior of the water-air mixture. Yet, increasing the gas velocity in the two-phase mixture increases the drill cuttings lifting capability and the local liquid phase velocity which increases the drag force acting on the cuttings (Evren M. Ozbayoglu, 2010; M. E. Ozbayoglu, Sorgun, Saasen, & Svanes, 2010). It was observed that increasing foam velocity decreases the amount of cuttings accumulated in the wellbore. However, drill pipe rotation has no significant influence on the cuttings transport capacity of high-quality foams in contrast to the case of low-quality in which an increase in pipe rotation greatly reduces the cuttings concentration (Xu et al., 2013).

Some studies (Yu et al., 2004; Nguyen et al., 2010; Li et al., 2012) considered attaching gas bubbles or oil droplets to cuttings to improve hole cleaning. In a recent study (Li et al., 2012), surfactant was used to change the wettability of the cuttings to amphiphobic by adhering the surfactant to the cuttings surface. Consequently, drilling debris were removed from the horizontal section by using 0.4% of the surfactant, which was able to suspend more than half of the cuttings.

Polymers are used with foam to improve its stability and enhance the cuttings transport in highly inclined and horizontal wells. Polymer controls the foam viscosity and flow pattern; however, a low concentration of polymer has no effect on the cleanout efficiency (Xu et al., 2013). In another study (Denney, 2006), adding HEC polymer enabled more cuttings to be delivered out of the flow loop. However, an increase in friction pressure was observed. It was suggested to use high foam quality (90 %) together with a high flow rate (6 ft/sec) for proper cleaning. At elevated pressure and temperature, the foam quality has slightly changed resulting in poor cutting transport. Moreover, Chen et al. (2007) determined the critical velocity of high-quality foams and reported the increase in critical velocity with the reduction of foam quality. Similar observations were reported by Prasun and Ghalambor (2018) based on lab experiments and modeling studies. Therefore, foam-based drilling fluids suffer from changing flow pattern as the inclination angle increases which causes separation of gas and liquid phases. At velocities greater than the critical value, increasing the foam quality enhances the cuttings removal. When foam velocity is less than the critical velocity, foam quality has a minor effect on hole cleaning. Properties of foam based fluids are considerably affected by high-pressure high-temperature conditions and hence their cuttings transport efficiency.

2.2.7. Field application

Discrepancies have been observed between laboratory measurements and field observations in comparing the hole cleaning performance of oil and water-based fluids. In the field, oil-based fluids have been claimed to be better in removing cuttings from horizontal wells as compared to water-based fluids with similar rheological properties. However, laboratory experiments confirmed that no differences were noticed in the presence of pipe rotation; however, OBMs performed better than WBMs without rotation (Sayindla et al., 2017; Werner et al., 2017).

Upscaling of laboratory measurements is the best methodology to achieve high cleaning efficiency since the properties of the fluids are tested in similar well conditions, which eliminates the possibility of poor performance due to the effect of field parameters on the properties of drilling fluids. Most of the disagreements between lab and field measurements are attributed to neglecting the effect of relevant parameters, problems with upscaling lab measurements, or considerable differences between the experimental and field conditions.

2.3.Parameters affecting hole cleaning

Cutting transport is influenced by various parameters. Changing each parameter has its own impact on hole cleaning. There are several variables to control and vary to optimize the process. Nevertheless, the effect of each parameter differs if the well is vertical, inclined, or horizontal. Figure 2.3 illustrates various vital variables that affect hole cleaning. The variables are based on their influence on hole cleaning and their controllability in the field. The flow rate, fluid rheology, hole size, and hole angle, and rate of penetration have a strong influence on hole cleaning. However, flow rate and fluid rheology are the preferred adjustable parameters in the field due to their controllability.

Table 2.5 Comparing the field and lab performance of sweeps.

Fluid Formulation	Findings	
	Lab	Field
Fiber sweep	Using fibers hinders the settling of drill cuttings (Ahmed & Takach, 2009a; Elgaddafi et al., 2012; George et al., 2014). High-density fiber sweeps enhanced cuttings removal in a horizontal section under static conditions (Majidi and Takach, 2011; Song et al., 2016).	Low viscosity fiber sweep and high-density sweep showed efficient hole cleaning in a horizontal section (Bulgachev & Pouget, 2006; Cameron, Helmy, & Haikal, 2003).
Water-based drilling fluid Oil-based drilling fluid with Oil-water ratio of 80/20.	With same viscosity profile, WBMs and OBMs showed similar cutting removal efficiency with pipe rotation, while, oil-based fluids are more efficient without pipe rotation (Sayindla et al., 2017; Werner et al., 2017).	Oil based fluids are better in hole cleaning than KCl WBMs at low temperatures (up to 50°C) (Werner, Lund, Myrseth, Saasen, & Gyland, 2016).
Ester based drilling fluid	Temperature and pressure have an effect on the rheological properties of the mud (Kenny, 1996).	Effective hole cleaning due to well management of rheological properties based on lab work (Kenny, 1996).
Water-based drilling fluid	-	Effective in carrying cuttings in shallow coal bed methane reservoirs at low temperature conditions (Lyu et al., 2019).
Pseudo-oil (Acetal) based mud	-	The efficiency of cuttings transport results from fluid properties especially with reacting shales. Pipe rotation with using high-density mud significantly enhanced the cuttings transport (Gao & Young, 1995).
Synthetic oil-based mud	-	Low viscosity OBM combined with rotating system shortens the drilling time and eliminated the poor hole cleaning problems (Kopally, Thyagaraju, & Kali, 2006).

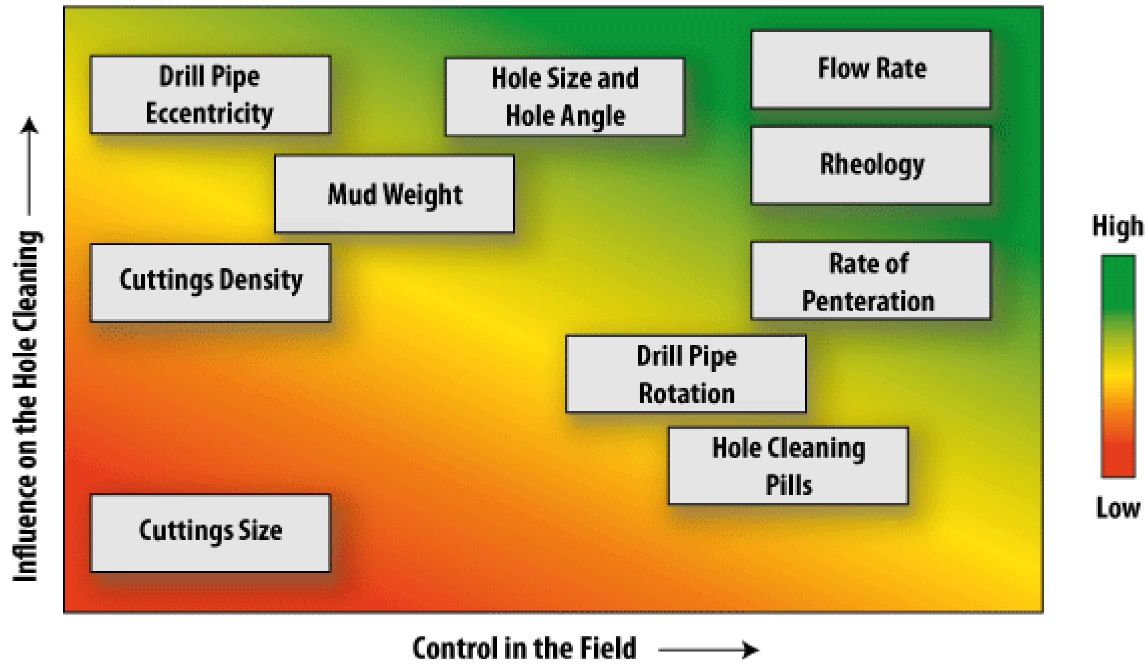


Figure 2.3 Factors affecting cuttings transport in highly deviated wells (Peter, Adari, Ergun, Arild, & Stefan, 2007).

2.3.1. Flow region

Studies showed that turbulent flows have high cutting transport efficiency. Under turbulent flow conditions, hole cleaning efficiency is not strongly affected by mud rheology or other parameters such as pipe rotation. Strong mixing effects of turbulent eddies and momentum diffusion, which depend mainly on fluid velocity and density (Table 2.6), are the main contributors to hole cleaning. However, under the laminar flow condition, cuttings transport becomes dependent on mud rheology (i.e., fluid behavior index (n) and fluid consistency index (K)). The bed height decreased as the n/K ratio was increased (Peter et al., 2007).

Table 2.6 The effect of flow regime on cuttings transport.

Key Factor	Range	Drilling fluid	Cuttings Size / Type	Findings	Reference
Reynolds number	Turbulent & Laminar Flow Rate 200-400 GPM Angles 90^o - 87^o n/k 0.004-0.006	WBDF PAC Solutions and CMC+XCD	3.175 mm crushed sandstone with a specific gravity of 2.56.	The turbulent region is better for cuttings transport at all angles studied, the region is not affected by wellbore angle or the mud rheology	Peter et al., 2007
	Turbulent & Laminar Angles 0^o – 90^o Flow rates 100-200 GPM	Water and WBM formulated with bentonite	6.35 mm Drilling Carthage marble ASTM.	Under turbulent flow, cuttings transport is not strongly affected by rheology.	Okrajni and Azar, 1986
	Turbulent, Transition & Laminar (37.9,45.4, 53.0, and 68.1 L/min) Angles 60^o - 90^o	Tap Water and Tap water + bentonite + barite Tap water + bentonite + barite + CMC	Coarse sand particles with an average size of 1.70 mm	The turbulent regime is the best for cuttings removal for all angles, followed by transition then laminar regime	Ismail et al., 2012
	Turbulent and Laminar Angles 60^o - 90^o Rotation 0.60.120 rpm	Water + CMC + XC and Water + CMC	Silica sand 1.7-2.0 mm the	Turbulence has a very strong effect on the hole cleaning	Peden et al., 1990

2.3.2. Flow rate

Table 2.7 presents the findings of several experimental and computational fluid dynamics (CFD) studies on the effect of flow rate on cuttings transport. The experiments were conducted at various combinations of relevant parameters or factors (drilling fluid type, cutting size, flow regime, angle of inclination). All experiments showed that the flow rate has a positive effect on cutting removal. The critical transport velocity (MTV) is defined as the minimum velocity needed to initiate the removal of flow protruding cuttings bed particles.

Table 2.7 Summary of flow rate effect on hole cleaning.

Range	Drilling fluid	Cuttings Size/Type	Findings	Reference
150 - 400 GPM Turbulent & Laminar Angles 90^o- 87^o n/k 0.004-0.006	WBDF PAC Solutions and CMC + XCD	3.175 mm crushed sandstone with a specific gravity of 2.56.	As the flow rate increases the cuttings bed erosion occurs in less time.	Peter et al., 2007
Flow rate 30-70 m^3/h Rotation 0 and 180 RPM Angle 60^o	Water and WBDF 0.15 % PHPA and 5 % bentonite + PHPA	3.175 mm spherical ceramic balls with a specific gravity of 2.4.	At 60^o, the increase in the flow rate lowers the cuttings concentration. The optimum flow should provide low cuttings concentration and reasonable frictional pressure loss.	Naganawa, 2013
CFD Model 120 - 180 GPM	The CFD model used is applicable for different fluids	3 and 8 mm	The flow rate increases the cleaning efficiency. Its effect is more pronounced with small particles than large ones.	Bilgesu et al., 2007
CFD Model 25 - 400 GPM	The model considers incompressible non-Newtonian fluids Density 8.33 to 12.5 ppg	0.0457 to 5.99 mm with specific gravity from 2.3 - 3.	As the flow rate increase, bed thickness reduces. Turbulent flow is better for preventing bed development.	Ozbayoglu et al., 2009

Range	Drilling fluid	Cuttings Size/Type	Findings	Reference
The Flow rate was found for each case by the developed model	CFD Model: a combination of Larsen & Moore models	0.021 and 2.6 g/cm^3 density of cuttings	For specific PV value, the required flow rate for removal is lower at more inclined configuration.	Mohammadsalehi and Malekzadeh, 2012

Cuttings bed formation starts once the mean fluid velocity is below the MTV. The equilibrium bed is reached when the fluid velocity above the bed surface is able to transport cuttings without further deposition to the bed or erosion of the bed. The flow rate is limited by rig hydraulic power, mud pump capacity, equivalent circulating density, the tendency of the open hole section to hydraulic erosion (Mohammadsalehi & Malekzadeh, 2012).

2.3.3. Rheology of the mud

Rheology is an important fluid property related to hole cleaning. For the horizontal and highly deviated wells, low-viscosity thin fluids are more effective in cuttings removal. The low viscosity fluid allows the establishment of turbulence flow condition at low flow rates, the turbulence causes the local fluid velocity to increase in the vicinity of bed particle, resulting in an increase in cuttings lifting and removal (Ozbayoglu et al., 2009). Table 2.8 summarizes the effect of rheological properties on cuttings removal studied under various conditions.

Table 2.8 Effect rheological properties on cuttings removal efficiency.

Key Factor	Range	Drilling fluid	Cuttings Size / Type	Findings	Reference
n/k	200-250 GPM n/k .006,.005,.004, and.0006	WBDF PAC Solutions and CMC+XCD	3.175 mm crushed sandstone with specific gravity of 2.56.	For horizontal configuration, decreasing n/k reduced the cuttings transport at a given flow rate.	Peter et al., 2007
Viscosity, Fluid behavior index (n)	Viscosity 0-300 cP Fluid behavior index (n) 0.2-1	Model developed for (in)compressible non-Newtonian fluids Density 8.33 to 12.5 ppg	Cuttings size range from 0.0457 to 5.99 mm and cuttings density varies from 2.3 to 3.0 sg.	Increasing the viscosity increases the bed area; higher viscosity hinders the turbulence of flow As n increases the velocity profile is well developed (bullet-like). Reducing n values results in a smaller bed due to the increase of velocity at the vicinity of the bed surface. The effect becomes more significant at higher flow rates	Ozbayoglu et al., 2009
Plastic Viscosity	Viscosity 0-60 cP	CFD Model: a combination of Larsen's & Moore's model	0.021 and 2.6 g/cm^3 density of cuttings	Increasing the plastic viscosity (46^o, 90^o) increasing the required flow for hole cleaning. The increase in required flow for hole cleaning has higher slop at 46^0 inclination	Mohammadsalehi and Malekzadeh, 2012

In horizontal and inclined wells (i.e. 90° - 60° inclination), increase in viscosity aids and enhances the cutting removal to some extent. However, increasing the viscosity above a critical value would decrease the removal efficiency (A. S. I. Ismail et al., 2012). The viscosity should be increased to reach the lower endpoint of the turbulent regime. An increase beyond the endpoint results in the reduction of cuttings removal. This is in agreement with an earlier study (Peter et al., 2007), which uses the n/k ratio for hole cleaning analysis. For power law type drilling fluids, n/k ratio increased when viscosity decreased. The bed height decreased as the n/k ratio increased under laminar flow condition. Thus, cuttings bed removal is better with low viscosity fluid when the flow is laminar (Peter et al., 2007).

The API Standard procedure recommends measuring fluid gel strength at 10 seconds and 10 minutes at low shear rate. The gel strength has a negative effect on hole cleaning since its increase would require more forces to remove the deposited particles from the bed. High molecular weight polymers have a large contribution to gel strength (A. Saasen & Løklingholm, 2002).

2.3.4. Hole angle

For hole cleaning analysis, hole angle is subdivided into three inclination ranges: high, intermediate, and near-vertical angles The transport mechanisms in these inclination ranges are rolling, lifting, and settling, respectively. Stationery cuttings bed form in high angles while moving and churning beds form in the intermediate angles. Increasing the inclination angle from 60° to 90° can have a positive effect on the cleaning efficiency (Ismail et al., 2012). A similar observation has been reported by earlier studies (Bilgesu et al., 2007; Ahmed et al., 2003) that reported the improvement of hole cleaning with the increase in inclination angle from 75 to 90 degrees. On the other hand, a recent study (Pandya et al., 2019) reported a mixed effect. Accordingly, the fluid rheology dictates the impact of inclination angle on hole cleaning performance.

Mohammadsalehi and Malekzadeh (2012) developed a model to predict the minimum flow rate required for hole cleaning using Larsen and Moore models. It was observed that increasing the inclination angle increases the required minimum flow rate for removal. The effect of hole inclination on hole cleaning is showed in Table 2.9.

Table 2.9 The effect of angle of inclination on hole cleaning.

Key Factor	Range	Drilling fluid	Cuttings Size / Type	Findings	Reference
Hole Angle	87^o and 90^o	WBDF PAC Solution	3.175 mm crushed sandstone cuttings with a specific gravity of 2.56.	Increasing the inclination angle increases the bed height. The increased angle enhances cuttings accumulation.	Peter et al., 2007
	Region 1 (0 to 45°), Region 2 (45 to 55°) and Region 3 (55 to 90°).	Water and WBM formulated with bentonite	6.35 mm drilling Carthage marble.	Increase of angle results in a reduction of cleaning rate, the effect has a larger magnitude in laminar flow. Worst cutting transport is observed at 40 - 45 degrees.	Okrajni and Azar, 1986
	60^o, 70^o, 80^o, and 90^o	Water and WBM formulated with bentonite, barite, CMC	1.7 mm Coarse sand particles	The increase of angle increases the removal of cuttings from the wellbore. The trend was similar for all angles at different velocity and different viscosities.	Ismail et al., 2012
	60^o, 75^o, and 90^o	The CFD model considered different fluids	3 and 8 mm	Increasing the angle from 75^o to 90^o increases the cuttings transport by a factor of 2 and 2.5 for 3 mm and 8 mm, respectively.	Bilgesu et al., 2007

Key Factor	Range	Drilling fluid	Cuttings Size / Type	Findings	Reference
	70^o - 90^o	The model considered incompressible non-Newtonian fluids with density 8.33 to 12.5 ppg	Cuttings size range from 0.0457 to 5.99 mm and cuttings density varies from 2.3 to 3.0 sg.	Bed thickness is observed to be almost constant during all angles of inclination. The relation of bed area to angle is approximately null.	Ozbayoglu et al., 2009
	46^o and 90^o	CFD Model: a combination of Larsen's & Moore's model	0.021 and 2.59 g/cm^3 density of cuttings	Increasing the angle from 46^o to 90^o at specific plastic viscosity results in a reduction in the required flow rate for cleaning.	Mohammadsalehi and Malekzadeh, 2012

2.3.5. Pipe rotation speed

The rate of cleaning of the settled cuttings was observed to increase as pipe rotation speed increases, especially at high inclination angles (Okrajni & Azar, 1986). The pipe rotation can cause secondary flows known as Taylor vortices. The vortices cause the frictional pressure loss to increase, thus it increases the shear stress on the cuttings bed surface. The resulted shear stress would eventually enhance the cutting removal (A. Saasen & Løklingholm, 2002). Table 2.10 shows the effect of drill pipe rotation on drill cuttings transport.

Table 2.10 Effect of drill pipe rotation on the drill cuttings transport.

Range	Drilling fluid	Cuttings Size/Type	Findings	Reference
0-180 RPM	Water and WBDF 0.15 % PHPA and 5% bentonite + PHPA	3.175 mm spherical ceramic balls with a specific gravity of 2.4.	Various flow rates were used: 30-70 m^3/h; 10 increments at an angle of 60°. Rotation improved cuttings transport. In addition to mechanical work which disturbs the cuttings bed.	Naganawa, 2013
0-150 RPM	Water and WBM formulated with bentonite	6.35 mm drilling Carthage marble.	Increasing the pipe rotation improve cuttings transport due to induced turbulence in addition to the mechanical influence on the cuttings bed. The effect is more significant at high angles" 55 to 90°.	Okrajni and Azar, 1986
0,30,60 RPM	The CFD model used is applicable for different fluids	3 and 8 mm.	Pipe rotation increased cuttings transport for all flow rates. However, the impact was more significant for small particles	Bilgesu et al., 2007
0,60,120 RPM	Water + CMC + XC and Water + CMC	1.7 - 2.0 mm silica sand.	Pipe rotation shows a great effect on the cutting transport, rotation of the pipe enhances the transport. The effect of the pipe rotation seems to be negligible as the hole size increase	Peden et al., 1990
0,50,100 ,150 RPM	Herschel-Bulkley fluids Foams 80 and 90 % quality	6.35 mm spherical sandstone particles with a density of 2.65 g/cm^3.	The effect of pipe rotation is minor in concentric annuli as compared to eccentric annuli. However, as the pipe becomes more eccentric the rotation speed effect becomes more significant. High RPM leads to lower cuttings concentration in the annuls	Heydari et al., 2017
0,25,50 RPM	SBM-invert emulsion (1.27/ml)	1.2 mm sand particles.	Increasing the pipe rotation from 0 to 25 RPM showed a huge increase in cuttings removal for all fibers concentrations at horizontal configuration. The pipe rotation needed further increase up to 50 RPM to show a significant increase in cutting removal efficiency at inclined (72°) configuration.	George et al., 2014

2.3.6. Eccentricity

The pipe eccentricity has a negligible effect on hole cleaning at low inclination angles (0° - 55°) for both turbulent and laminar flows (Okrajni & Azar, 1986). The effect becomes more noticeable at higher inclinations (55°- 90°). The eccentricity creates two regions in the flow cross-section: wide and narrow regions. The pipe causes the fluid to flow rapidly in the wide region while it causes the fluid to flow slowly in the narrow region. With drillstring rotation, the wall and pipe effects become complicated causing a reduction in flow speed at a given pressure gradient. The rotation of the pipe causes the fluid to move in a helical path from the narrow stagnant region to the high-speed wide region or vice versa. The flow creates an alternating acceleration to the fluid, resulting in an increase in frictional pressure loss (A. Saasen & Løklingholm, 2002).

