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DEVELOPMENT OF FIBROUS DRILLING FLUIDS FOR HORIZONTAL WELL CLEANOUT: PARAMETIC INVESTIGATION

BY

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ABSTRACT

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Title: Development of Fibrous Drilling Fluids for Horizontal Well Cleanout: Parametic Investigation

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Drilling fluids enhance drilling efficiency by facilitating cutting transportation, maintaining suspension, regulating pressure, and stabilizing rock formations. Fiber usage in drilling operations improves hole-cleaning efficiency without increasing fluid viscosity. This research investigates fibers' impact on CMC-based polymeric well cleanout fluids' carrying capacity and the influence of polymer and fiber concentrations and cutting size on cutting terminal velocity. In this study, synthetic monofilament fiber and carboxymethyl cellulose polymeric base fluid are used to assess fluid carrying capacity, and therefor, Box-Benhken design was used to analyze, model, and optimize all the parameters to achieve the possible minimum drilling cuttings terminal velocity. Results showed that increasing fiber and polymer concentrations improved the fluid's ability in enhancing its cutting-carrying capacity. Also, it shows that cutting size and polymer concentration significantly influence velocity. 0.85 CMC wt.%, 0.02 3mm fiber wt.%, and 1mm cutting size are the optimal conditions for reducing terminal velocity using Minitab.

DEDICATION

This thesis is dedicated to my parents for their constant motivation to explore my potential, and to my supervisor for his endless encouragement, guidance, and support.

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"My deepest gratitude goes first to my supervisor, Prof. Mustafa S. Nasser, whose proficient and enthusiastic mentorship and constant strive to achieve research excellence helped me accomplish this study. I would also like to extend my sincerest appreciation to my co-supervisor, Prof. Ibnelwaleed Hussain, and my colleagues Mohammed Alhajabdalla and Husameldin Mahmoud from Gas Processing Centre (Qatar University) for sharing their expertise and their significant efforts throughout the experimental work.

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CHAPTER 1: INTRODUCTION

1.1.Research Overview

Coal, natural gas, and other fossil fuels are the main energy sources worldwide. Oil and gas account for 51% of the country's total energy supply, followed by coal (29%), nuclear (4.8%), and renewable energies (10.6%)[1]. According to expert predictions for 2040, the world's demand for oil and gas is expected to continue to rise[2]; half of the world's energy needs will be satisfied by fossil fuels[3]. Drilling activity is anticipated to pick up significantly in 2022, reaching 49600 wells, before sharply increasing to roughly 60000 wells in 2026[4], following a sharp decline in the number of crude oil and gas wells drilled worldwide in 2020 to 39000 wells.

Drilling fluids serves multiple crucial functions during the process of well construction. These functions include facilitating the removal of drilled cuttings from the hole by transporting them to the surface, maintaining equilibrium or surpassing formation pressures within the wellbore to mitigate the risk of well-control complications, providing support and stability to the wellbore walls until casing can be installed and cemented or open hole-completion equipment can be implemented, preventing or minimizing harm to the producing formation(s), cooling and lubricating the drill string and bit, transmitting hydraulic power to the bit, and enabling the retrieval of information about the producing formation(s) through cuttings analysis, logging-while-drilling data, and wireline logs[5].

Drilling additives are substances incorporated into drilling fluids to enhance their overall performance. The additives include viscosifiers, fluid loss control agents, lost circulation materials, and lubricants[6]. Viscosifiers enhance the drilling fluid's viscosity, effectively augmenting its capacity to transport cuttings away from the wellbore[7]. Fluid loss control agents mitigate the quantity of drilling fluid lost to the formation[8]. Lost circulation materials (LCMs) are employed in drilling operations to minimize the undesired loss of drilling fluid into the surrounding formation[9]. Lubricants are used to mitigate friction between the drill string and the wellbore[10].