In inclined and horizontal wellbores, drill pipe eccentricity has a detrimental effect on cuttings transport (Heydari et al., 2017; Walker and Li, 2008). However, eccentric annulus with the wide area on the bottom and narrow area on top (i.e. annulus with negative eccentricity) showed improvement of cuttings transport (Peden et al., 1990), even though annulus with negative eccentricity rarely occurs in practice.

2.3.7. Cutting size

Increasing cutting size from 3 to 8 mm showed a noticeable difference in cutting transport (Bilgesu et al., 2007). Large particles were easier to transport at all flow rates. Fluid contact area increases with cutting size, which eases the application of drag and lifts forces on particles (E. M. Ozbayoglu et al., 2009). In spite of this, other studies reported different observations. According to Peden et al. (1990), smaller cuttings are easier to transport at all angles using low viscosity fluid. Nevertheless, larger cuttings are more efficiently transported using hi-viscous fluid at low inclinations (0^o - 50^o). Walker and Li (2008) conducted hole cleaning studies using solids with different diameters (fine, intermediate and coarse particles) and water as drilling fluid in a horizontal configuration. The intermediate (0.76 mm) particles were found to be harder to remove than the fine (0.15 mm) and coarse (7 mm) particles. A similar observation with polymeric fluid was reported by Ahmed et al. (2003).

2.3.8. Mud weight

Mud density is useful to stabilize the wellbore and prevents formation fluids from invading the wellbore. In addition, the density is vital for enhancing cuttings suspension/lifting. However, increasing density causes the ROP to decrease which increase the drilling cost (Mohammadsalehi & Malekzadeh, 2012). In horizontal configuration, tests showed the improvement of cuttings removal by 50 % when fluid density increased from 7 to 13.7 lbm/gal (Yu, Takach, Nakamura, & Shariff, 2007).

The empirical hole cleaning model (E. M. Ozbayoglu et al., 2009) showed the moderate effect of fluid density on cuttings bed development. Fluid density contributes to inertial and buoyancy forces. The increase in density results in an increase in Reynolds number and the turbulence, thus better cuttings transport. Moreover, fluid density increased the buoyancy force, which improves the lifting force resulting in better hole cleaning.

2.3.9. Rate of penetration

The Rate of Penetration (ROP) is an important parameter for a drilling project timeline. Nevertheless, high ROP would generate more cutting, which results in the need for effective cutting removal (Mohammadsalehi & Malekzadeh, 2012). Increasing ROP at a constant flow rate results in an increase in cuttings concentration. Hence, the flow rate must be increased together with ROP to compensate for the increase in cuttings generation. It is worth to mention that increasing the flow rate does not totally offset the effect of increased penetration (Bilgesu et al., 2007). The effect of rate of penetration on hole cleaning is obvious if other parameters are kept constant. The increase in the rate of penetration increases the generation of cuttings; thus, increases the cuttings concentrations in the annuals. In the presence of pipe rotation, an increase in ROP has less impact on hole cleaning as compared to the case without pipe rotation. In addition, ROP is highly related to the fluid flow rate. A high rate of penetration requires a higher flow rate in order to minimize the effect of increased cuttings generation (Heydari et al., 2017).

2.3.10. Hole size

Hole size is an important parameter which has an influence on cuttings transport and its interference with other parameters, Cuttings with size ranging from 1.7 to 2.0 mm were used with highly-viscous water-based mud (CMC and XC polymer) to test the hole size effect (Peden et al., 1990). Increasing the annulus size at all angles affected both cuttings suspension and rolling. The minimum transport velocities of both increased as the hole size was increased. Studies regarding hole size are limited. However, it can be interpreted that hole size is directly related to fluid velocity; as the hole size decreases, the velocity increases, resulting in a positive effect on the cuttings removal.

2.4. Guidelines for selecting fluids sweeps for horizontal well cleaning

In horizontal wells, high viscous sweeps are not recommended with non-rotating drill string because higher fluid velocity is required to initiate the movement of bed particle. Due to pipe eccentricity and the formation of stagnant flow regions, cuttings deposition easily happens in horizontal wells. Drill string rotation is necessary in this case to direct the deposited solids toward the high-velocity wide region where less amount of cuttings are present due to effective solids removal (Power et al., 2000; Sandeep Gopal Valluri, Miska, Yu, Ahmed, & Takach, 2006). On the other hand, high density (weighted) sweeps have the competency to improve cuttings transport because of strong buoyancy force, which offsets the gravitational force in highly deviated wells and reduces the settling tendency of the cuttings. However, to improve the transport of large solids and decrease the torque, conventional weighting materials should be replaced with fibers and plant-derived materials. Abrasive materials are able to erode the silt beds where cuttings settle down combined with barite in case of sagging. Cuttings shape and size should be carefully considered because stuck pipe problems in highly deviated wellbores result in the deposition of fines because coarse cuttings can be removed using conventional circulation and pipe rotation. Combining weighted sweeps with abrasive materials assisted the removal of fine cuttings (Power et al., 2000).

High-density sweeps should be carefully used in deep offshore drilling because of the narrow mud window. Suspended cuttings affect friction and hydrostatic pressure head, and hence ECD should be considered. In the industry, less than 1 % of annular cuttings is recommended to avoid the side effect of excessive ECD with pipe rotation and circulation time (Power et al., 2000; Surjaatmadja & Rosine, 2005).

The hole cleaning performance of drilling fluids is greatly affected by drill string rotation. Thus, an integrated design that considers the effect of both fluid sweeps and downhole equipment on cuttings transport is recommended.

2.5. Laboratory techniques used to evaluate formulation stability and cuttings settling

Stability of each component in a mud formulation can be investigated using thermogravimetric analysis (TGA), Scanning electron microscopy (SEM), and x-ray diffraction (XRD) (X Yang, Shang, Liu, Cai, & Jiang, 2017). Water activity experiments are conducted for shale formation to ensure the compatibility between the drilling fluid and the formation (Xian-yu Yang et al., 2015). Moreover, filtration experiments are performed using a high-pressure filter press. Lubricity tests are essential for long horizontal wells to avoid high friction factors between the drill pipe and the hold/casing.

The settling of drill cuttings can be simply tested using Plexiglas cylindrical column equipped with a high-speed camera (Elgaddafi et al., 2012; Qingling et al., 2018). Moreover, a spectrophotometer has also been recently used to detect cuttings dispersion in a drilling fluid compared to a standard medium such as water (Lyu et al., 2019). The main technique to evaluate the cuttings removal efficiency is the flow loop experiment. Lab-scale flow loops are used to evaluate the effect of wellbore inclination on cuttings transport. The inner pipe can be static or rotating; meanwhile, eccentricity can be maintained. Flow loops are often designed to be capable of orienting to any inclination angle from vertical to horizontal to represent all scenarios of a deviated hole. Various sizes of flow loops have been built, ranging from lab-scale to field-scale. Moreover, advanced flow loops have pipe-viscometer sections to study hydraulics and rheology. Horizontal separator and hydrocyclone are used in some flow loops to recover the cuttings (Ahmed and Takach, 2009; Xu et al., 2013).

Figure 2.4 Field-scale flow loop (Xu et al., 2013).

Recent advances in flow loop designs show the adaptation of multiphase facilities such as using multiphase pumps, air compressors, heat exchangers, solids injectors and collectors, and foam generator (Chen et al., 2007; Gumati et al., 2013).

Rheological properties such as plastic viscosity, gel strength, yield point are measured at ambient and elevated temperatures to investigate the effect of various parameters on hole cleaning. Foam generator viscometer is used to measure the rheological properties of foams (Duan, Miska, Yu, Takach, Ahmed, & Hallman, 2008). Rotational viscometers and rheometer are used to measure the rheology of drilling fluids by placing the fluid sample between two concentric cylinders. Moreover, viscosities, yield point, and gel strength of the drilling fluids are measured according to the American Petroleum Institute (API) standard (Song et al., 2016a).

Various materials have been used to simulate drill cuttings, such as glass beads, river peal gravels, and coal (Lyu et al., 2019). Sand is the most commonly used among these types. Spheres having various densities made of titanium, aluminum, and steel with diameters between 1 to 10 mm are also used in flow loop investigations (Qingling et al., 2018). The pressure transmission apparatus investigates the interaction between different drilling fluids with shale.

2.6. Gap Analysis

The intensive research work has highlighted several gaps in the literature:

- Drilling sweeps tests and studies did not investigate fiber's aspect ratio effect on FCF stability and cutting suspension and carrying capacity performance.

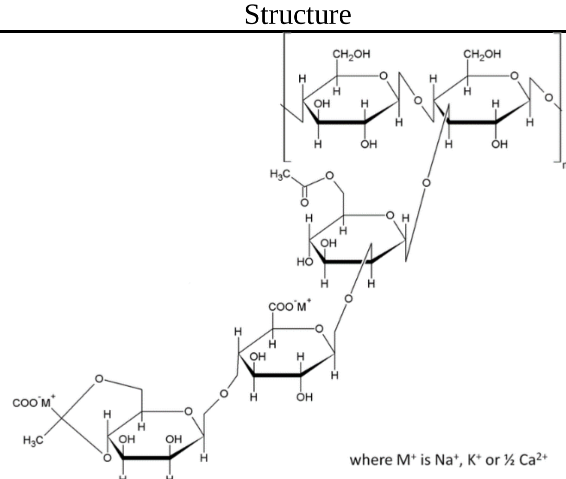
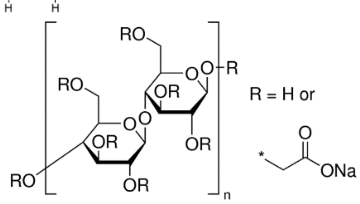
- Studies of settling behavior and deposition of fine cuttings with size less than 0.5 mm are very limited.
- No studies were conducted to correlate the electrokinetic of the base polymer (surface charge) and cuttings suspension or transportation.
- Numerous published work is done either on a lab-scale or flow loop scale. The literature lacks in pilot-scale experimental studies for cutting stability and settling behavior in different FCFs, mimicking severe field drilling conditions. Pilot-scale could save cost and time by avoiding working directly on sophisticated flow loop systems.

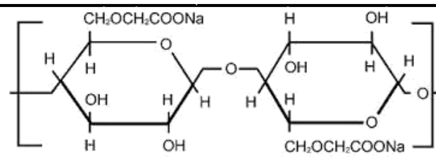
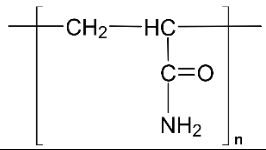
Chapter 3: Materials and Methods

3.1. Materials

White virgin polypropylene monofilament synthetic fibers with a specific gravity of 0.91 and a melting point around 163°C – 177°C were obtained from FORTA, USA. Fibers utilized were of two aspect ratios: 3 or 12.5 mm in length and 100 µm in diameter. Various polymeric water-based drilling fluids were prepared. Table 3.1 shows the structure and source of each base polymer used; all solutions were prepared using deionized water unless mentioned.

Table 3.1 Polymers structure and source used for drilling fluids base formulation.

Name	Structure	Source
Xanthan Gum (XG)		Arshine pharmaceutical co. ltd, Hunan, China
Carboxy Methyl Cellulose Sodium (CMC)		Research lab fine chem industries, Mumbai, India

Name	Structure	Source
Polyanionic Cellulose (PAC-R)		MI SWACO, Texas, USA
Non-ionic Polyacrylamide (PAM)		SNF, Andrézieux, France

Real cuttings were obtained from wells located in Oklahoma, United States. In addition, borosilicate glass beads of different sizes (1-2.5 mm) were obtained from Sigma- Aldrich Company Ltd., Germany.

3.2. Methods and Experimental procedures

3.2.1. Polymeric fiber-containing water-based solutions preparations procedure

Predetermined amounts of polymer were weighted and steadily added to deionized water in large beakers. The gradual addition of polymer powder was carried out while mixing (IKA mixer, Germany) (Figure 3.1) at 600 rpm for 30 minutes, followed by prolonged 1-3 hours mixing at higher 600-1200 rpm; mixing time and shearing intensity varies based on the solubility and concentration of the polymer. The suspensions were left to hydrate for 24 hrs. Mixing speed was maintained high enough to avoid lump formation while avoiding excessive mixing; that introduces air into the suspension.

Following hydration, polymeric suspension underwent 10 minutes of agitation to ensure homogeneity. Subsequently, fibers were added to the polymeric mixture while mixing at

450 rpm for 2 minutes. To ensure good fibers dispersion, the fibers' clumps were separated manually using a spatula before their addition to the polymer suspension. Some fibers were dyed with red color to resolve the visibility problems associated with a few polymers such as XG suspension.

Figure 3.1 EUROSTAR 20 digital mixer (IKA, Germany).

3.2.2. Solids Characterization

3.2.2.1. Scanning Electron Microscope (SEM)

SEM was used to generate images that illustrate the microstructure and texture of cutting solid particles. Particles were left to dry in an oven at 85°C for 24 hours. The SEM tests were then conducted using Nova Nano SEM 450, FEI.

3.2.2.2. Sieving of Clay Sample

Dry cuttings were sieved by a Sieve Shaker (Gilson, USA) (Figure 3.2 (a)) using different sieve sizes (number: 35, 60, 120, and 230) to separate the desired particle sizes (0.063 to 0.500 mm).

3.2.2.3. Particle Size Distribution (PSD)

Sample of sieved 0.500 mm cuttings was analyzed by particle size distribution, using Mastersizer 3000 (Malvern Instruments Ltd., UK) (Figure 3.2 (b)).

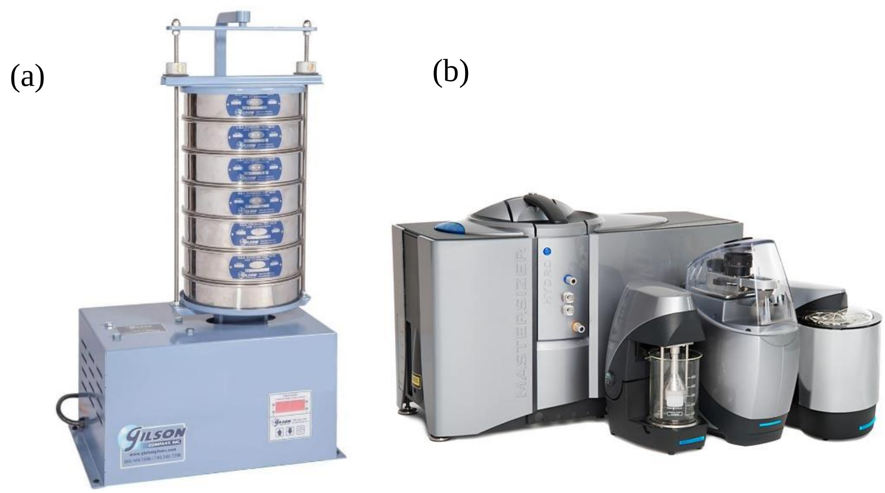


Figure 3.2 (a) 8in Sieve Shakers (Gilson, USA) and (b) Mastersizer 3000 (Malvern Instruments Ltd., UK).

3.2.3. Fiber's Stability Assessment Method

In this study, fibers stability within the formulation is assessed by the amount of fibers that remain in suspension for 24 hours at ambient and elevated temperatures. A stable fluid is capable of suspending fibers throughout its volume for an extended time (Figure 3.3 (a)). In contrast, the unstable suspension is unable to retain fiber in dispersion form for a long period, allowing the migration of fiber particles to the upper section of the suspension column (Figure 3.3 (b)). A similar approach was established by George et al. (George et al., 2012), where the upper 20% of the graduate cylinder was identified as an accommodation zone for migrating fiber particles. In the unstable formulation (Figure 3.3 (b)), the accommodation zone (fiber bed) volume increases as more fiber particles migrate and its concentration also increases. The addition of polymer in water reduces fiber migration. Therefore, fibers suspension of pure water is used as a baseline reference for the assessment of fibrous fluid stability. In 250 ml-graduated cylinders, different fibers suspension samples were prepared and left in the oven for one hour under static condition, and then the fiber bed volume was recorded as reference (Table 3.2 and Table 3.3).

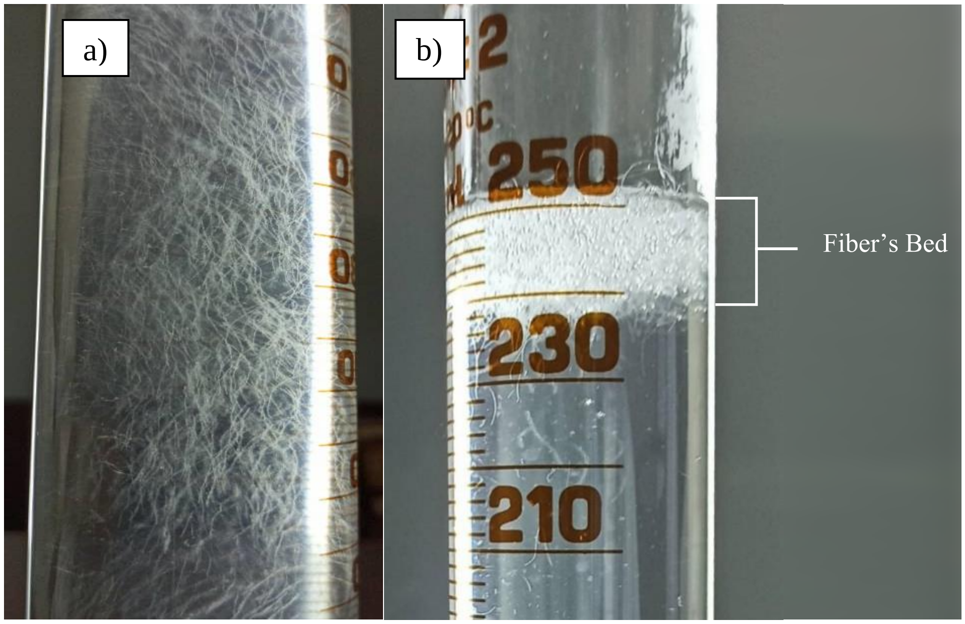


Figure 3.3 Fibrous suspensions after one hour of quiescent period: (a) stable suspension; and (b) unstable suspension.

Table 3.2 Fiber bed formed in water using 3.00 mm long fibers.

Fiber Concentration (Wt.%)	Reference Bed Volume (mL)		
	25 ºC	52.5 ºC	80 ºC
0.02	5.0	2.5	2.0
0.04	6.5	5.0	4.0
0.05	7.0	5.8	5.0
0.06	7.2	6.5	6.0
0.08	10.0	7.5	6.4

Table 3.3 Fiber bed formed in water using 12.5 mm long fibers.

Fiber Concentration (Wt.%)	Reference Bed Volume (mL)		
	25 ºC	52.5 ºC	80 ºC
0.02	40.0	16.0	12.0
0.04	65.0	23.0	16.5
0.05	68.5	29.5	20.3
0.06	72.0	36.0	24.0
0.08	88.0	41.0	24.5

Equation (1) expresses the stability of fibrous suspensions (S_S) in terms of the tested fiber Bed Volume "**BV**" (ml) and Total Suspension Volume "**TV**" (ml); where BV is the measured bed volume in the polymeric solution and TV is testing cylinder volume. Water is used as the reference fluid expressed as the reference bed volume (**RBV**) which was presented in Table 3.2 and Table 3.3. Accordingly, suspension relative stability is considered to be 0% when the base fluid is water. In contrast, 100% stability is when the suspension is fully stable with zero bed volume.

$$S_S = \frac{BV - RBV}{TV - RBV} \quad (1)$$

3.2.4. Fiber's Stability Regression Model Experimental Design

Response Surface Methodology (RMS) and Box-Behnken Design (BBD) are experimental design statistical tools that are used for evaluating complex multi-variables systems, analyzing the two-variables interaction effect, and optimizing the response of multiple variable processes (Ferreira et al., 2007; Robinson, 2014). The main advantage of the RSM-BBD approach is performing an analysis of several parameters with fewer experimental trials than other methods.

For the stability regression model, three factors: base fluid concentration, fiber concentration, and temperature were investigated in various polymeric water-based fluids (CMC, PAM, and XG suspensions) with fiber lengths of 12.5 and 3 mm. The upper and lower limits for each factor are summarised in Table 3.4. Based on the BBD method, 15 sets of experimental trials (Table 3.5) were required for each fiber length. In total, 90 experimental trials were required considering three different polymers and two fiber lengths. Experimental runs were randomized to minimize the error and exclude any bias, while all conditions were kept constant.

Table 3.4 Regression factors' upper and lower limits**.**

	Factor Levels			
Factor	Symbol	low (-1)	central (0)	high (+1)
Base Fluid polymer Concentration (vol.%)	A	1	4.5	8
Fiber (wt. %) *	B	0.01	0.045	0.08
Temperature (°C)	C	25	52.5	80

*Two lengths of fibers: 3 and 12.5 mm

Table 3.5 Three factors Box-Behnken experimental design.

Run	Polymer Concentration (A)	Fiber Concentration (B)	Temperature (C)
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

A model of second-order polynomial equations was used to predict the relationship between the factors and stability as a function of polymer concentration, fiber concentration, and temperature. The equation is shown in Eq. 2:

$$Y = n_0 + n_1 X_A + n_2 X_B + n_3 X_C + n_4 X^2_A + n_5 X^2_B + n_6 X^2_C + n_7 X_A X_B + n_8 X_A X_C + n_9 X_B X_C \quad (2)$$

where Y is the response variable; A, B, and C are independent variables; n_0 is a model constant variable; n_1, n_2, and n_3 are linear coefficients; while n_4, n_5, and n_6 represent the quadratic effects; n_7, n_8, and n_9 represent interaction effects of the model. All response results used for regression are presented in Table 4.1

3.2.5. Total Suspended Solids (TSS) Measurements

Particles ranging in size from 0.1 to 1.2 μm are usually defined as colloids, while particles with sizes larger than 1.2 μm are defined as Total Suspended Solids (TSS) (Berho et al., 2004). The working mechanism of UV-vis spectrometers is based on light-particles interaction. It functions through light scattering techniques. Such devices are used for TSS measurements. Light-particle interaction is classified into absorption and diffusion. Absorption takes place when particles are subjected to light and absorb light prohibiting it from passing through. The second mechanism of light scatting is diffusion, which is composed of diffraction, reflection, and refraction (Azema et al., 2002). Previous studies (Berho et al., 2004; Rieger et al., 2004) confirm that measurements of TSS using spectrometer are reliable and can be very precise. Inevitably, there might be some inaccuracies due to the optical characteristics of some solutions such as xanthan gum. Despite this and even if inaccuracies persist, the results are still qualitatively reliable (Berho et al., 2004; Rieger et al., 2004).

Measurement of TSS concentration is required for comparative evaluation of the characteristics of cuttings suspensions in different solutions (Table 3.6). Therefore, a set of test procedures were established to achieve this objective. A laboratory spectrophotometer HACH DR3900 (Figure 3.4) of 320 -1100 nm wavelength was employed in quantifying TSS concentration with an accuracy of ±1.5 nm. The TSS tests were performed in a 100 ml graduated cylinder with 0.03g of cuttings; the size of cuttings was 0.063mm; this size was used in all TSS experiments unless mentioned. To unify the measurement of TSS, time and location of measurements were fixed; the time was varied for each set of experiments, yet the location was fixed throughout the study, and the top 20 ml was extracted using a pipette. Subsequently, fiber-free samples were placed in the spectrometer's cuvette cells, and TSS were measured.

Figure 3.4 Spectrophotometer DR3900 (HACH, USA).

Table 3.6 Fluid formulations used in TSS measurements.

Sweep fluid	Polymer concentration (wt.%)	Fibers concentration (wt.%)
XG	0.1,0.2,0.4,0.6, and 0.8%	0.02,0.04,0.06, and 0.08%
CMC	0.1,0.2,0.4,0.6, and 0.8%	0.02,0.04,0.06, and 0.08%
PAC	0.1,0.2,0.4,0.6, and 0.8%	0.02,0.04,0.06, and 0.08%

In order to identify the error associated with TSS measurements, the established test procedure reproducibility was assessed. Two identical settling experiments were conducted, less than 10 % difference was found between readings.

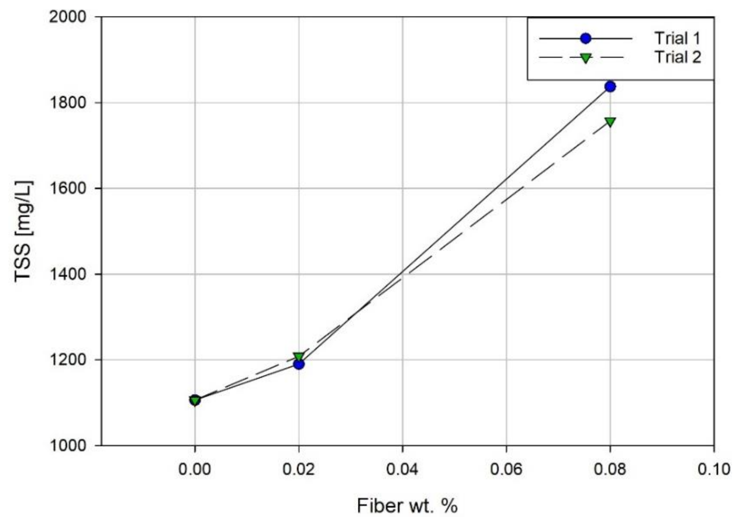


Figure 3.5 TSS reproducibility measurements attained from two settling cylinders with CMC solution with 0.063 mm.

3.2.6. Zeta Potential measurements

Colloidal particles acquire an electric double layer over their surface due to the presence of charges on the surface. Ion dissolution, ion adsorption, and ionization are the key phenomena leading to this process. An electric double layer is developed due to the existence of two primary layers in its structure – the inner Stern layer and the outer diffuse layer (Figure 3.6).

Colloidal particle stability is typically described by the incidence of repulsive electrical charges on the surface of the particle. Prediction of colloidal particle stability can is accomplished through the interaction forces between the particles. In the presence of predominate repulsive forces, the colloidal system will remain dispersed. Contrariwise, when the interface forces are of inefficient repulsion, the particles settle down and the suspension may become unstable. Particles of similar charges repel each other, so this repulsion needs to be lessened if destabilization is targeted (Nasser & James, 2006b, 2006a, 2007; Tadros, 1986, 1990). For particles undergoing aggregation, they have to overcome the force of repulsion by compressing the electrical double layer (Figure 3.6), which is controlled with the polymer concentration and electrolyte (Tadros, 1990). Aggregation of colloid particles may happen through polymer particle adsorption (bridging), charge neutralization, and polymer-particle surface interaction (Nasser & James, 2006b). The possibilities of having stable or unstable dispersion can be accurately determined through the zeta potential measurements. These measurements can reflect the degree of polymer anionic charge density, defined henceforth as suspension "anionicity".

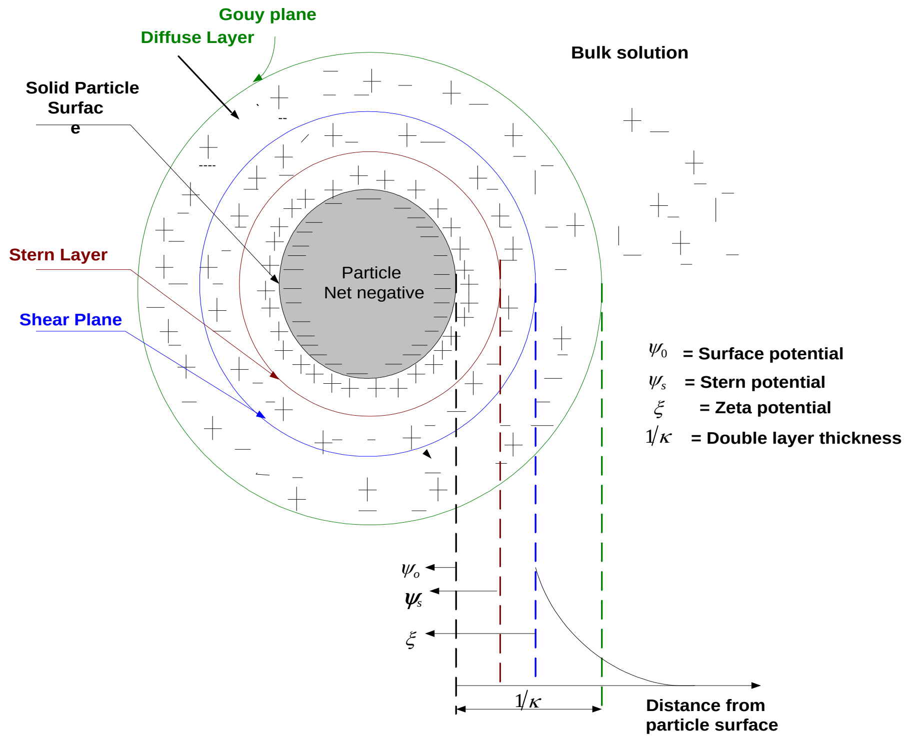


Figure 3.6 Schematic illustration of the charge distribution around a particle.

The surface zeta potentials of the cuttings in the suspensions were measured using Zeta sizer Nano ZS (Malvern Instruments Ltd., UK) at room temperature. Samples were prepared with a specified concentration of polymer in a 100-ml beaker. Then, cuttings were added to the polymeric suspension while mixing. Lastly, the suspension was transferred to the zeta sizer capillary cell to take measurements.

Figure 3.7 Zetasizer Nano ZS (Malvern Instruments Ltd., UK).

3.2.7. Rheological Measurements

The flow behavior of base fluids was evaluated using a strain-controlled rheometer (Anton Paar MCR 302, Austria). Polymeric suspensions were prepared with concentrations of 0.1, 0.25, 0.5, 0.75, and 0.12 wt.% as elaborated in the previous section; a rheometer with cup and bob geometry was used for the rheological testing, samples were carefully loaded and trimmed into the geometry. The rheometer torque resolution is 1.0×10^{-10} N·m, and the torque ranges from 3.0×10^{-8} to 2.0×10^{-1} N·m. The cup and bob measuring geometry dimension are as follows: cone angle -120°, measuring bob radius – 13.334 mm, measuring cup radius –14.461 mm, and measuring gap -1.127 mm. The tests were performed at 20, 52.5, 80°C ± 1.0°C and the shear rate was varied from 0.01 to 1000 s^{-1}.

Figure 3.8 Anton Paar Rheometer Model MCR 302.

3.2.8. Lab-Scale Settling column

A pilot-scale settling column was designed and manufactured to mimic field drilling operations. The column of a cylindrical geometry was surrounded with cuboid to eliminate the distortion happening due to the curved system (Figure 3.9).

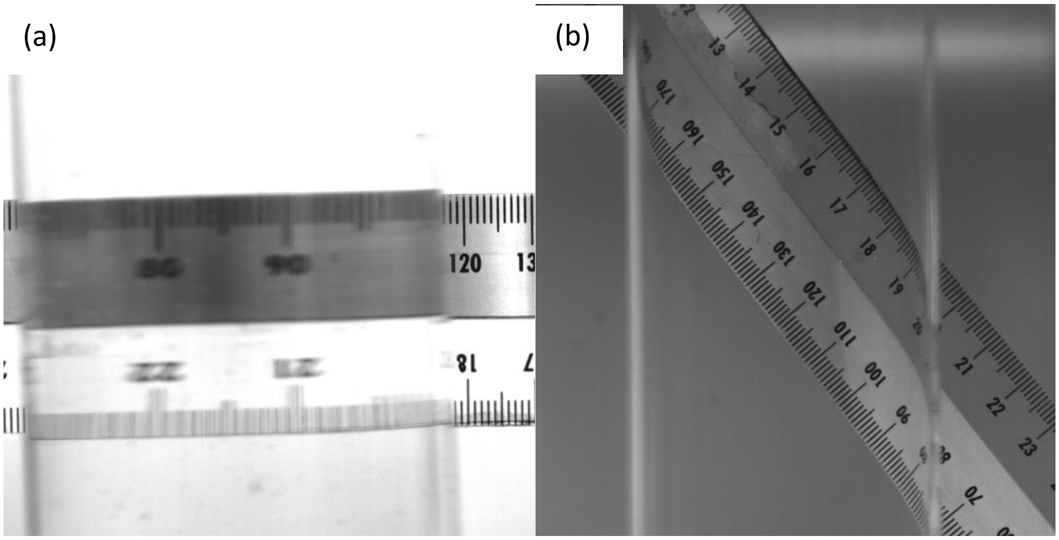


Figure 3.9 imaging without (a) and with (b) surrounding cuboid glass.

The settling column height and diameter are 150 cm and 19.5 cm, respectively. Rotating shaft of 1 HP and 900 RPM capacity is attached to an inner column of 9 cm diameter and 10 cm bit of irregular surface (Figure 3.10 & Figure 3.11). The total column volume is 0.0354 m^3 (35.4 L). The discharge point located at the bottom of the column is controlled by a manual valve. A Digital high-speed camera (Photon SA3, Japan) is utilized to capture particle movement inside the column.

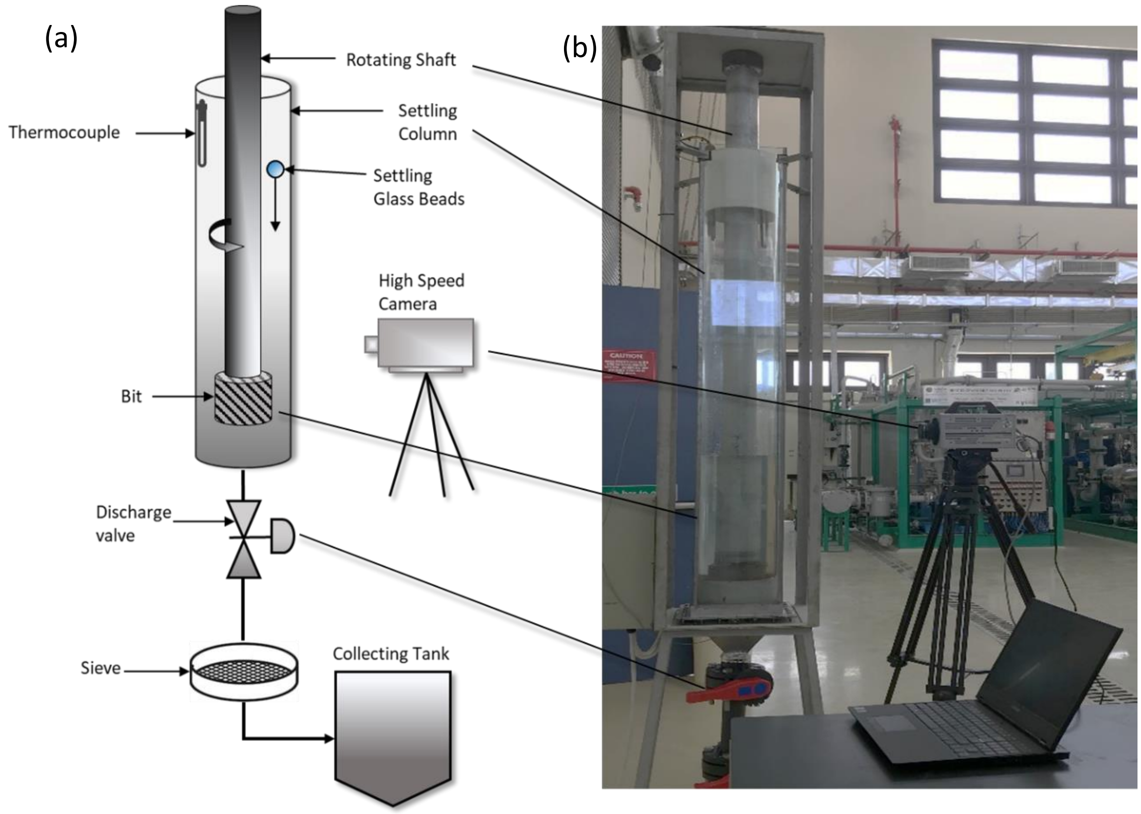


Figure 3.10 Schematic (a) and picture (b) of settling column.

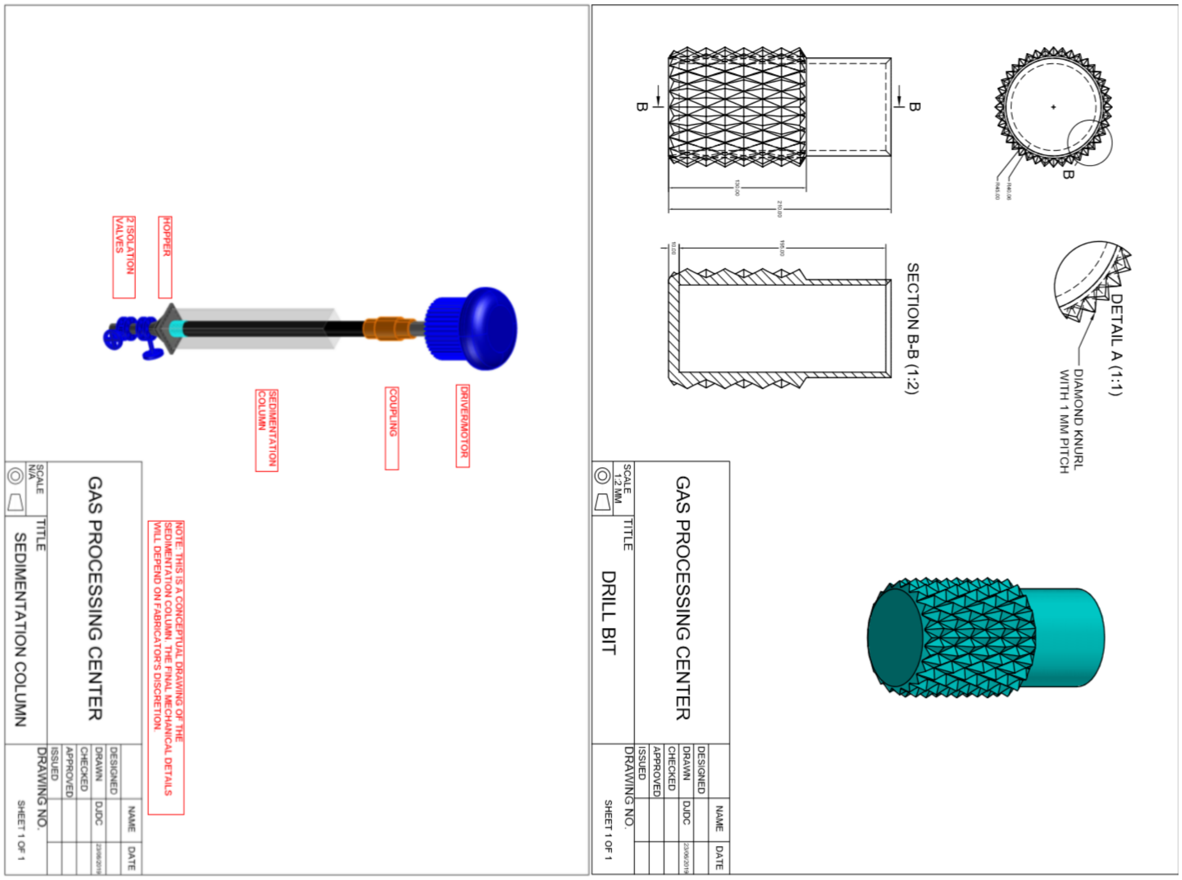


Figure 3.11 Design of settling column and drill bit.

Settling column experiments were conducted at various times and with a range of fiber concentration. After a prespecified time, 20 percent of the total volume is discharged through the bottom. The collected fluid is filtered, and glass beads weight after separation from fibers is recorded.

Chapter 4: Results and Discussion

4.1. Part A: Stability of Fibrous Dispersion Optimization using Response Surface Methodology and Box-Behnken Design

4.1.1. Introduction

Fibers are used in water-based drilling and completion fluid formulations. They are utilized in various applications such as well-fracturing and cutting transportation (Guo, Ma, Zhao, & Gao, 2015; M.-C. Li et al., 2020; Qingling et al., 2018). Cuttings transport (hole cleaning) depends on various parameters, including the viscosity and density of drilling fluid, flow rate, wellbore geometry, inclination angle, annular velocity, cuttings/particles shape, size, and weight. These parameters control the hole cleanout efficiency affecting operational cost (S. G. Valluri et al., 2006). Numerous studies (Elgaddafi et al., 2012; Elgaddafi, Ahmed, & Growcock, 2016; Guo et al., 2015; Jiang et al., 2016) have shown the effectiveness of fibrous drilling sweeps in horizontal and highly deviated wells. The addition of a small amount (concentrations less than 0.06 wt.%) of flexible monofilament fiber into drilling fluids has minimal effect on their rheological properties (Elgaddafi et al., 2016). Nevertheless, drilling fluids containing fibers with concentrations higher than 0.09% experience significant changes in rheological properties. Adding 0.4% fiber into hydroxypropyl guar gel increased fluid viscosity by three orders of magnitude (Guo et al., 2015). With increasing fiber concentration, consistency index "*K*" increased and fluid-behavior index "*n*" decreased, exhibiting a more rigorous shear thinning behavior of the fibrous fluid (Jiang et al., 2016). An experimental investigation conducted on spherical glass beads reveals that; the addition of a small amount (0.02-0.04%) of fiber to a 0.35% xanthan gum suspension reduced the particles settling velocity approximately by 50% (Elgaddafi et al., 2012).

The presence of fiber in drilling sweeps provides additional lifting capacity to remove cuttings that cannot be removed or lifted by conventional drilling fluids. In addition to the viscous drag of base suspension, the fiber drag aids the lifting of particles in suspension by forming a stable fiber network (Elgaddafi et al., 2016). The functionality of fibrous suspension is due to mechanical interaction between particles and the fiber network and hydrodynamic interactions between the suspension and particles. Within fibrous fluids, fiber particles disperse randomly within the fluid system in static conditions, resulting in a very disordered orientation (Figure 4.1 (a)). Whilst under dynamic conditions, a gradual increase in shear rate detangles some of the fiber networks and tends to orient fiber particles in the direction of the flow (Figure 4.1 (b)). Excessive increase in shear rate results in a parallel orientation of fiber particles and the flow field (Figure 4.1 (c)).