Fibers are commonly employed as a fluid additive within the oil and gas sector to enhance the efficacy of hole-cleaning, mitigate fluid filtration loss, and improve the effectiveness of hydraulic fracturing operations. Typically, a small amount of fiber is dissolved in the base fluid to produce the desired effects without raising the base fluid's viscosity. However, maintaining a consistent distribution of fibers can be difficult in the presence of wellbore conditions, which is crucial for ensuring the optimal performance of the fibers. Therefore, acquiring a more comprehensive comprehension of the stability of fiber suspensions in base fluids is imperative to enhance their effectiveness in drilling and completion procedures[11].

Fibrous drilling fluids have demonstrated significant promise in removing challenging solid materials resistant to conventional fluid systems. The incorporation of fiber into fluids leads to a significant decrease in the settling velocity of particles, primarily attributed to the establishment of a network structure formed by the fibers[12]. Incorporating fiber into the primary fluid substantially improves the effectiveness of hole cleanout, leading to a substantial decrease in the height of the equilibrium bed[13].

1.2.Tangible Objectives

The objectives of this study were as follows:

1. Improve the understanding of fibrous cleanout fluids theoretically and experimentally.
2. Development of different Fibrous Cleanout Fluid (FCF) based formulations for horizontal wells.

3. Investigate the effect of a viscosifying polymer on the stability of fibrous cleanout fluid (FCF) based formulations.
4. Investigate the effect of different aspect ratio Fibers to enhance the mud-cutting carrying capacity and cutting transportation.
5. Develop numerical models to predict the cleanout performance for different FCFs and recommend the best practices for using FCFs.
6. Performance test for FCF using pilot-scale studies to mimic the industrial operating conditions.

1.3.Research Contribution

Numerous studies have examined the impact of combining fibrous drilling fluids on the cleanout process of horizontal wells. However, to the of our knowledge, the findings of this study will have a significant contribution in the field of oil and gas drilling operations. The major contributions in this study are:

- For the first time, different length/aspect ratios of fibers in well drilling/cleanout formulations are tested on a pilot scale under different operating conditions.
- Detailed parametric investigation of different cleanout parameters (cutting, fibers aspect ratios, polymer dose) using a statical model are well introduced, and final optimized formulations are reported.
- Investigation of the electrokinetic effect of the different polymeric (ionicity) solutions on cutting suspension is reported.

1.4.Research Outcomes (Publications)

1. Mohammed, A. A. A., Alhajabdalla, M., Mahmoud, H., Nasser, M. S., Hussein, I. A., & Ahmed, R. (2023). Settling of Drilling Cuttings in Polymeric Solutions: A Parametric Investigation. ACS Omega 2023,8(24), 21830–21841 https://doi.org/10.1021/ACSOMEGA.3C01505

2. Mahmoud, H., Alhajabdalla, M., Mohammed, A. A. A., Nasser, M. S., Hussein, I. A., Ahmed, R., & Karami, H. (2022). Pilot-scale study on the suspension of drill cuttings: Effect of fiber and fluid characteristics. Journal of Natural Gas Science and Engineering, 101, 104531. https://doi.org/10.1016/J.JNGSE.2022.104531
3. Mahmoud, H., Mohammed, A. A. A., Nasser, M. S., Hussein, I. A., & El-Naas, M. H. (2023). Green drilling fluid additives for a sustainable hole-cleaning performance: a comprehensive review. Emergent Materials, Accepted. https://doi.org/10.1007/S42247-023-00524-W

CHAPTER 2: LITERATURE REVIEW

2.1.Types of Reservoirs

There are numerous categories and classifications for natural gas and oil reservoirs. The Petroleum Resources Management System (PRMS) divides reservoirs into two main categories: conventional and unconventional[14]. Conventional reservoirs are defined as being accessible and not requiring sophisticated technology to recover their storage. Unconventional terms describe reservoirs with different origins, extraction techniques, storage locations, and other characteristics. Due to pressure inside the wellbore, conventional oil drilling techniques are less expensive than unconventional ones because oil/gas fluid flows out of the reservoir.