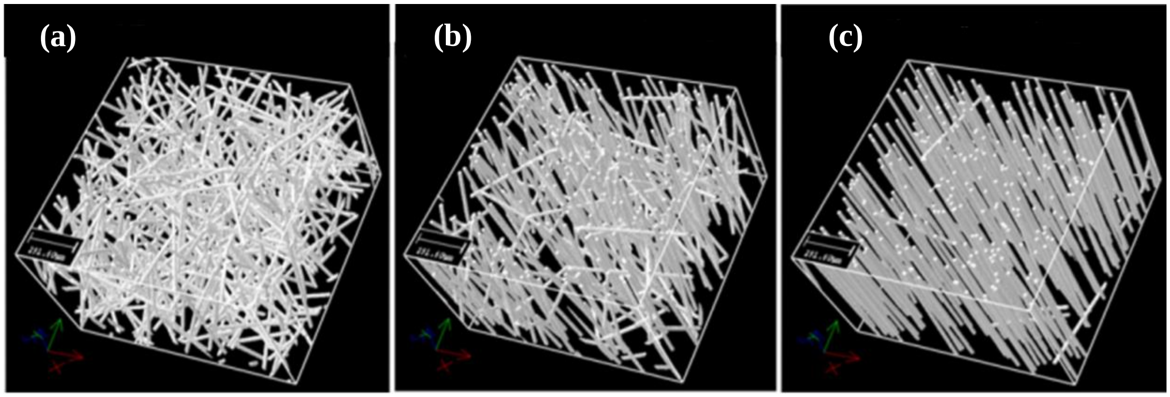


Figure 4.1 3D fiber orientation (a) low-degree, (b) mid-degree, and (c) high-degree of orientation (Pradhan, Das, Chattopadhyay, & Singh, 2012).

The main problem that complicates the use of fibrous fluids is the instability of the fiber network, which enhances the carrying capacity of the fluids. The stability of fibrous fluid is defined as the ability of fiber particles to remain dispersed in the fluid for an extended time. Only a few studies (George et al., 2012; Pradhan et al., 2012; Yamanoi, Maia, & Kwak, 2010; Yamanoi & Maia, 2010) have been performed to investigate the segregation behavior of fiber particles in drilling and completion fluids. For example, George et al. (George et al., 2012) established a mechanistic model that describes behavior fibers in a multiphase complex fluid system, with fluid rheological properties as the main modeling parameters. Fibers tend to horizontally orient while separating within the drilling fluid. High-density fluids require higher yield stress to prevent fibers from segregation. Low fluid behavior index "*n*" and high consistency index "*K*" are favorable for the stability of fibrous suspensions.

The implementation of computational fluid dynamic (CFD) and design of experiment (DOE) techniques enabled the identification of dominating factors affecting a specific parameter in field operations (Naderi & Khamehchi, 2017, 2018). Ensuring the stability of fibrous fluid is the first step toward efficient cuttings transportation and removal. Therefore, the objective of this work is to identify optimum conditions for fibers network stability in various base fluids, including suspensions of carboxymethyl cellulose (CMC), polyacrylamide (PAM), and xanthan gum (XG). Box-Behnken Design (BBD) and response surface methodology (RSM) are employed to obtain statistical models for fiber stability optimization and identification of their stability regions. Factors including polymer concentrations, fiber concentrations, fiber aspect ratio, and temperature are subjected to sensitivity analyses, highlighting their ascendancy and interactional effect on the formulation stability.

4.1.2. Stability Models Regression

Stability results are summarized in Table 4.1; data represent the experimental conditions and the observed stability in percentages.

Table 4.1 Box-Behnken experimental design responses data (%).

Run	Polymer Con. (X_A)	Fiber Con. (X_B)	Temperature (X_C)	12.5mm fibers			3 mm fibers	
				CMC (Y_1)	PAM (Y_2)	XG (Y_3)	CMC (Y_4)	PAM (Y_5)
1	1.0	0.02	52.5	0.9	1.7	82.9	1.0	0.4
2	8.0	0.02	52.5	100.0	100.0	100.0	100.0	100.0
3	1.0	0.08	52.5	42.6	28.2	66.5	0.0	0.0
4	8.0	0.08	52.5	100.0	100.0	100.0	100.0	100.0
5	1.0	0.05	25.0	6.3	0.0	100.0	0.0	0.0
6	8.0	0.05	25.0	100.0	100.0	100.0	100.0	100.0
7	1.0	0.05	80.0	9.0	13.8	0.0	0.0	1.2
8	8.0	0.05	80.0	100.0	100.0	100.0	100.0	100.0
9	4.5	0.02	25.0	100.0	100.0	100.0	100.0	100.0
10	4.5	0.08	25.0	100.0	100.0	100.0	100.0	100.0
11	4.5	0.02	80.0	100.0	28.6	100.0	98.4	99.0
12	4.5	0.08	80.0	100.0	77.8	100.0	97.5	97.9
13	4.5	0.05	52.5	100.0	100.0	100.0	100.0	100.0
14	4.5	0.05	52.5	100.0	100.0	100.0	100.0	100.0
15	4.5	0.05	52.5	100.0	100.0	100.0	95.9	97.5

A second-order polynomial regression model was generated to determine the relationship between the factors and the stability response Y_1, Y_2, and Y_3 of 12.5 mm fiber in CMC, PAM, and XG, respectively. The results are shown below:

$$Y_1 = -61.7 + 48.85 X_A + 231 X_B + 0.531 X_C -3.482 X^2_A + 3899 X^2_B - 0.00464 X^2_C – 99.4 X_AX_B - 0.0070 X_AX_C - 0.00 X_BX_C \quad (3)$$

$$Y_2 = -68.7 + 41.88 X_A + 892 X_B + 0.96 X_C - 2.68 X^2_A – 10761 X^2_B - 0.0181 X^2_C – 63.1 X_AX_B - 0.00359 X_AX_C + 14.9 X_BX_C \quad (4)$$

$$Y_3 = 136.8 + 3.62 X_A - 930 X_B - 0.77 X_C - 1.537 X^2_A + 6863 X^2_B - 0.082 X^2_C + 39.0 X_AX_B + 0.2597 X_AX_C - 0.0 X_BX_C \quad (5)$$

The coefficients of the regression equations with a positive sign indicate a synergistic effect, whereas the negative sign of the coefficients represents the antagonistic effect on the stability response (Das & Mishra, 2017). In other words, the coefficients with positive signs have a positive effect on stability, while terms with a negative sign are of negative impact. For instance, in Eq. 3, linear terms X_A, X_B, and X_C, and quadratic term X^2_B have positive signs, which reflects their influence toward increasing the stability. Other coefficients of the equation with negative signs such as second-order terms X^2_A and X^2_C have a negative effect on the response leading to a decrease in stability as these terms decreases.

The probability P-value is used to determine the significance of coefficients and the influence of the combined terms of interaction. Coefficients with p-values smaller than 0.05 tend to have a significant effect on the response (Tian, Hao, Xu, Yang, & Sun, 2017). Table 4.2 shows the regression terms and their corresponding p-values. For example, Y_1 model significant terms are n_0, X_A, X^2_A, and X_AX_B, where all insignificant terms could be removed without affecting model prediction.

Table 4.2 The regression coefficients and P-values 12.5 mm fibers.

	CMC (Y_1)		PAM (Y_2)		XG (Y_3)	
	Term	P-Value	Term	P-Value	Term	P-Value
n_{0*}	-61.7	0.000	-68.7	0.000	136.8	0.000
X_A**	48.85	0.000	41.88	0.001	3.62	0.031
X_B***	231	0.123	892	0.187	-930	0.758
X_C****	0.531	0.909	0.96	0.169	-0.77	0.104

	CMC (Y_1)		PAM (Y_2)		XG (Y_3)	
X^2_A	-3.482	0.000	-2.680	0.016	-1.537	0.098
X^2_B	3899	0.436	-10761	0.337	6863	0.535
X^2_C	-0.00464	0.436	-0.0181	0.193	-0.0082	0.535
X_AX_B	-99.4	0.047	-63.1	0.484	39.0	0.665
X_AX_C	0.007	0.872	-0.0359	0.710	0.2597	0.038
X_BX_C	0	1.000	14.9	0.219	0	1.000

* *n_0 regression constant, ** X_A polymer cont., *** X_B fiber conc., **** X_C temperature.*

The coefficient of determination, denoted as R^2, is the proportion of variance in the dependent variable ($Y_{1,\,2,\,\text{or}\,3}$). A unity value of R2 indicates high strength to the relationship between independent and dependent variables. Results show that the generated models correlation has high fitting values, with R2 values of 0.99, 0.95, and 0.91 for stability in CMC, PAM, and XG, respectively.

The same regression models were also applied for studying the 3 mm fibers stability in polymeric suspension. Y_4 and Y_5 are fiber stability percentage in CMC and PAM, respectively.

$$Y_4 = -43.74 + 49.896\,X_A - 38\,X_B - 0.012\,X_C - 3.9740\,X^2_A + 332\,X^2_B + 0.00006\,X^2_C + 2.41\,X_AX_B + 0.00000\,X_AX_C - 0.258\,X_BX_C \quad (6)$$

$$Y_5 = -46.21 + 50.350\,P + 14.7 + 0.0038\,T - 4.0004\,X^2_A - 84\,X^2_B + 0.000171\,X^2_C + 0.96\,X_AX_B - 0.00318\,X_AX_C - 0.317\,X_BX_C \quad (7)$$

Table 4.3 shows the coefficients of regression and p-value for each term. For CMC (Y_4) and PAM (Y_5) fluids, the most significant factors affecting the stability of fiber were polymeric fluid concentration (X_A) and its quadratic term(X^2_A). XG (Y_6) results for short fibers (3mm) showed total stability for all polymer concentrations and temperatures; therefore, model regression methods were not applicable. The R^2 values of the 3mm fiber stability regression models were relatively higher— 0.99 for both CMC and PAM, reflecting a high degree of significance of both models.

Table 4.3 The regression coefficients and P-values for the 3 mm fibers.

	CMC (Y_4)		PAM (Y_5)	
	Term	P-Value	Term	P-Value
n_0*	-43.74	0.000	-46.21	0.000
X_A**	49.896	0.000	50.350	0.000
X_B***	-38	0.704	14.7	0.671
X_C***	-0.012	0.419	0.0038	0.592
X^2_A	-3.974	0.000	-4.0004	0.000
X^2_B	332	0.740	-84	0.903
X^2_C	0.00006	0.958	0.000171	0.835
X_AX_B	2.41	0.770	0.96	0.866
X_AX_C	0.00000	1.000	-0.00318	0.613
X_BX_C	-0.258	0.805	-0.317	0.665

** n_0 regression constant, ** X_A polymer cont., *** X_B fiber conc., **** X_C temperature.*

4.1.3. Model Validation

The correlation plots of model predictions against experimental results for all responses Y1 to Y5 are shown in Figure 4.2 to 4.5. Estimation of the coefficient of determination indicates that the stability dependent variable can be predicted through modeled equations, employing the intended independent variables. Figure 4.4 shows the XG plot for one fiber aspect ratio, as the second aspect ratio showed almost total stability under all tested conditions. Thus, regression for the 3mm-fiber stability data was not feasible in XG suspension. Coefficients of determination reflect good model prediction against experimental runs for all present figures, with R^2 values larger than 0.90. All model predictions are bounded between 0 and 100 percentages as values above or below this range do not reflect any physical meaning.

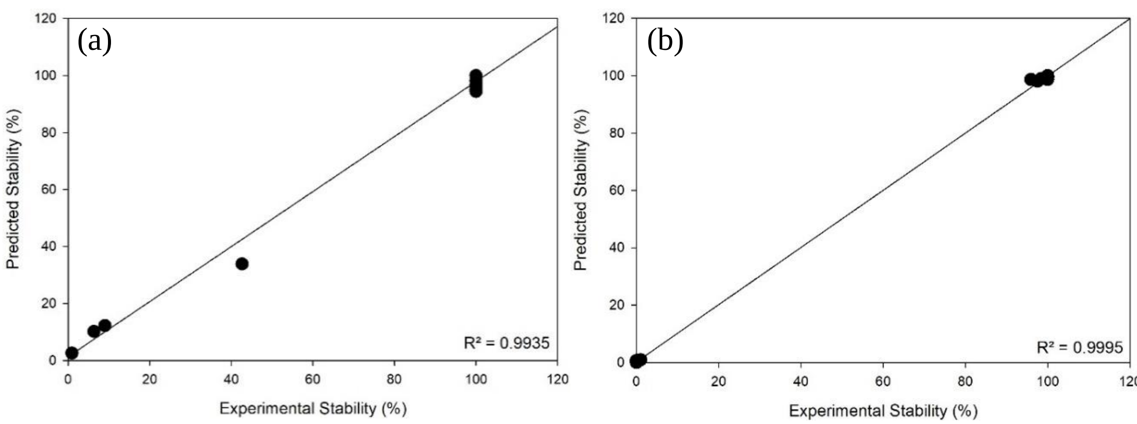


Figure 4.2 Predicted response of model against experimental response for the stability of fiber a) 12.5, b) 3 mm in CMC fluid.

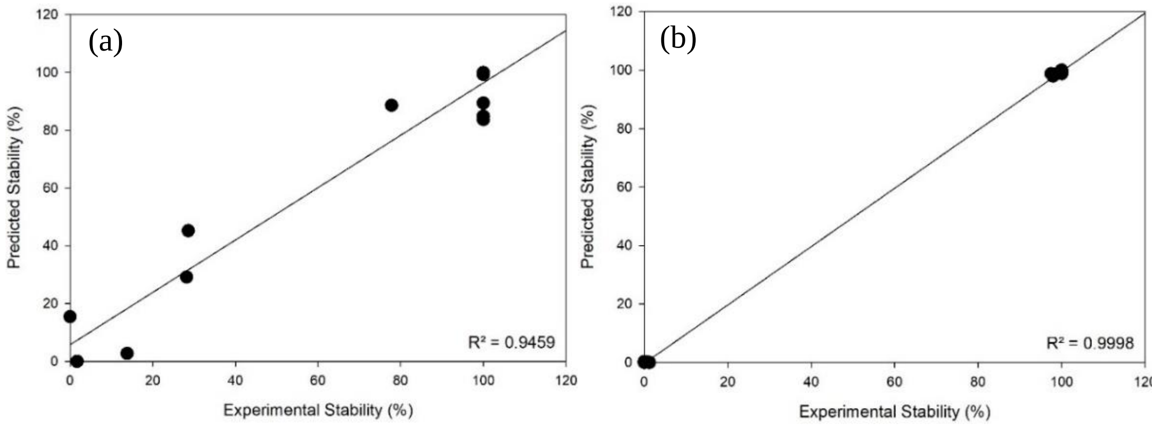


Figure 4.3 Predicted response of model against experimental response for the stability of fiber a) 12.5 b) 3 mm in PAM fluid.

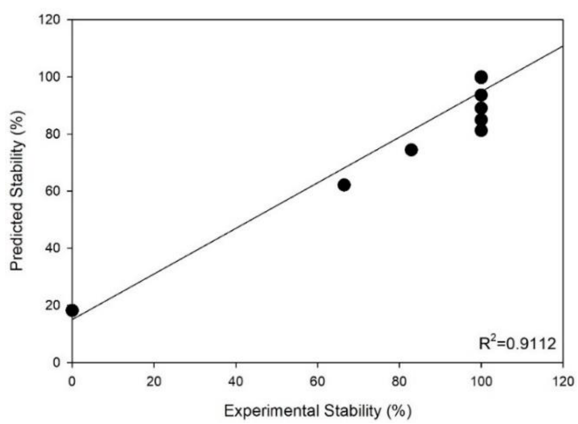


Figure 4.4 Predicted response of model against experimental response for the stability of fiber 12.5 mm in XG fluid.

Figure 4.2 and Figure 4.4 were plotted with 15 data points ranging from 0 to 100. Some points do not appear on the plot as they overlap other points, yet they are considered in best line fitting (e.g., Figure 4.4).

In order to further validate the generated models, four conditions (I-IV) were selected based on calculations of the center point between the high, mid, and low levels of factors (Table 4.4). The data points X_A, X_B, and X_C (polymer concentration, fiber concentration, and temperature) were inputted in the models, and the outputs were compared to experimental results conducted under the same conditions. The points are in descending order for all parameters. For instance, point I has the highest polymer concentration (7.1%), while point IV has the lowest concentration (3.6%).

Table 4.4 model validation data points.

Condition #	Polymer Conc. (X_A)	Fiber Conc (X_B)	Temperature (X_C)
Condition I	7.10	0.0725	73.10
Condition II	6.25	0.0650	66.25
Condition III	4.50	0.0500	52.50
Condition IV	3.60	0.0425	45.60

Stability predictions were obtained using equations 3 to 5 for 12.5 mm fibers and equations 6 and 7 for 3 mm fibers. Table 4.5 compares the fibers' experimental and predicted stabilities and the corresponding error percentage.

Table 4.5 Experimental Confirmation.

Response	12.5 mm fibers in CMC (Y_1)			
Conditions	I	II	III	IV
Model prediction	100.00	100.00	99.98	84.10
Experimental	100.00	100.00	100.00	100.00
Error %	0.00	0.00	0.02	15.90
Response	3 mm fibers in CMC (Y_4)			
Conditions	I	II	III	IV
Model prediction	100.00	100.00	98.68	82.84
Experimental	98.80	100.00	100.00	98.94
Error %	1.21	0.00	1.32	16.27
Response	12.5 mm fibers in PAM (Y_2)			
Conditions	I	II	III	IV
Model prediction	100.00	100.00	100.00	85.28
Experimental	86.90	82.76	100.00	74.20
Error %	15.07	20.83	0.00	14.93

Table 4.5 Experimental Confirmation.

Response	3 mm fibers in PAM (Y_5)			
Conditions	I	II	III	IV
Model prediction	100.00	100.00	98.79	82.87
Experimental	100.00	99.48	100.00	98.40
Error %	0.00	0.52	1.21	15.78
Response	12 mm fibers in XG (Y_3)			
Conditions	I	II	III	IV
Model prediction	100.00	100.00	99.73	99.22
Experimental	100.00	100.00	100.00	100.00
Error %	0.00	0.00	0.27	0.78

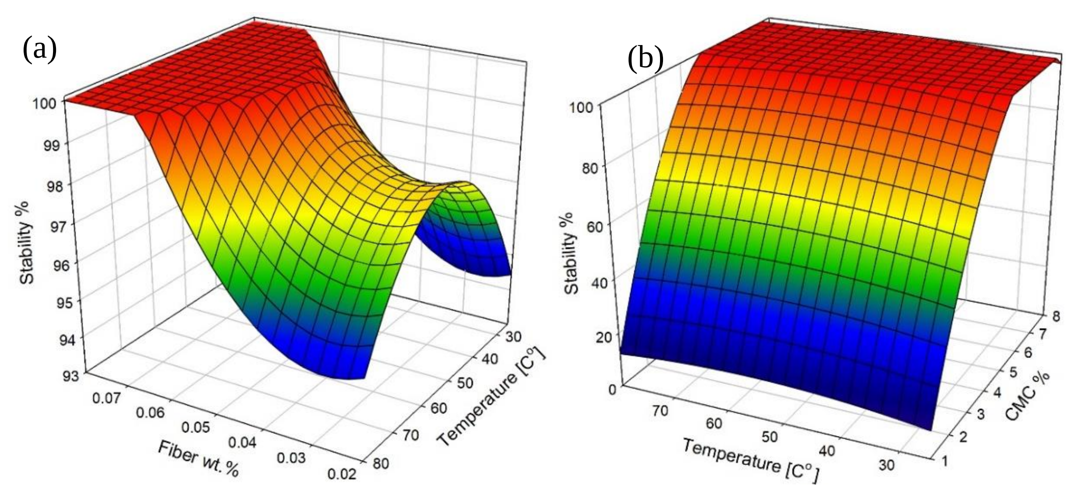
A good agreement between experimental and predicted values is found, with all points below a 20% error margin. The lowest error values are observed at point I, and the error in prediction gradually increases as the test data approach the constraints of lower (-1) factors.

4.1.4. Response Surface Analysis

3-D response surface plots explained the regression equations used in predicting the effect of fluid concentration, fiber concentration, and temperature on fiber stability. The response surface plots were generated by plotting two factors over their respective ranges, while the third factor was kept at a constant value: 0.45 wt.% for fluid concentration, 52.5 °C for temperature, or 0.05 wt.% for fiber concentration. The results are demonstrated in Figure 4.5-4.7. Stability results were bounded between 0-100%; any lower or higher percentages imply to same physical characteristics. Increasing the CMC concentrations increases the stability of the fibers (Figure 4.5 (b) and (c)). The stability of 80% can be reached with 0.28 and 3.45 CMC concentration, respectively, for 12.5 and 3 mm fibers. The same trend can be observed (Figure 4.5 (e) and (f)) despite the change of fiber length. Increasing the fiber concentration or temperature shows a negligible increase in fiber stability; therefore, the CMC concentration effect is the dominating factor for fibers stability.

Figure 4.6 shows fiber suspension in the PAM solution. Temperature, fiber concentration, and fiber length effect are insignificant compared to the polymer concentration effect. Increasing the polymer concentration increases the fibers suspension. 80% stability can be achieved with a concentration of 0.44 and 3.45, respectively, for 12.5 and 3mm fibers. At a fixed polymer concentration, the temperature effect becomes more significant, as a gradual increase in temperature decreases fiber stability making it unstable for 12.5 mm fibers. Rheological tests (Figure 4.8) reveal that high concentrations of PAM are sensitive to temperature change. An increase of PAM suspension temperature leads to a reduction in suspension viscosity, which is responsible for fiber suspension.

XG has the highest viscosity compared to other suspensions (Figure 4.8). The temperature effect on the viscosity only appears beyond 50 °C; therefore, XG is preferable for high-temperature conditions. Fibers stability in XG is also dominated by the polymer concentration. At a high temperature (80°C), a low concentration of XG is not capable of preserving fibers in suspension. Nevertheless, the increase of polymer concentration overcomes the temperature effect, resulting in a stable suspension. Fiber concentration does not affect the system stability; increasing the fiber concentration shows a negligible effect on system stability at high and low temperatures and concentrations (Figure 4.7).



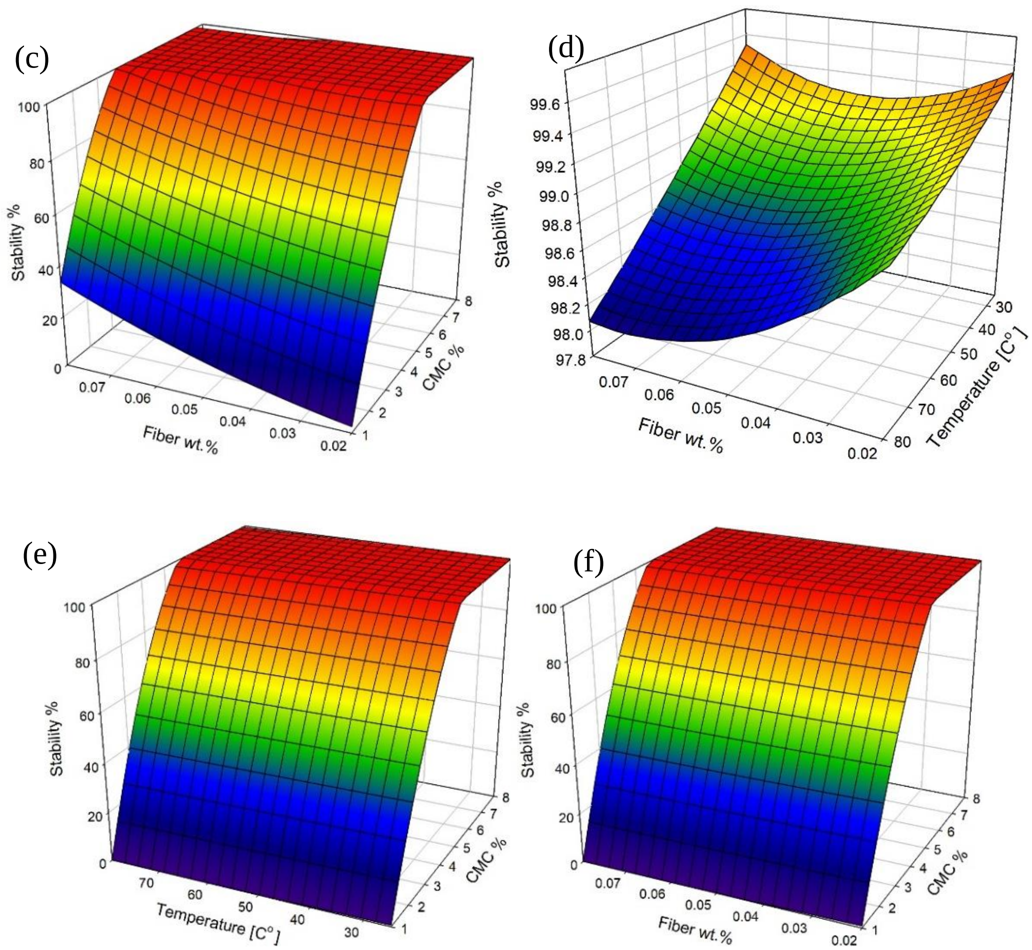


Figure 4.5 Effect of (a) temperature and fiber concentration, (b) temperature and fluid concentration, (c) fiber concentration and fluid concentration on the stability of the fiber length 12.5 mm in the CMC fluid, and effect of (d) temperature and fiber concentration, (e) temperature and fluid concentration, (f) fiber concentration and fluid concentration on the stability of fiber length 3 mm in the CMC fluid.

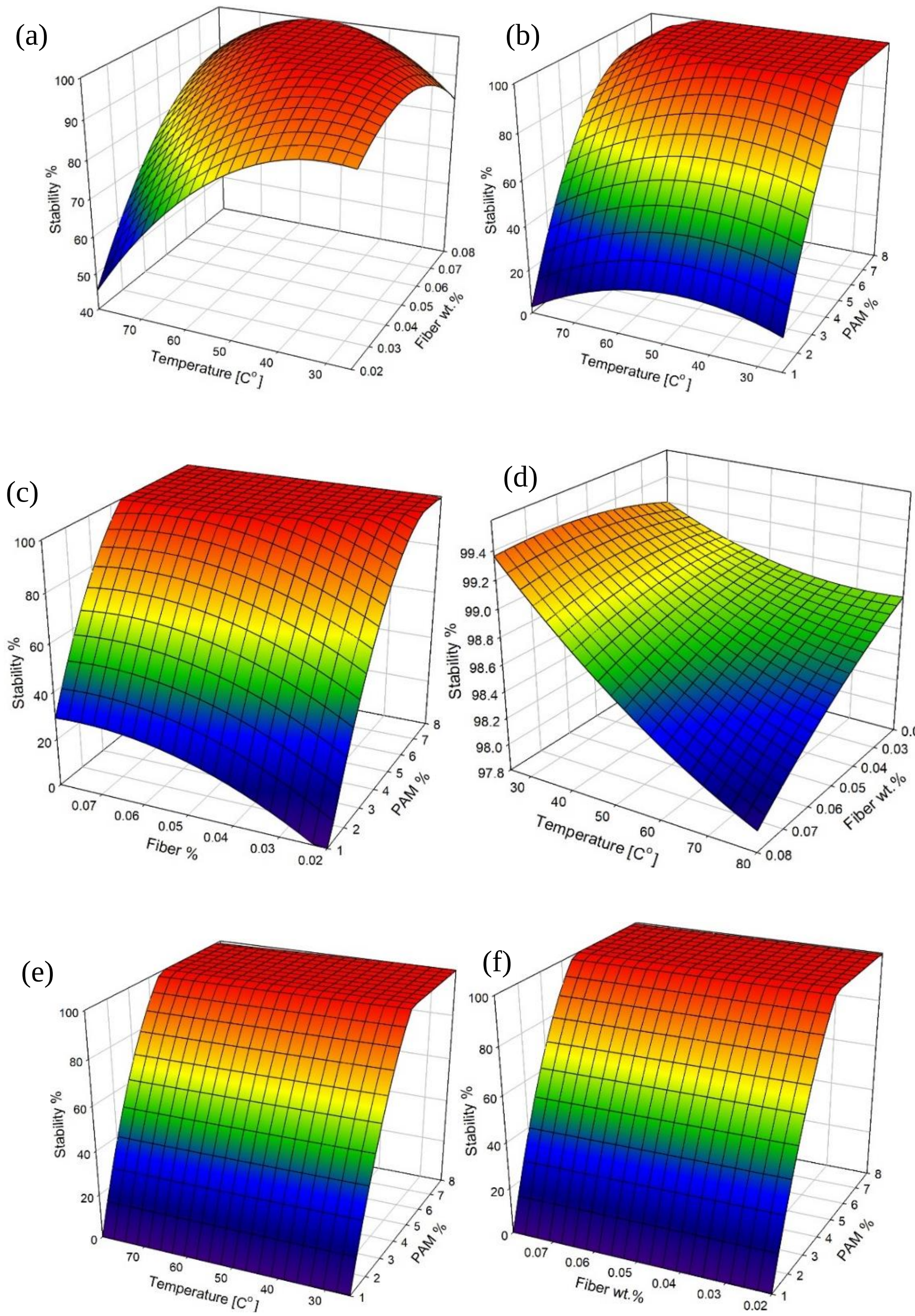


Figure 4.6 Effect of (a) temperature and fiber concentration, (b) temperature and fluid concentration, (c) fiber concentration and fluid concentration on the stability of the fiber length 12.5 mm in the PAM fluid, and effect of (d) temperature and fiber concentration, (e) temperature and fluid concentration, (f) fiber concentration and fluid concentration on the stability of fiber length 3 mm in the PAM fluid.

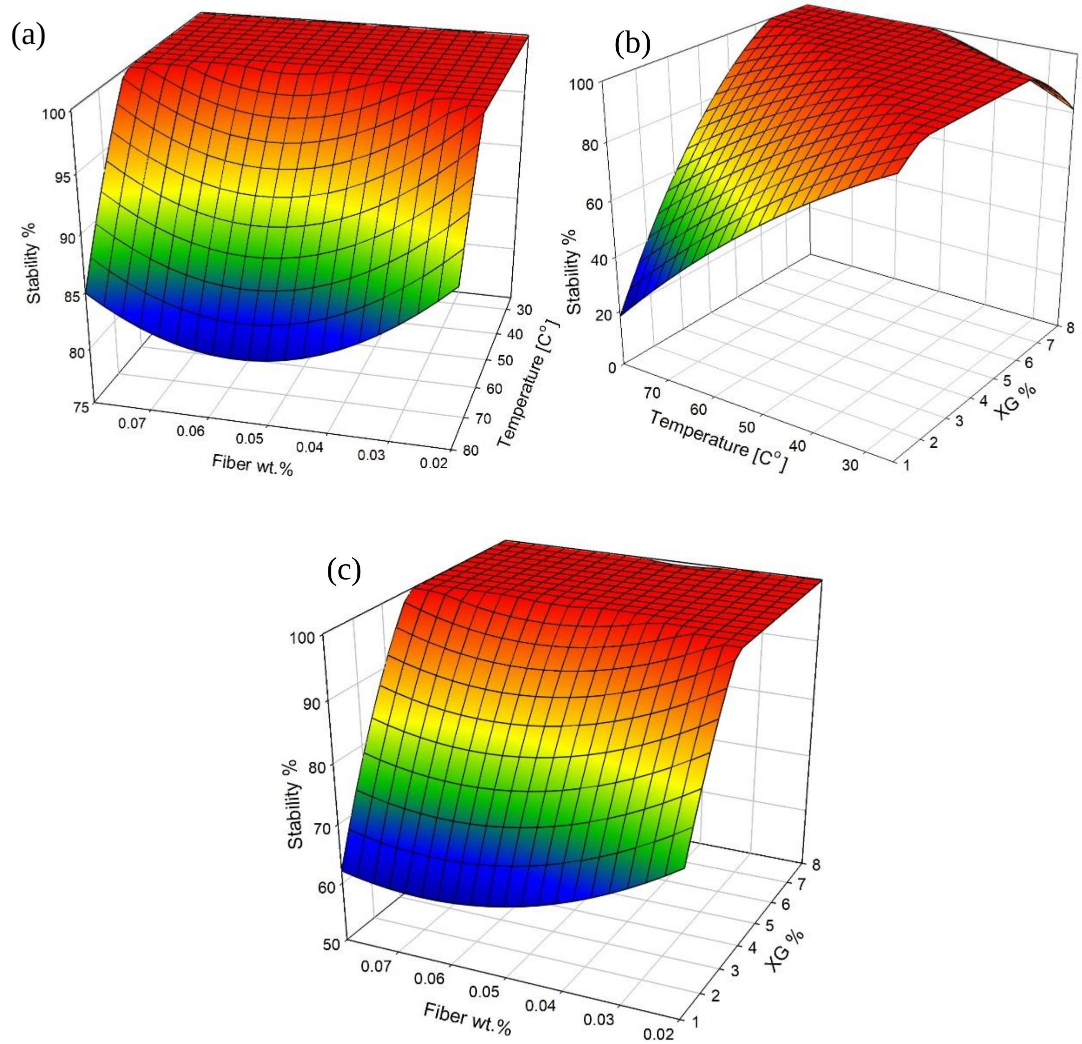


Figure 4.7 Effect of (a) temperature and fiber, (b) temperature and fluid concentration, (c) fiber and fluid concentration on the stability of the fiber length 12.5 mm in the XG fluid.

The fibers' aspect ratio has a distinctive effect on stability, along with the temperature and polymer concentration. A comparison of Figure 4.5 (a) and (d) shows that the fiber aspect ratio effect differs depending on fibers concentration. At low fibers concentrations, the 12.5 mm fibers tend to resist instability induced by temperature rise before reaching a breaking point. Subsequently, the stability decreases; however, the decrease is insufficient to destabilize the system. On the other hand, 3 mm fibers show a similar trend with no resistance to temperature change. At high fibers' concentration, 12.5 mm fibers show better stability at elevated temperatures, while the 3 mm fibers lowest stability is observed at high fibers concentration and high temperature, yet it is also within the stable range. This paradox is explained by fiber entanglement tendency. 12.5 mm fibers have a higher probability of forming a structured fibrous network due to higher chances of entanglement. The structured network formed aids the suspension within the system. In contrast, it is harder for 3 mm fibers to form a network, yielding in an increased amount of individually dispersed fibers that float to the pre-defined unstable region.

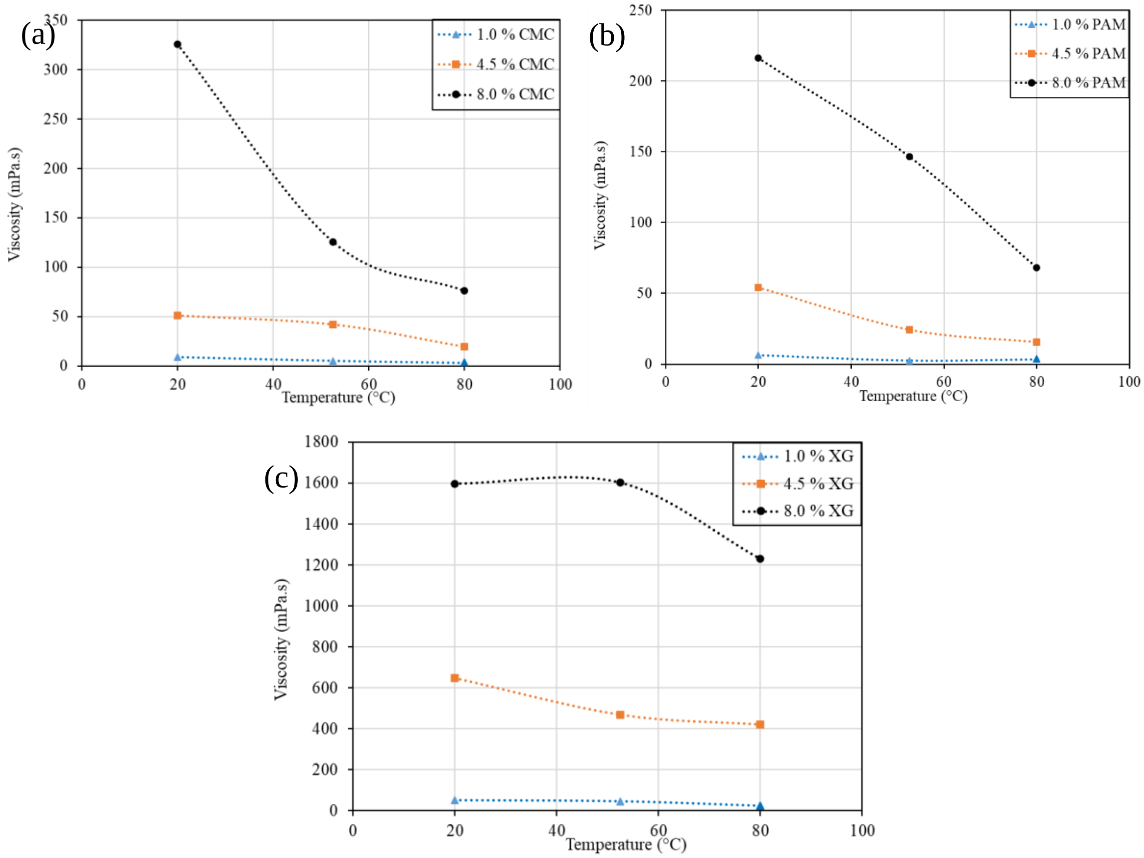


Figure 4.8 Initial viscosity at different concentrations of a) CMC, b) PAM, and c) XG fluids as function of fluid temperature at a low shear rate (10 s^{-1}).

4.1.5. Optimization

Desirability function is a common method used to assess the optimization response surface. The predicted values obtained from the response are transformed into a dimensionless scale *d*. Desirability function ranges between d=0 and d=1, with zero indicating unacceptable response values and unity reflecting a completely desirable response (Derringer & Suich, 1980). The optimization was accomplished by targeting 100% stability at ambient (Table

4.6) and elevated temperatures (Table 4.7). Optimization results, desirability values, and suspensions are summarized in the tables below.

Table 4.6 Response optimization and desirability at ambient temperature.

Parameter							Suspension		
Response	Goal	Lower	Target	Upper	Predicted Response	Desirability	Polymer (vol. %)	Fiber (wt.%)	Temp. (ºC)
Y1	Target	0.000	100.000	101.000	100.000	1.000	4.500	0.066	25.000
Y2	Target	0.000	100.000	101.000	99.900	0.999	6.232	0.075	25.000
Y3	Target	0.000	100.000	101.000	100.000	1.000	1.692	0.080	25.000
Y4	Target	0.000	100.000	101.000	100.000	1.000	4.534	0.020	25.000
Y5	Target	0.000	100.000	101.000	100.000	1.000	4.544	0.020	25.000

Table 4.7 Response optimization and desirability at elevated temperature.

Parameter							Suspension		
Response	Goal	Lower	Target	Upper	Predicted Response	Desirability	Polymer (vol. %)	Fiber (wt.%)	Temp. (ºC)
Y1	Target	0.000	100.000	101.000	100.000	1.000	4.500	0.063	80.000
Y2	Target	0.000	100.000	101.000	94.500	0.974	6.373	0.078	80.000
Y3	Target	0.000	100.000	101.000	100.000	1.000	5.578	0.020	80.000
Y4	Target	0.000	100.000	101.000	100.000	1.000	4.578	0.020	80.000
Y5	Target	0.000	100.000	101.000	100.000	1.000	4.540	0.020	80.000

All desirability values were acceptable (d> 0.95) with the achieved targeted 100% stability. Response results confirm the dominating effect of polymer concentration on stability. Figure 4.9 and 4.10 illustrate the factors that influence fiber stability optimization. The vertical straight line for each factor reflects the selected factor level, and the dotted horizontal line reflects the predicted response value. At high polymer concentration, fiber and temperature curves flatten, diminishing factors interaction. Figure 4.9 (a) and (b) reveal that the rise in temperature results in higher stability sensitivity with respect to fibers wt.% change, where fibers concentration curvature increases. Figure 4.10 (a) and (b) show the fiber aspect ratio effect on stability optimization. Fibers with smaller aspect ratios have stability independence to fiber concentration and temperature with total dependency on polymer concentration.

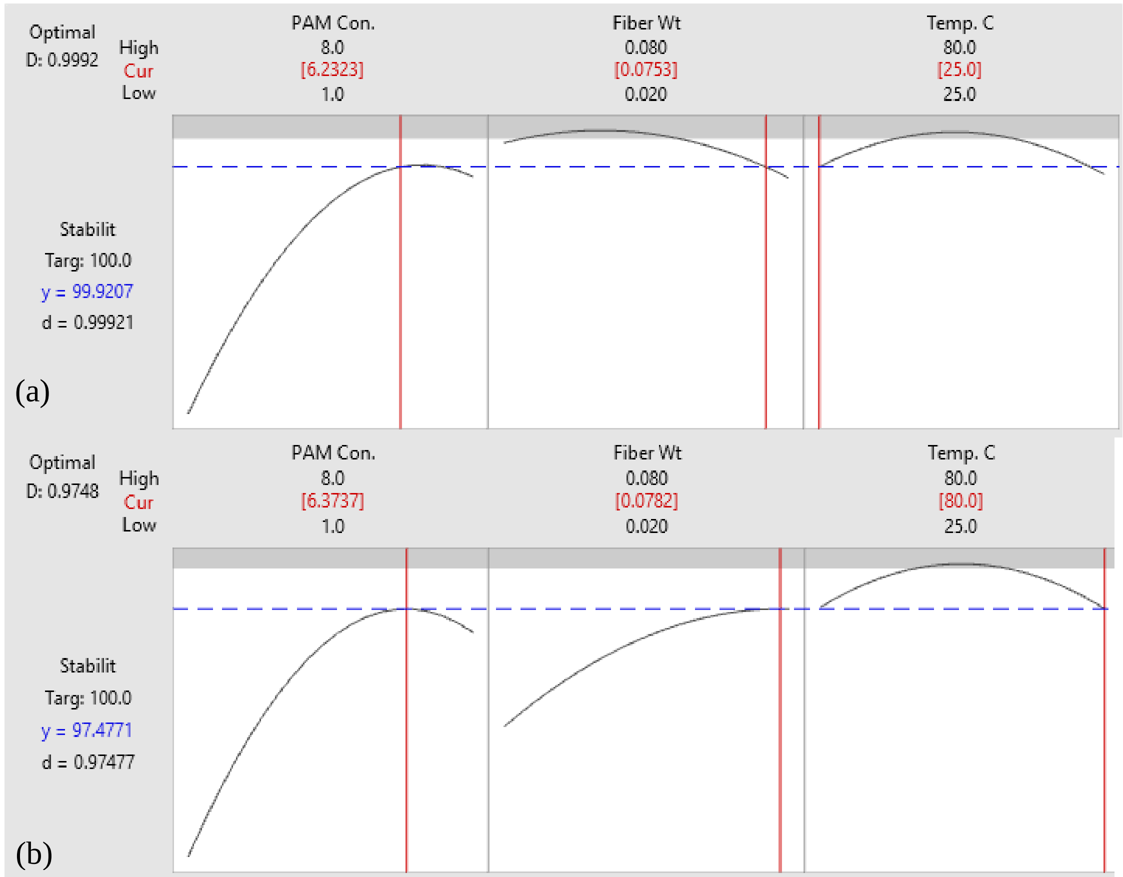


Figure 4.9 PAM (Y_2) optimization response at (a) 25 ^oC (b) 80 ^oC.