On the other hand, because the flow pressure in conventional reservoirs is insufficient, complex techniques are needed to extract the oil or gas from the ground. Among other unconventional reservoir techniques, hydraulic fracturing uses water to spread pre-made cracks throughout the wellbore so that oil or natural gas can flow[15], [16]. Coal bed methane (CBM), tight gas, shale gas, and natural gas hydrate (NGH) are significant unconventional resources[17], [18].

Among the numerous significant characteristics of oil and gas reservoirs are permeability and porosity. Rock permeability refers to a rock formation's capacity to transport a fluid (such as gas or oil); the connection of pores within a formation raises reservoir permeability[15], [16]. Rock porosity is calculated as the ratio of pore volume to bulk rock volume **Equation 1**. The geological characteristics of different kinds of oil and gas reservoirs are shown in **Figure 1**. Sandstone and other similar formations have a high permeability because they are made of enormous, well-connected pores. Shale and siltstones have less permeability and fewer interconnected pores than other rock types.

$$\emptyset = \frac{V_{pore}}{V_{bulk}} \quad (1)$$

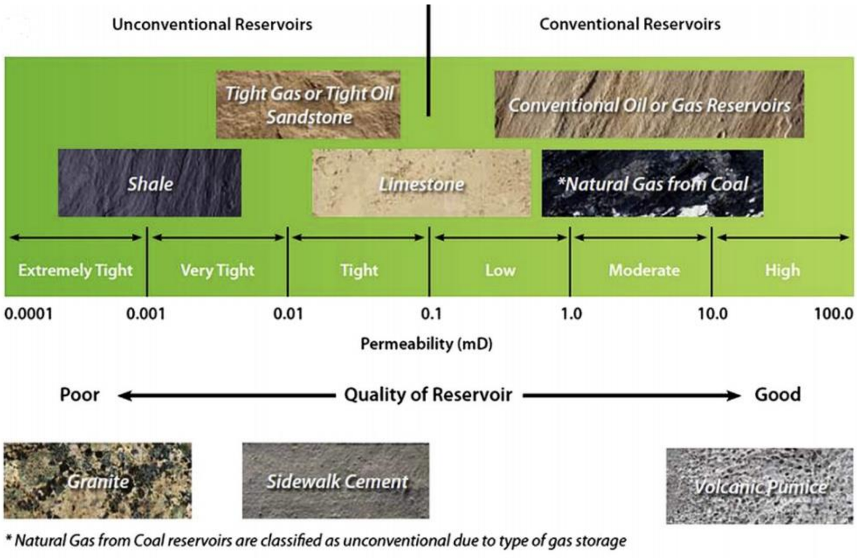


Figure 1. Sources of unconventional gas[19]

2.2.Types of Drilling Muds

Drilling fluids are frequently used and come in a variety of forms. Some wells require different types at different hole depths or a combination of different types. The various fluid types can be roughly divided into a few groups. According to their base substance, drilling fluids can be divided into three categories: water-base, oil-base, and water-oil-base (emulsions). Water-based drilling fluids are the most widely used mud system. Most of the time, they are less expensive, simpler to maintain, and almost as shale-inhibitive as oil muds in a few special kinds of systems. The most basic water-based mud systems begin with water mixed with clays and other chemicals to create a homogeneous mixture that, depending on viscosity, resembles a cross between chocolate milk and malt. The fluid's continuous phase, which is mud, is water. Petroleum products like diesel fuel are used as the base fluid in oil-based mud. Oil-based muds are advantageous for various reasons, such as increasing lubricity, enhancing shale inhibition, having superior cleaning abilities with less viscosity, and withstanding higher temperatures without degrading. Pseudo-oil-based muds and inverted emulsion oil muds are the two types of oil-based muds. It will become an inverted or water-in-oil emulsion if the water content exceeds 5%. Synthetic-based fluid is mud that uses synthetic oil as its base fluid. This is most frequently used on offshore rigs because it has the same properties as oil-based mud but is less harmful than an oil-based fluid. Both synthetic and oil-based fluids present analytical and environmental challenges.