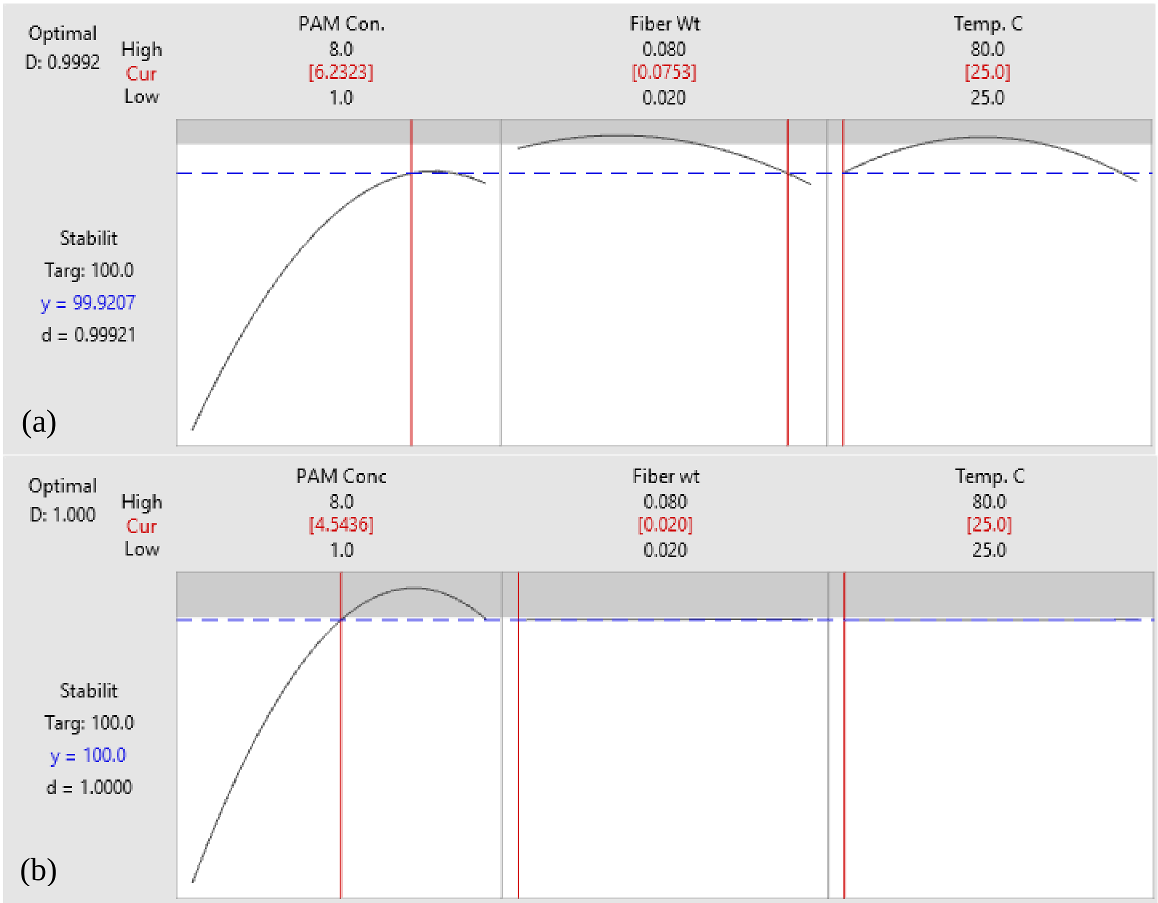


Figure 4.10 PAM (Y_2 & Y_5) optimization response for (a) 12.5 and (b) 3 mm fibers respectively.

4.1.6. Conclusions

The fiber stability was investigated using Box-Behnken design to predict models of fiber stability as the function of fluid concentration, fibers concentration, and temperature. The fiber stability was investigated using two fiber aspect ratios in several water-based fluids (CMC, PAM, and XG). The results can be summarized as follows:

- Models showed that the base fluid concentration had a dominant effect on fiber stability. The increase in fluid concentration enhances system stability. At low fluid concentrations, temperature impact on system stability becomes more significant; increasing system temperature lowers the suspension viscosity and destabilizes the system. Therefore, the effect of temperature is associated with polymer concentration.

- The rheological measurement showed that some polymers could be sensitive to elevated temperatures, changing suspension rheological properties. CMC and PAM showed high sensitivity to temperature changes, while XG showed less temperature sensitivity. The increase of temperature up to 50^{o}C did not affect XG viscosity.
- Stability experiments on 3 mm fiber in XG suspension exhibited complete stability for all experimental runs; therefore, it was excluded from the regression.
- Fibers of high aspect ratio showed better resistance to suspension destabilization. The increased length increases the possibility for individual fibers to entangle, forming a structured network. In contrast, short fibers tend to escape network formation and become more sensitive to factors influencing system stability—temperature and solution concentration.

4.2. Part B: Investigation of Fine Particles Settling in Polyanionic fibrous formulations

4.2.1. Introduction

Conventional drilling fluids often exhibit good performance with respect to cleaning vertical wells. However, cuttings transport in deviated or horizontal wells is challenging (N. V. Boyou et al., 2019). The difficulty in inclined wells is that cuttings tend to settle laterally on the low side of the wellbore, forming a stable stationary bed (also known as cuttings bed). Cutting particles suspended in a non-yielding fluid under a static state are exposed to buoyancy and gravitational forces, while under dynamic conditions, they are subjected to hydrodynamic forces in addition to buoyancy and gravity (Mahmoud et al., 2020). The settling of cuttings occurs due to the inability of the drilling fluid to fully suspend dense cuttings (Wong Jenn Yeu et al., 2019).

In recent years several studies (Mao, Yang, Zhang, Zhang, & Huang, 2020) have been conducted to improve the carrying capacity of water-based muds (WBMs). Yeu et al. (2019) & Yi et al. (2017) investigated the potential of increasing the hole cleaning efficiency by employing low- and high-density polyethylene beads. Also, polypropylene (PP) beads were introduced in other studies (Natalie V Boyou et al., 2018; Hadyan Hakim et al., 2018; I. Ismail et al., 2017) for cuttings transport enhancement. PP beads had the highest effectiveness in a horizontal configuration (Natalie V Boyou et al., 2018; Hadyan Hakim et al., 2018; I. Ismail et al., 2017). Moreover, polymer bead studies were conducted considering a wide range of particle size (0.5 to 4 mm). The beads showed better performance in a vertical configuration as compared to inclined and horizontal orientation. The beads working mechanism relies on hindering effects induced by the beads within the system, increasing collisions between cuttings. In 2017, a study was conducted by Movahed et al. (2017) on particles of various sizes in the range of 1.5 - 7.86 mm. It was observed that utilizing Hydrated Basil Seeds (HBS) fibers hinder settling under static and dynamic conditions, as the fibers impose extra drag force on particles. Song et al. (2016) showed that the addition of cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs) aids the properties of WBMs. The negative charge on CNCs produces overall repulsive forces, while CNFs entangle and form a flexible network. Both attributes promote increment in yield point and gel strength, which are related to hole cleaning. This has also been explored in a prior study by Elgaddafi et al. (2012), concluding that fiber-containing fluids reduce the settling of spherical suspended solid particles (2-8 mm). A recent study by Elgaddafi et al. (2016) argues that the settling of solid spherical particle experiences a reduction in terminal velocity due to the fiber network. Extensive flow loop experiments demonstrated that fibers could improve cuttings removal if coupled with pipe rotation. A significant improvement was seen at 72^o inclination, despite minor improvement in horizontal configuration (George et al., 2014). An extensive experimental study was conducted by Duan et al. (2008) on cuttings transportation in extended reach wells utilizing water and polymeric fluid. The study highlights that the fluid rheology and pipe rotation are the key factors for cuttings transportation (0.45, 1.4, and 3.3 mm). Higher concentrations of small cuttings were observed in the horizontal annulus compared to large cuttings. The addition of polymer to water drilling fluid enhanced the small cuttings transportation, yet larger cuttings exhibited slight transportation enhancement. Further studies of Duan et al. (2009) showed that the fluid type and velocity could affect the cuttings settling and resuspension. Cutting deposition velocity is found to be two to three times larger than cuttings resuspension velocity. Water fluid exhibited higher cuttings bed erosion, while polymeric fluid showed better results in terms of preventing bed formation.

Different sizes of cuttings are generated in the wellbore, depending on several factors including but not limited to; formation geological properties, drilling bit type, and exposure time (CHALLAMEL, 2000; Arild Saasen, Dahl, & Jødestøl, 2013). Cuttings smaller than

1 mm in size were found to represent 60% by weight the rock cuttings samples obtained from hard formations (<2800 m depth), which are drilled with polycrystalline diamond compact (PDC) bit (S. Yi, Wang, Yi, & Chang, 2013). Reyes et al. (2015) cutting analysis included various depths ranging up to 125m in the shale formation. Among 79 samples extracted using PDC and Roller Cone (RC) bits, 28 samples at the least had 50% cuttings of size <1mm, with a higher fraction for cuttings of size 0.1mm (Reyes et al., 2015).

Stuck pipe and hole blowout are well-known problems related to poor hole cleaning. To the best of our knowledge, very few studies have been conducted on settling and transporting fine/colloidal particles (≤0.5mm). It is crucial to emphasize that coarse particle transport differs from that of fine particles (Bulgachev & Pouget, 2006), leading to many problems, as fine particles agglomerate and settle faster than individual particles. In this work, the settling behavior of fine particles (≤0.5mm) in different water-based fluids is investigated experimentally, and the impact of fibers on settling is assessed. Furthermore, the electrokinetic behavior of water-based polymeric suspensions and their cutting carrying capacity is studied using zeta potential and viscosity measurements.

4.2.2. Cuttings Characteristics

Energy-dispersive X-ray spectroscopy (EDX) analysis was conducted. Figure 4.12 shows the elemental chemical composition of clay cuttings. To avoid particles sticking on sieve plates, clay particles were placed in an oven at a temperature of 85^{o}C for 24 hours. Dry cuttings were sieved by a Sieve Shaker (Gilson, USA) (Figure 3.2 (a)) using different sieve sizes (number: 35, 60, 120, and 230) to separate the desired particle sizes (0.063 to 0.500 mm). Scanning Electron Microscopy (SEM) was used to observe cuttings shape and texture

(Figure 4.11). The SEM tests were conducted using Nova Nano SEM 450, FEI. The results indicate that the cuttings are plate-like with irregularities on the edges.

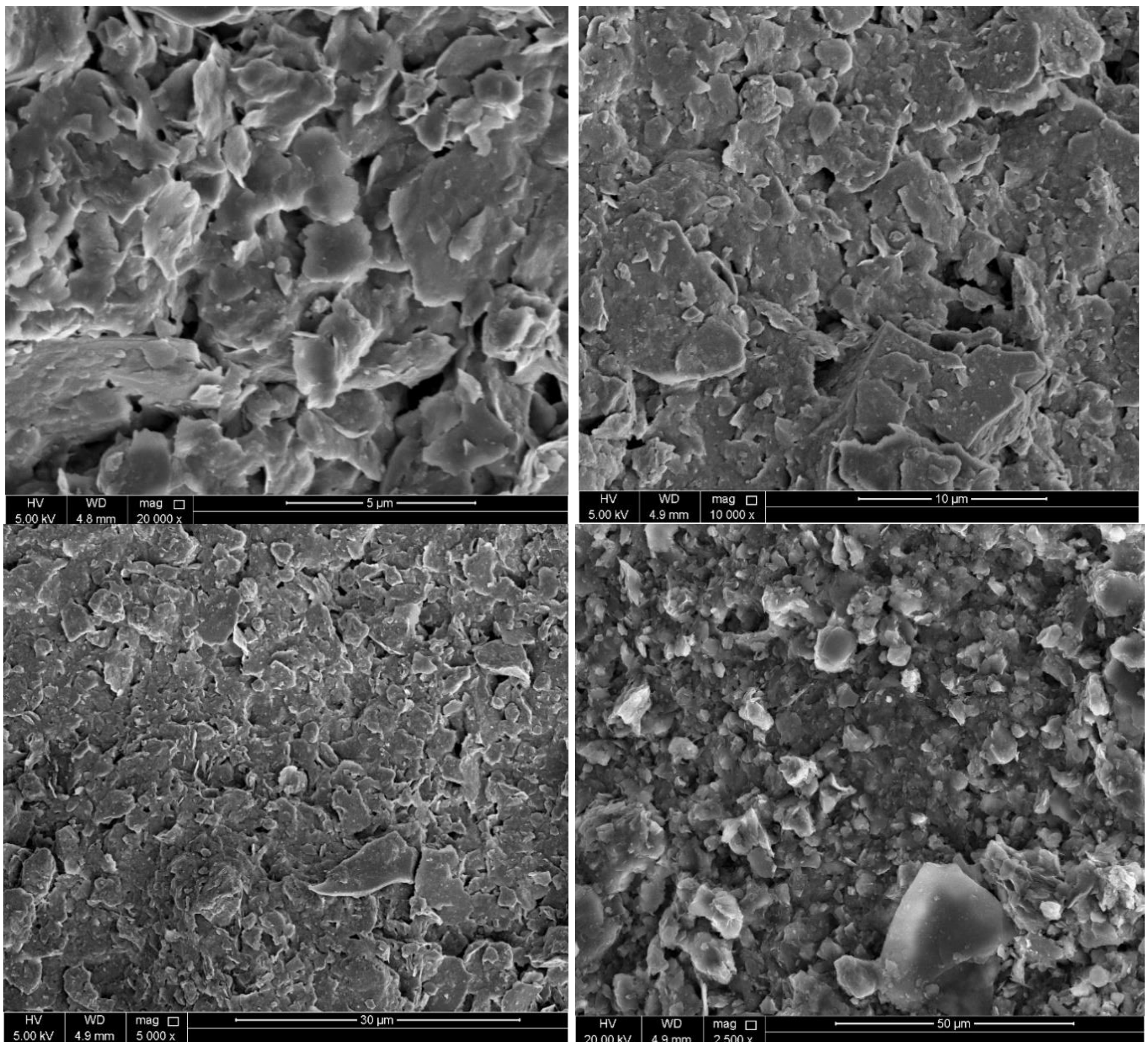


Figure 4.11 SEM images of extracted raw cuttings.

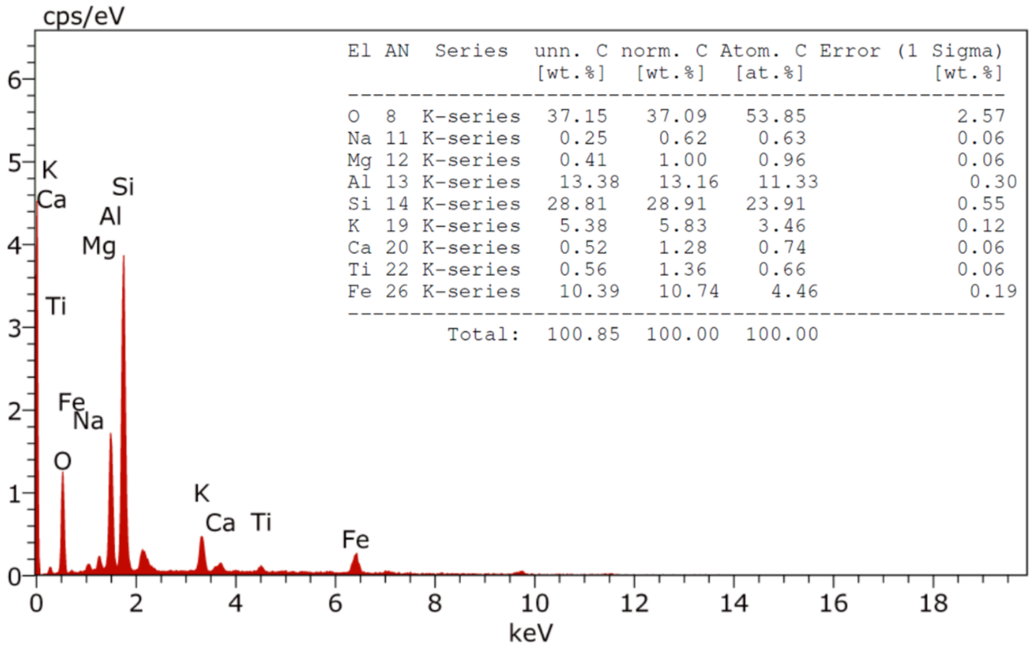


Figure 4.12 Chemical composition of the obtained cuttings.

Cuttings size distribution was measured using Mastersizer 3000 (Malvern Instruments Ltd., UK) (Figure 3.2 (b)) and the sieved sample was analyzed. The results (shown in Table 4.8) suggest that 60.53% of the sample is slit, 12.67% is clay, and the remaining as fine and medium-sized sand. The cuttings sample can be classified as silt, clay, and sand. API drilling fluid material standardization commit defines cuttings of a size larger than 74um as sand; a slit is defined between 2 and 74um, fine solids 44-74, and clay from sub-micron to 100 um (Engineers, 1999); however, the classification is not fixed and can differ based on applications.

Table 4.8 Particle size distribution for the sieved 0.63um.

Size	Volume %	Fraction
<4µm	12.67	Clay
4-63 µm	60.53	Silt
63-125 µm	11.73	Very fine sand
125-250 µm	13.91	Fine sand
125-500 µm	1.16	Medium sand
500-1000 µm	0	Coarse sand
1000-2000 µm	0	Very coarse sand

4.2.3. Impact of Solution Anionicity on Cuttings Suspension

Knowledge of the drilling fluid base suspension and particle interactions is essential for particle transportation. The influence of attractive and repulsive forces —between the fine particles and the base suspension— on particle stability is determined by employing zeta potential (ZP) measurements (Shaikh, Nasser, Hussein, & Benamor, 2017). Particle mobility is correlated to voltage readings obtained by the ZP. A large magnitude of positive or negative ZP values indicates good dispersion. Solutions with small ZP values exhibits a relatively weak attraction force between the suspended particles and the base fluid; thus, particle movement is less restricted. Suspensions with ZPs above +20 mV or below −20 mV are described as stable suspensions. The electric double-layer induces the electrostatic repulsion between particles, forming a stable suspension. (Duman & Tunç, 2009). Increasing the counter ion concentration can affect the electric double layer (Figure 3.6), which compresses the double layer due to repulsive energy reduction. Consequently, destabilizing the suspension system (Durán, Ramos-Tejada, Arroyo, & González-Caballero, 2000; Magzoub et al., 2017).

Table 4.8 demonstrates that 12% of the cuttings are less than 4 μm in size, reflecting the applicability of zeta potential and electric double layer theory. Figure 4.13 shows the variation in cuttings' suspension stability with respect to the increase in the CMC anionicity. Increasing the polymer concentration (anionicity) causes the supernatant (top-clear zone) volume to decrease within 24 hours. The zeta potential of deionized water containing cuttings particles is found to be -19 mV. This value reflects the instability of water-particle suspension. Nevertheless, with the increase in CMC concentration, the suspension seems to become more stable incrementally.

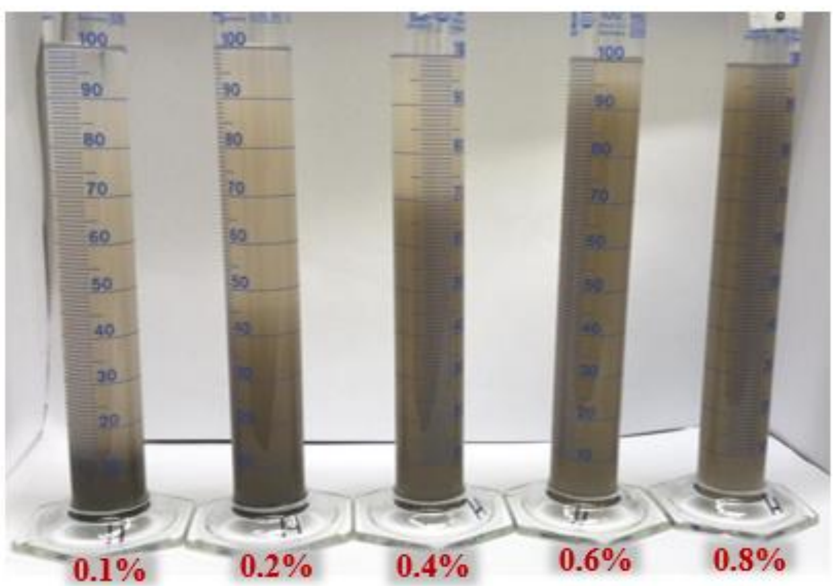


Figure 4.13 CMC concentration effect on suspension without fibers after 24 hr, using 0.063mm cuttings.

Figure 4.14 shows the effect of polymer concentration on ZP and TSSs. The slight addition of 0.1 wt.% XG increased fine particles' stability by -20mv increase in the negative zeta potential (Figure 4.14 (a)). Further increments up to 0.8 wt.% resulted in a plateau around -62 mV. Introducing a small amount (0.1 wt.%) of CMC shifts zeta potential from -20 to -55 mV, and it further decreases to -83 mV upon the incremental addition of CMC (Figure 4.14 (b)). Finally, PAC suspensions had the highest rate of change to zeta potential values compared to other suspensions. Adding 0.1 wt.% of PAC increased the negativity of zeta potential by -43 mV while 0.8 wt.% PAC shifts it to -140 mV ((Figure 4.14 (c)); eventually, all suspensions became stable. The stabilization is attributed to viscous forces that increase with polymer concentration (Figure 4.15); also, particle-particle and particles-polymer repulsive forces influence the settling of cuttings.

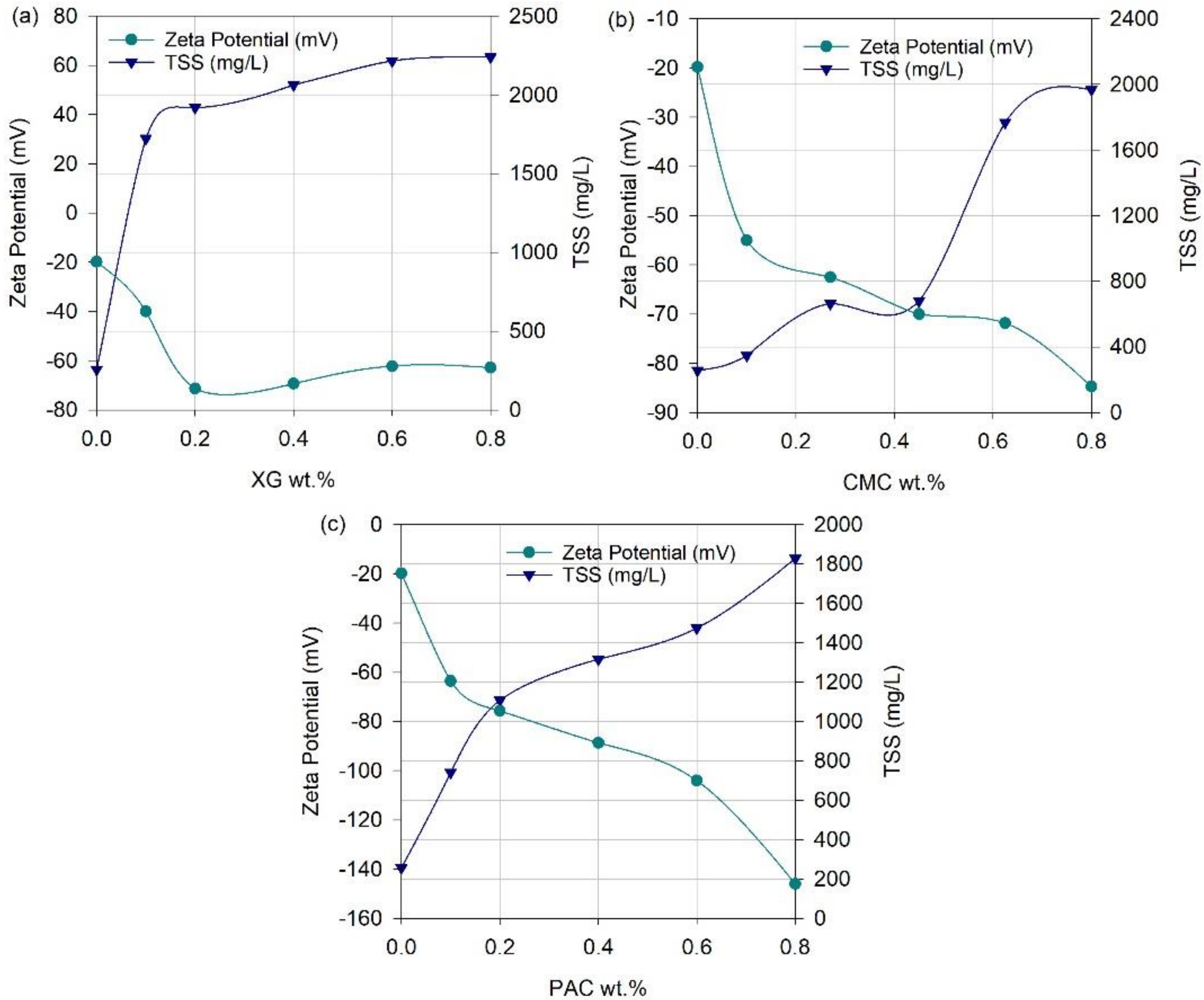


Figure 4.14 Zeta potential and TSS of top 20 ml of the mixture after 24 hr vs. polymer concentration: (a) XG; (b) CMC; and (c) PAC, using 0.063mm cuttings.

Supernatant turbidity, reflected by spectrometer TSS measurements, showed a correlation to the polymer concentration. TSS content of the top 20% volume was measured after 24 hours of a quiescent condition. The measured TSS values increased with the polymer concentration increase, and it reached over 1600 mg/L for all tested base polymers (Figure

4.14). The TSS trend with polymer concentration was unique for each suspension: XG had a dramatic increase at 0.1 wt.%, while CMC showed a small-steady increase up to 0.4 wt.% and significant increment afterward. PAC started with a high rate of change in TSS around 0.2%, and then the rate was lower for higher concentrations.

Figure 4.15 shows the flow behavior of XG, CMC, and PAC suspensions. The test results reveal that all suspensions exhibit non-Newtonian flow behavior. Mostly, increasing the shear rate resulted in a continuous viscosity reduction, indicating shear thinning properties of all fluids. For high polymer concentrations (1.20-0.75 wt. %), particles in XG suspension experience higher viscous drag than particles suspended in CMC and PAC. For lower polymer concentrations (0.1 &0.25 wt.%), the flow behavoir is slightly different. XG suspension has the most significant viscous drag, while particles in PAC suspension exhibit higher viscous drag than in CMC suspension.

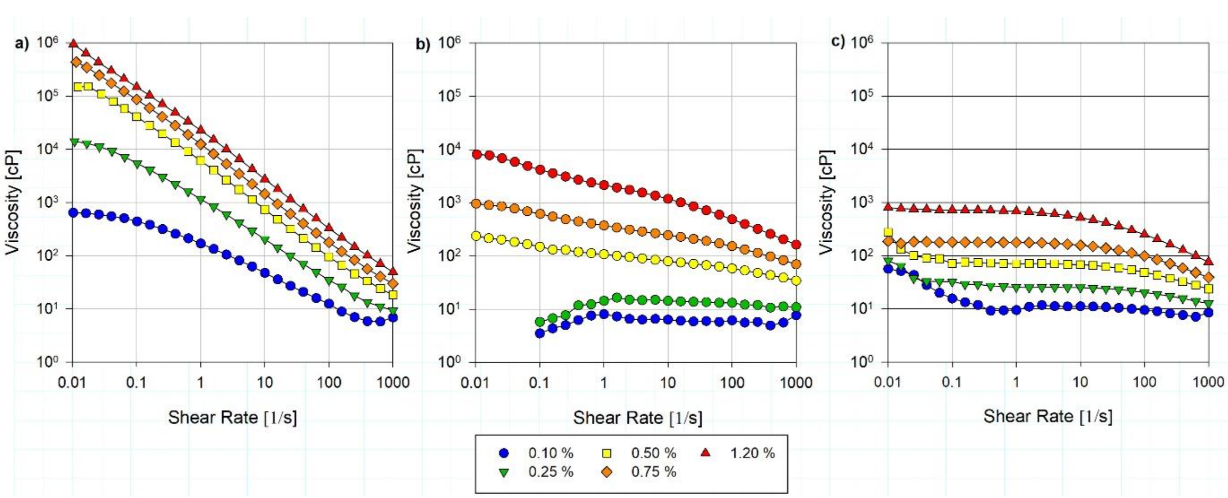


Figure 4.15 Flow behavior of fiber-free polymeric suspensions (a) XG (b) CMC (c) PAC.

Spectrometric TSS measurements, together with ZP readings, demonstrated the impact of the anionicity on fine particles stability in the suspensions. However, such measurements can be misinterpreted if the influence of other factors, such as suspension viscosity, was neglected. Therefore, equating the viscous drag force —associated with the fluid's flow behavior— is vital to distinguish if the anionicity contributes to the stabilization of particle-laden suspensions. The observations from Figure 4.14 highlight the combined effect of the zeta potential and viscosity on TSS. Isolated anionicity effect can be examined by equating suspension viscosities. Only the low shear rate range is considered in this analysis; the viscosity in this range of shear rate dictates the viscous resistance of the fluids against particle settling.

XG and CMC suspensions with similar rheological characteristics are considered in the low shear rate range (i.e. 0.01 to 0.1 s^{-1}), in which 0.1% XG and 0.75% CMC suspensions exhibit roughly the same viscosity curves (Figure 4.17). For each suspension, the zeta potential and the corresponding TSS values were obtained. The zeta potential and TSS values of 0.1% XG and 0.75% CMC are approximately -40 and -80 mV, and 1750 and 2000 mg/L, respectively. The results summarized in Figure 4.16 illustrate the effect of anionicity on particle-laden suspension stability. An increase in the negativity of zeta potential increased TSS concentration (Figure 4.16 (a)).

Similarly, considering the rheological characteristics of 0.5% CMC and 0.75% PAC in the shear rate range of 0.01 to 0.1 s^{-1}, the viscosity effect on the suspension stability can be eliminated. Hence, applying the same analysis, a similar result is obtained, as presented in Figure 4.16 (b). Therefore, the particle-particle interface and electrostatic repulsion between negatively charged particles surface and negatively charged anionic polymers; both influence particles suspension. This comparison explicitly confirms the positive effect of anionicity on particle-laden suspension stability (Michaels, 1954; Nasser & James, 2006b). Nevertheless, polymer molecular structure differences could also contribute to particles electrokinetic, yet the structure influence on particle suspension is limited compared to the overall charge density. Such behavior was observed in previous studies conducted on anionic high molecular weight polyacrylamide (PAM) of various molecular structures (Shaikh et al., 2017).

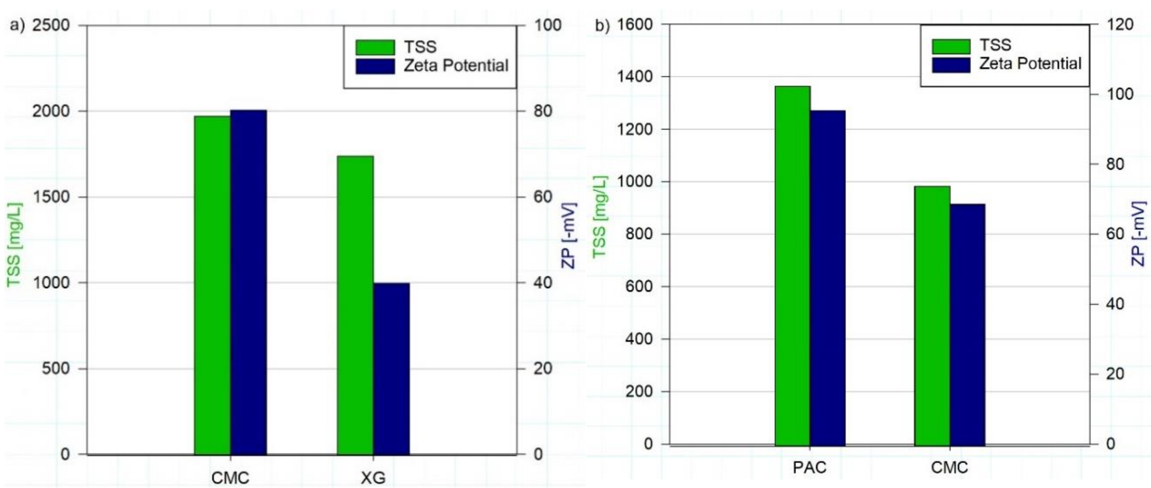


Figure 4.16 Effect of anionicity on the stability of particle-laden suspensions with similar rheological characteristics at low shear rates (less than 0.1 s^{-1}): a) 0.1% XG and 0.75% CMC; and b) 0.5% CMC and 0.75% PAC, using 0.063mm cuttings.

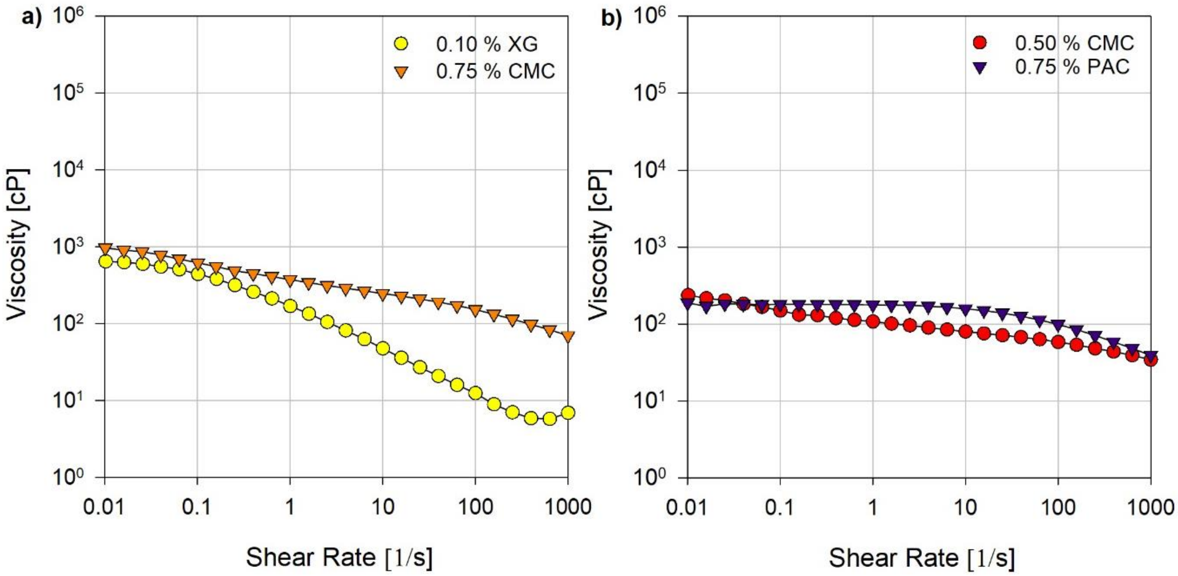


Figure 4.17 Similar rheological characteristics at low shear rates (less than 0.1 s^{-1}): a) 0.1% XG and 0.75% CMC; and b) 0.5% CMC and 0.75% PAC.

4.2.4. Effect of Fiber addition on Solution Carrying Capacity

Fiber performance tests were carried out to investigate the effect of fiber-cuttings interface on hindering the cuttings settling. The polymer concentration is fixed at 0.45 wt.% for three tested polymeric suspensions, and the test duration was set at 24 hours. Cuttings of 0.063 mm mean diameter were used in the investigation while varying fiber concentration from 0.02 to 0.08% by weight of the mixture. It was reported in previous studies (Ahmed & Takach, 2009a; Marti, Höfler, Fischer, & Windhab, 2005; Rajabian, Dubois, Grmela, & Carreau, 2008) that the addition of a small amount of fiber (0.10 wt.%) has a negligible influence on fluid rheology and pressure loss. Moreover, fibers added to crosslinked fluids had insignificant influences on apparent viscosity (Zhao, Ma, Guo, Gao, & Omeiza, 2016).

Alternatively, increasing fiber concentrations above 0.1% affects the rheological properties of base fluid (Guo et al., 2015).

Deionized Water (DW) failed to suspend particles without the aid of polymer or monofilament fibers. The fiber-free base suspension (BS) of XG had significant particle suspending capacity (Figure 4.18). The addition of polymer increased TSS concentration from 257 to 2332 mg/L. The observations did not reveal any significant differences in TSS values measured against fiber addition (0.08%). Fiber addition did not improve XG suspension particle carrying capacity; due to the high XG viscosity (10^5 cP at low shear rates), which was independently able to suspend all the fine particles.

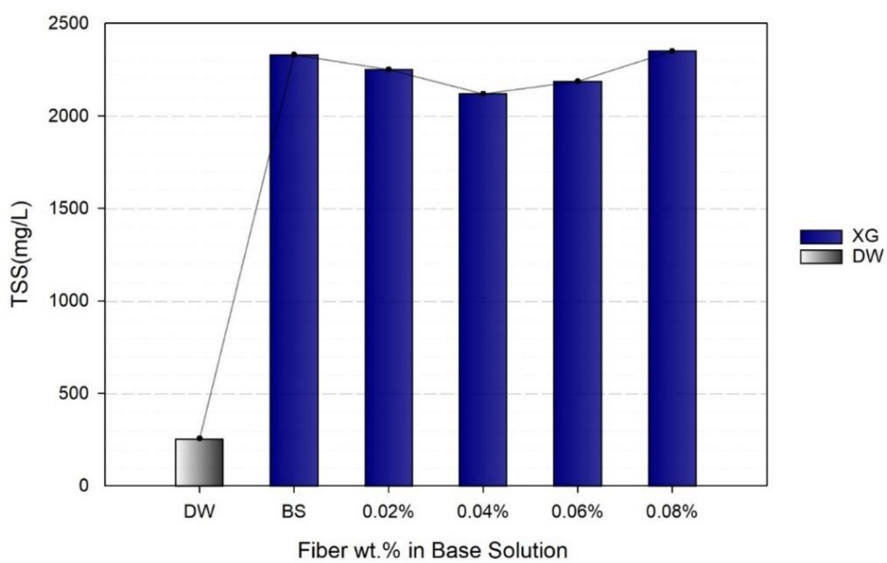


Figure 4.18 Variation of TSS with fibers concentration in 0.45% XG suspension with the addition of 0.063mm cuttings.

Figure 4.19 (a) shows the combined effect of polymer and fiber on CMC-based suspensions' carrying capacity. The addition of 0.45% CMC increased the TSS of DW from 257 to 1100 mg/L. The trend of increase to TSS with fiber concentration has demonstrated an enhancement in the carrying capacity of BS. The TSS of BS increased from 1100 to 1194, 1384, 1644, and 1840 mg/L when fiber concentration increased from 0.0 to 0.02, 0.04, 0.06, and 0.08%, respectively. An increase beyond 0.08% of fiber concentration may further lower the settling of particles. However, it is not recommended as higher fiber concentration might increase fluid viscosity and cause bottom hole pressure to rise.

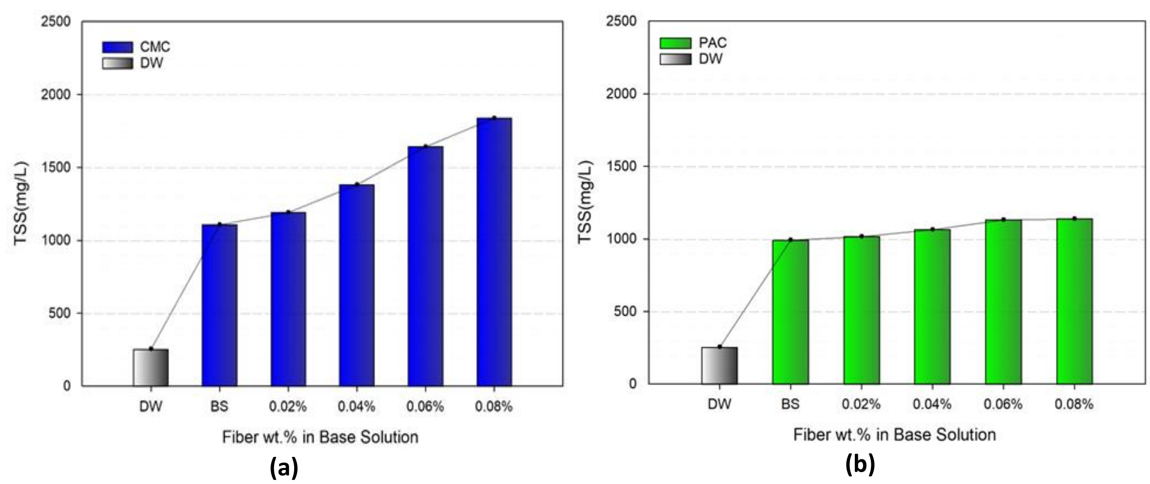


Figure 4.19 Variation of TSS with fibers concentration in 0.45% CMC (a) and PAC (b) suspensions with the addition of 0.063mm cuttings.

PAC suspension (BS) solid carrying capacity in the presence of fibers was similarly assessed. Adding 0.45% PAC has elevated the TSS concentration of DW from 260 to 1000 mg/L (Figure 4.19 (b)). Subsequently, all fiber concentrations were marginally capable of aiding suspension of particles, reaching 1140 mg/L of TSS. Improvements in PAC suspension carrying capacity by fibers were relatively insignificant. The homogenous presence of fiber networks throughout the fluid medium is essential for fiber's functionality. PAC-fiber poor performance could be related to the instability of the fiber network created in the suspension. PAC suspension had the lowest low-shear-rate viscosity that is not sufficient to overcome fibers high bouncy and prevent fiber's migration to the surface. Moreover, PAC viscosity at low shear rates was constant, indicating Newtonian behavior.

Figure 4.20 summarizes fiber's effect on the cuttings carrying capacity of all tested baseline suspensions. The performance of fiber in these suspensions can be classified into three categories: i) ineffective, ii) marginally effective, iii) significantly effective. Accordingly, the fiber performance is ineffective in XG suspension, marginally effective in PAC suspension, and significantly effective in CMC suspension.

The significant differences in fiber performance are justified by two factors: (1) the distinct fiber network stability within various suspensions and (2) the initial carrying capacity of each solution. The baseline suspension of XG (fiber-free) had an initial very high cutting carrying capacity to keep particles in suspension for extended times. As a result, the expected improvement from the fiber addition was not observed. Unlike XG, PAC-based suspension had a low initial cutting carrying capacity, yet; fiber performance was extremely poor. PAC suspension had low viscosity with inadequate yield stress to prevent fiber network surface migration or uniformity disperse fibers throughout the suspension. The inability to homogeneously disperse fibers in PAC-based suspension has directly affected their performance. In contrast, the fiber-free baseline suspension of CMC had a limited cutting carrying capacity (similar to PAC), and suspension viscosity was sufficient to stabilize the fiber network; therefore, the impact of fiber addition on the cutting carrying capacity was substantial in CMC-based suspension. Fiber's network stability is directly proportional to suspension viscosity; this stability is crucial for fiber functionality. Nevertheless, an excessive increase in solution viscosity tends to diminish the effectiveness of fibers. As the viable gap of enhancement to suspension's carrying capacity was already attained by viscous forces, therefore; fibers addition in such solutions (e.g., XG) has no effect.