2.3.(WBM and OBM) Environmental Aspects

The world's primary source of energy is provided by the oil exploration and production (E&P) industry. The environmental impacts of E&P activities, however, are a source of worry for people all over the world. The oil and gas industry uses drilling fluids as one of its drilling wastes. The second-largest volume of by-products produced by the E&P industry is drilling fluid and drill cuttings[20]. Drilling operations use both oil-based fluids (OBF) and water-based drilling fluids (WBF)[21]. When drilling wells, drilling fluids perform a number of vital functions. They move back and forth between the well and the platform frequently while drilling an oil well. Once drilling enters the reservoir phase[22], used drilling fluid that has been tainted with oil returns to the surface. If improperly disposed of, the residue can harm terrestrial, aquatic, and aerial ecosystems by reducing soil fertility, harming flora and fauna, and posing health risks because hazardous oil components like benzene, toluene, ethylbenzene, and xylene volatilize into the atmosphere. In this regard, officials have decided that drilling fluids made of non-water and water-containing free oil may not be disposed of in quantities greater than 1%[23]. Treatment of oily waste generated during E&P activities is therefore a significant difficulty. Discharge, down-hole injection, and on-land disposal are all options for managing drilling waste. If they meet certain environmental standards, certain drilling fluids and drill cuttings may be dumped into the sea in different parts of the world. Since the beginning of the 1990s, regulations have been in place that forbid hydrocarbon losses and site closure after drilling without treatment[24]. Technologies for remediation include dewatering, distillation, solvent extraction, cuttings reinjection, fixation, land farming, and (bio) remediation, to name a few. Each of these factors affects how favourable drilling operations are for the economy and the environment[22]. **Table 1** compares WBM and OBM considering the most crucial environmental factors.

Table 1. Comparison between WBM and OBM considering environmental aspects

WBM	OBM
- Environmentally friendly	- Environmentally nonfriendly
- Low initial cost	- High initial cost
- Easy discharge	- Difficult discharge
- No fire hazard.	- Potential fire hazard
- No critical health risk.	- Posing health risks to workers.
- No damaging to rubber parts of the circulation system	- Damaging to rubber parts of the circulation system
- Easy cutting separation	- Difficult cuttings separation

2.4.Cutting Transportation Patterns

Cuttings are solid particles produced by the interaction of the drill bit with the formation. A two-phase flow system is produced due to the generated cuttings blending with the fluid medium. Cuttings and drilling fluid interact hydrodynamically, which affects how the cuttings are distributed in the annulus. Transporting cuttings also depends on the characteristics of the fluid (such as flow rate) and the cuttings (such as size and density). Cuttings flow in pipes can be classified as suspended symmetric, suspended asymmetric, moving bed, and stationary bed **Figure 2**, according to experimental studies[25], [26]. Other reports have further divided the flow patterns into categories like cutting clusters and suspension/saltation clusters[27]. Small particles in the slurry (solid/liquid) mixture settle slowly when arranged horizontally. In these circumstances, the amount of turbulent mixing is greater, resulting in a well-mixed (homogenous) solution of the particles. A vertical concentration gradient (heterogeneous) is seen for particles with a diameter greater than ten microns and various settling rates. A packed bed develops when the particle settling rate exceeds the fluid washing rate.

In a packed bed flow, the fluid flow velocity is divided into four categories: low, moderate, moderate-high, and high flow. As a result of the bed accumulation caused by the low-velocity flow, the pipe will begin to build up pressure. The packed bed will deform at moderate to moderately high flow rates; as a result, the bed moves either in moving bed dunes or separate dunes. Higher flow rates will further deform the sand into smaller bodies and suspended particles, which will then move or creep in the direction of the flow[26], [28], [29].