Fundamentally, cuttings tend to agglomerate at the wellbore downside when drilling fluid characteristics, such as annular velocity, mud weight, and viscosity, fail to provide sufficient carrying capacity to either transport cuttings to the surface or hold particles in suspension. Fibers can prevent cuttings deposition and aid the lifting forces associated with transportation or suspension of particles. Fibers' working mechanism is based on the hydrodynamics of fiber-fiber and fiber-cuttings interaction; fiber-fiber entanglement forms structured networks throughout the drilling fluid medium. The fiber networks intercept the path of free-falling cuttings, capturing particle by direct mechanical contact, and due to fiber bulk network high bouncy, the captured cutting moves as a plug within the network or remains in suspension.

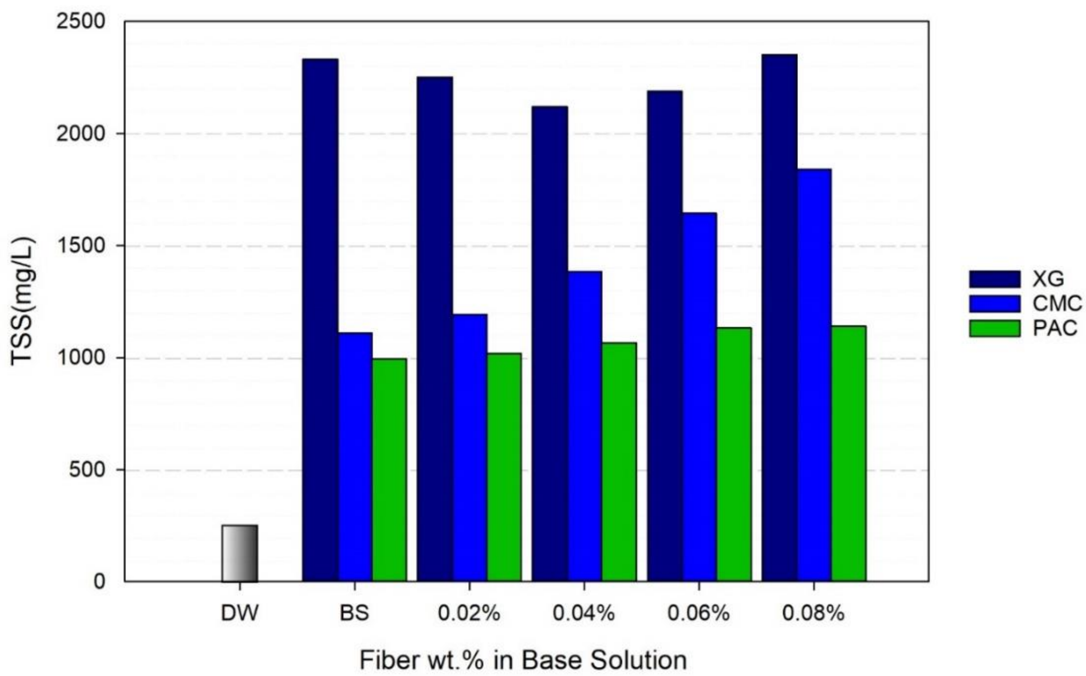


Figure 4.20 Summary variation of fibers concentration for particles suspension in XG suspension.

4.2.5. Effect of Time on Cutting Suspension in Fibrous Solution

Quiescent period tests were accomplished by employing suspension of water and 0.45% CMC. Tap water was used as a baseline for comparison with fiber-free and fibrous CMC suspensions. The results demonstrated the strong dependence of TSS on time in the early settling regime (Figure 4.21). The addition of fiber tends to minimize TSS dependence on time, resulting in more stable solid-liquid suspension that does not segregate with time. In the late settling regime, the suspensions become more stable, as indicated by TSS constant values. Water has the lowest capability to suspend fine particles. After 1.5 hours of quiescent condition, TSS reduced to less than 1000 mg/L. The CMC suspension was capable of suspending particles up to 12 hours, exhibiting less TSS reduction compared to water. With the addition of fibers, the polymeric suspension was able to suspend particles in static conditions for a prolonged time. An increase in fiber concentration increased the cutting carrying capacity of polymeric suspension. All fibrous fluids had similar TSS profiles with time: sharp TSS reduction in the early settling regime and stable TSS in the late settling regime. The results obtained from the current investigation are in good agreement with previous studies (Elgaddafi et al., 2012, 2016) conducted on large particles.

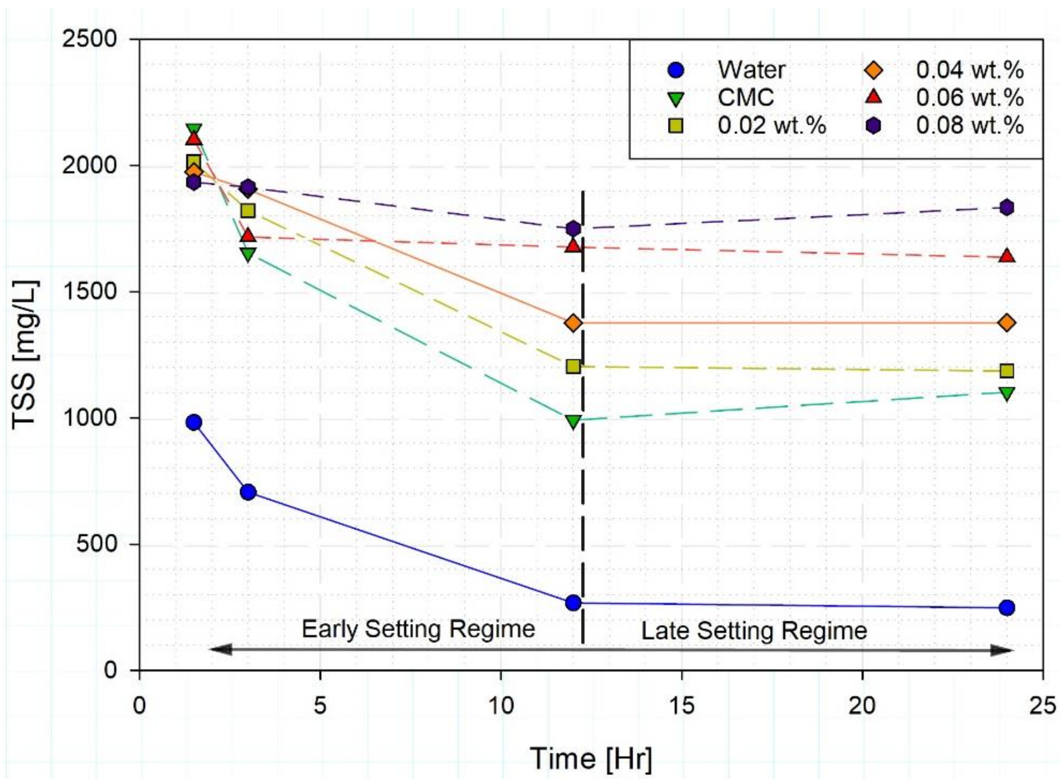


Figure 4.21 Measured TSS vs. time for 0.45% CMC for various fiber wt.% (0.02-0.08%) and using 0.063mm cuttings.

4.2.6. Effect of Cuttings Size on

Investigation of cutting size (diameter) effect on polymeric suspension was carried out using fine cuttings with size less than or equal 0.25 mm (0.063, 0.125, and 0.25 mm). Each cutting size was mixed with a 0.45% CMC suspension. Experiments were conducted considering two- quiescent-time frames (12 and 24 hours). As expected, in a 12-hour time frame, base suspension and 0.02% fibrous suspension results are almost identical (Figure 4.22 (a)), and TSS values overlap in the medium size (12.5 mm) range. Results presented in Figure 4.22 (b) reveal fibers' effect on suspension cutting carrying capacity after a prolonged period (24 hours), where TSS curves did not exhibit overlapping. The effect of fiber on carrying capacity improvement was approximately consistent for all particle size range. 0.08% fiber addition enhanced suspension and increased TSS measurement by 60% for small size cuttings (0.063-mm). Other particle size ranges were also positively affected by the introduction of 0.08 % fiber. Based on particle size, there were minor variations in the carrying capacity improvements. The size of cuttings influences fibers carrying capacity effectiveness; particles of smaller size exhibit a slower settling rate yet are more difficult to be entangled, and if captured, are highly affected by the fiber network. On the other hand, particles of larger size hold higher masses (fast settling rate) with a higher probability of fiber-cuttings interaction. Although larger cuttings are easier to capture, fiber's effectiveness on these cuttings is less compared to smaller cuttings; due to the increased momentum that larger cuttings possess, which balances the upright bouncy of the fiber network.

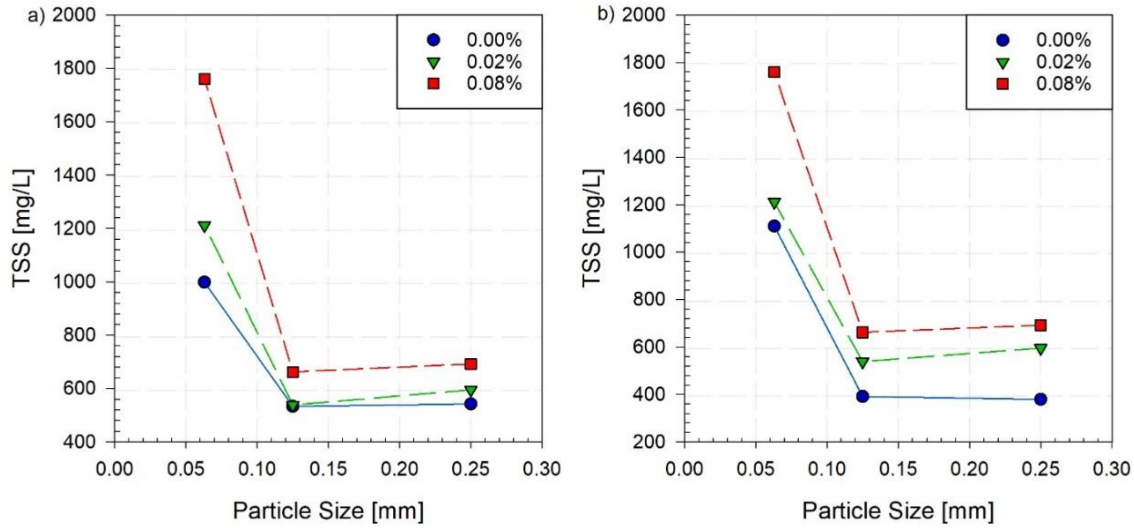


Figure 4.22 TSS vs Particle size after: a) 12 hours; and b) 24 hours in 0.45% CMC suspension, and various (0.02- 0.08%) fibers concentration.

Overall, the TSS measurements correlate favorably with previous studies (Elgaddafi et al., 2016, 2012) that assessed the cutting carrying capacity of polymeric suspensions with coarse cuttings of up to 8 mm in diameter. The findings support the involvement of viscous resistance (imposed by solution viscosity) and the physical interaction due to fiber drag. Finally, it highlights the presence of electrostatic hindering due to anionic repulsion. Drilling operations can be postponed for extended times due to an uncertain event. For practical drilling operations, water-based muds formulated with anionic polymers and fibers show good particle suspension capabilities when tested in 24-hour periods. Therefore, the negative charge density of water-based muds should be increased to the highest level whilst maintaining the suspension viscosity within the operational limits and considering environmental aspects related to used polymer. Fibers can be added to water-based muds in the range of 0.02-0.08 %, as this range is proven to enhance cuttings lifting capability depending on cuttings size and wellbore conditions.

4.2.7. Performance in Pilot-Scale Settling Column

Pilot-scale experiments were conducted to evaluate the performance of fibrous fluids in a large scale setup. XG solution of (0.3%) containing 0.04% fibers (12.5 mm) is prepared. The experiments were carried out under 125 rotation speed and ambient temperature. Borosilicate glass beads with a 1 mm diameter were used to simulate drilling cuttings. The glass beads are uncharged and do not dissolve or react with its medium; thus, the effect of fibers can be studied without the influence of polymer anionicity.

Initially, particle settling time must be identified; the time required to reach terminal settling velocity and steady-state condition. An amount equivalent to 1% was injected into the system under the previously mentioned conditions. Glass beads were given enough time, ranging from 2 to 8 minutes before discharging of fluid from the bottom.

Figure 4.23 shows the cutting deposition percent after various intervals. The cutting deposition percentage reflects the number of cuttings obtained from the discharged fluid. Observations show that 4-minute deposition time is enough for 1 mm particles to reach their terminal velocity. The trend is almost is a straight line; thus, the selection of settling time in the range of 4-8 minutes is suitable for further analysis, without biasing the experimental measurements.

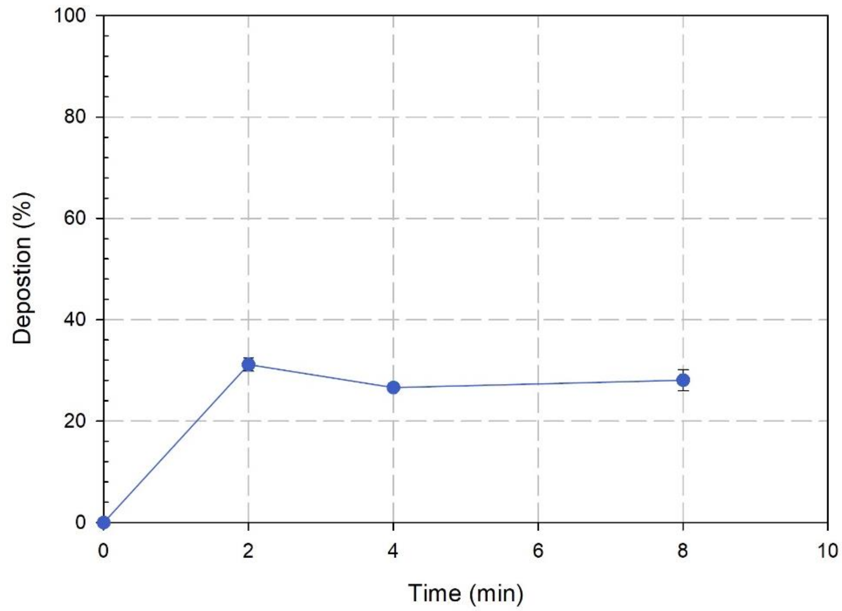


Figure 4.23 1mm-glass beads (1%) deposition against time at 125 RPM in XG solution (0.3%) containing fibers (0.04%).

Consequently, fiber hindering performance was investigated under the same conditions and settling time of 5 minutes (Figure 4.24). Fibers were able to reduce the particle deposition by 15% percent. The settling column results differ from lab-scale outcomes due to several reasons. The glass bead does not acquire any charges on their surfaces; therefore, suspension due to particle-particle and particle-polymer electrostatic repulsion does not exist. In addition, unlike real cuttings, glass beads are of perfect spherical geometry with a smooth surface. All the above-mentioned factors influence the particles settling path and deposition rates.

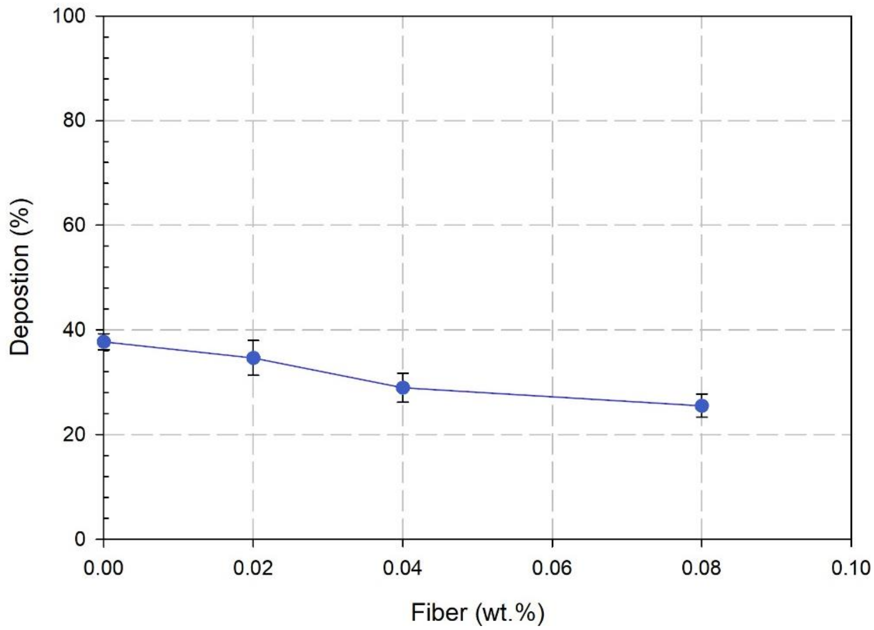


Figure 4.24 1mm-glass beads deposition against fiber (wt.%) concentration at 125RPM in XG solution (0.3%).

4.2.8. Conclusions

The addition of both anionic polymers and fibers to Water-Based Muds (WBMs) improve its cutting carrying capacity and provide an environment-friendly alternative to Oil-Based Muds (OBMs). The carrying capacity of test fluids was investigated after 24 hours of a quiescent period to examine the impact of base polymer anionicity (surface negative charge density) and fiber content. The main findings are as follows:

- Polymer anionicity has a positive effect on cutting suspension and carrying capacity. The positive effect is caused by electrostatic repulsion between polymer-particle and particle-particles induced by the electric double layer and particle-suspension interactions.

- Fiber performance is directly related to its stability within the base suspension. The fiber-fiber interaction forms a stable network structure that hinders cuttings settling because of mechanical action and hydrodynamic interference.
- Suspended cuttings in the suspension measured by TSS increased with fiber concentration. The addition of 0.08% fiber increased TSS concentration by 65%.
- Cuttings settling time dependency decrease through the increase of fiber wt.% in the solutions. Particles settling in a higher fiber concentration solution are less sensitive to time; late settling regimes are attained with high TSS concentrations.
- For prolonged intervals and under static conditions, the addition of fibers is major in terms of settling velocity reduction for small cuttings (<0.5 mm).
- Cuttings size influences the carrying capacity performance of fibers suspensions. Smaller cuttings settle at slower rates and are more difficult to be intercepted by the fiber network. However, they are highly affected once captured. Conversely, larger cuttings possess more masses (faster settling rates) and are easier to capture.
- The Pilot-scale investigation revealed a difference in fibrous solution performance. Nevertheless, the difference is associated with the nonexistence of electrostatic forces, as the glass beads are of an un-charged surface. Consequently, supporting the importance of these particle-particle and particle-polymer interaction.

Chapter 5: Overall Conclusions and Future Perspectives

The utmost objective of this work was to develop FCFs for water-based mud for horizontal and vertical hole cleaning applications, which shall provide an environmentally friendly alternative to the existing toxic oil-based muds. Achieving this objective requires the fundamental knowledge of fibers stability within various polymer suspensions, as well as an understanding of the electrokinetics related to polymeric formulations and cuttings.

As a consequence, polymeric suspension characteristics such as viscosity at low and high shear rates, surface charge density, molecular structure affecting the stability of the fiber, and cuttings suspension have been studied. The investigation was performed through developed stability tests in the prespecified region, zeta potential, and total suspending solid measurements. Maintaining stable uniform dispersion is essential to enable fibers' functionality for the anticipated purposes.

Response Surface Methodology (RSM) and Box-Behnken Design (BBD) of three different polymers in terms of solution concentration, fiber concentration and aspect ratio, and temperature were utilized. Observations showed that long fiber has higher entanglement ability forming fiber-fiber connections, forming structure networks of high separation resistivity. While short fibers have a lower tendency for fiber-fiber entanglement, they exhibit a higher degree of separation and agglomerate in the fluid upper surface. In high temperature (80 ^{o}C), polymers of low sensitivity to temperature showed better fiber's stability, such as XG. Regression model and RMS analysis have shown that base fluid concentration has a predominated influence on fiber's stability, relativity to the fiber aspect ratio, concentration, and fluid temperature. Suspensions with viscosities above 50 mPa.s are able to sustain fiber's suspension at ambient and elevated temperatures.

Fibers addition of small amounts (0.08 wt.%) succeeded in hindering fine cuttings (d <0.5 mm) deposition and withstand suspensions for prolonged periods (24 hours). Total suspended solids measurements were increased by 65% for the fiber-containing solution. Fibers' functionality is attributed to fiber-fiber and fiber-particle interfaces. Fiber-fiber networking is essential in the formation of structured flexible networks with high bouncy. Free falling particles are trapped into the bulk of the network, forming one large compound. The formation of a fibrous network containing settling particles reduces the deposition rate of cuttings by physical and hydrodynamic interception, hence better cleanout properties. Furthermore, the presence of anionic polymers with various anionic strengths contributes to the hindering of cuttings settling. An increase in solution anionicity (surface negative charge density) was found to be associated with cuttings suspension; particle-particle and particle-polymer electrostatic repulsive forces creates a situation that prevents the settling of fine particles and preserves their suspension

Base polymeric fluids with higher anionicity result in higher cuttings suspension. Implementation of anionic polymers can aid the lifting force of the drilling fluids by increasing the cuttings carrying capacity, which results in sufficient hole-cleaning performance. Moreover, fiber-containing fluids show good cuttings carrying capacity with insignificant changes to fluid rheological properties. Therefore, they are promoted for hole cleanout applications without any additional pumping cost.

In the future, the outcomes of this work can be utilized as a basis for the formulation of efficient hole cleaning anionic fluids; this includes functionalized (charged) fibers. Furthermore, flow-loop testing of these formulations with different hydraulic systems is needed to evaluate the cleaning performance with higher accuracy and assess their feasibility. Additionally, performance studies on mixtures of different fiber aspect ratios and/or mixtures of various base polymers with different charge density, structure, and molecular weight are essential for optimized FCFs for hole cleaning applications.

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