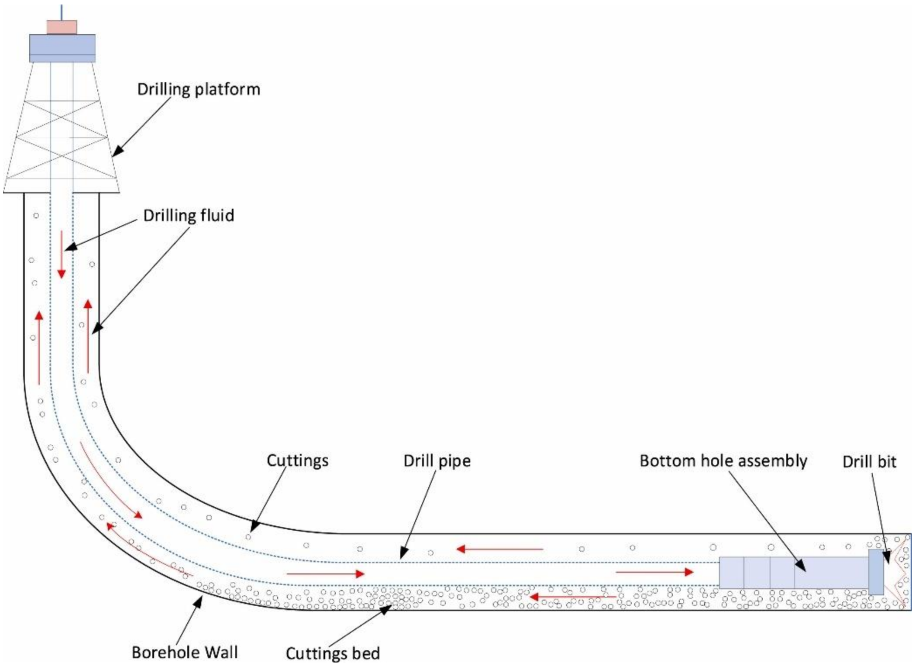


Figure 2. Cutting flow patterns schematic[30]

Cutting transportation in a particular pattern is negatively impacted by fluid flow velocity. Cuttings deposition (bed formation) occurs when fluid velocity is reduced below the Minimum Transport Velocity (MTV), the minimum velocity needed to move cuttings particles. Instead, increasing the fluid velocity above the MTV while a stationary bed is present causes non-uniform shear and pressure to be applied to the cutting surface. These uneven forces bring particle re-suspension into the fluid medium[31], [32]. The three-layer model of cuttings transportation of a stationary bottom bed, a middle moving bed, and suspended moving particles is typically used due to the complexity of field conditions[31].

2.5.Drilling Fluid Additives

Drilling fluid additives are substances added to drilling fluids to improve their functionality and characteristics. Several functions of drilling fluid additives include:

- Viscosifiers: These additives enhance the viscosity of drilling fluids, thereby facilitating the processes of hole cleaning, cuttings suspension, and filter cake formation[6], [7]. Xanthan gum, carboxymethyl cellulose (CMC), and guar gum are among the viscosifiers that are commonly utilized.

- Weighting agents: Incorporating these additives enhances the density of the drilling fluids, thereby facilitating the management of formation pressures and mitigating the risk of wellbore collapse. Barite, hematite, and calcium carbonate are among the weighting agents that can be utilized[33].
- Fluid loss control agents: These additives mitigate the loss of water or oil from the drilling fluids to the formation, thereby facilitating the preservation of fluid volume and the prevention of formation impairment. Fluid loss control agents such as starch, lignite, and asphalt can serve as illustrative examples.
- Shale inhibitors: The utilization of these additives inhibits or mitigates the hydration and dispersion phenomena observed in shale formations, thereby contributing to the stabilization of the wellbore and the mitigation of torque and drag. Potassium chloride, amines, and glycols are among the shale inhibitors that have been identified[34].
- Lubricants: These substances serve as additives that mitigate the friction between the drill string and the wellbore. Their presence facilitates the enhancement of penetration (ROP) rate, minimizes wear and tear, and prevents differential sticking. Various types of lubricants include vegetable oils, esters, and graphite[10].
- Fibers: These additives facilitate the formation of a cohesive network within drilling fluids, thereby contributing to the optimization of cuttings transport, reduction of particle settling velocity, and enhancement of hole cleaning efficiency[11]. Various types of fibers can be identified, including synthetic monofilament, natural, and glass fibers.

2.6.Main Types and Characteristics of Fibers Used in Drilling Fluids

Fibers are supplementary components that establish a cohesive structure within drilling fluids, thereby facilitating the optimization of cuttings transport, mitigation of particle settling velocity, and enhancement of hole cleaning efficiency. Several primary categories and distinguishing features exist about the fibers employed in drilling fluids.

- Synthetic monofilament fibers: thin strands of synthetic materials, such as polypropylene, polyester, or nylon, are observed in this context. The materials in question exhibit a relatively low specific gravity, approximately 0.9, alongside a notable tensile strength and commendable chemical and temperature resistance[35]. Drill cuttings suspension in polymeric fluids can be enhanced by using particles with diverse lengths ranging from 3 to 12 mm and concentrations spanning from 0.00 to 0.08 wt%[34].
- Natural fibers: These fibers are made from raw materials like cellulose, cotton, or wool. Synthetic fibers exhibit superior characteristics to natural fibers, including higher specific gravity (approximately 1.5), greater tensile strength, and enhanced resistance to chemicals and temperature[36]. Different forms (e.g., chopped, ground, or milled) and concentrations (ranging from 0.5 to 2.0 wt%) can augment water-based mud's viscosity and fluid-loss control.
- Glass fibers: These fibers are composed of glass or silica materials. The material exhibits a notable specific gravity of approximately 2.5, possesses considerable tensile strength, and demonstrates significant chemical and temperature resistance[37]. The utilization of these additives spans a range of dimensions, ranging from 1 to 10 mm, and concentrations, varying from 0.1 to 0.5 weight percent. This application serves to enhance the robustness and flexibility of oil-based drilling fluids[38].

2.7.Fibers Effects on the Rheological Properties and Stability of Drilling Fluids

Fibers are among the additives that can potentially influence drilling fluids' rheological characteristics and stability. Rheological properties encompass the fundamental attributes of a fluid that elucidate its flow dynamics, including viscosity, shear stress, and shear rate[39]. Stability pertains to the fluid's capacity to uphold its inherent characteristics and operational efficacy across diverse circumstances, encompassing variations in temperature, pressure, and contamination levels. Many studies have examined the impact of fibers on drilling fluids' rheological properties and stability. These investigations have focused on:

- Rheological Behavior and Filtration of Cellulose Fiber-Containing Water-Based Drilling Fluids. The present study investigated the impact of cellulose fibers on various rheological properties, including viscosity, yield stress, gel strength, and filtration characteristics of water-based drilling fluids. The study revealed that including cellulose fibers in fluids can enhance viscosity and yield stress while mitigating fluid loss and reducing filter cake thickness[40].
- Drilling Fluid Rheological Properties Measurement in Real-Time Using a Fiber Bragg Grating Sensor. This investigation introduces an innovative approach to assess the rheological characteristics of drilling fluids by employing a fiber Bragg grating (FBG) sensor. The FBG sensor, a variant of an optical fiber sensor capable of detecting alterations in strain and temperature, is utilized in this research. The proposed methodology enables the real-time and highly accurate measurement of fluids' apparent viscosity, plastic viscosity, and yield point[41].
- Synthetic polymers used as fluid loss additives in water-based drilling fluid have rheological and filtration properties that are influenced by the molecular flexibility of the molecules. This investigation aimed to examine the impact of molecular

flexibility on the efficacy of synthetic polymers when used as additives to mitigate fluid loss in water-based drilling fluids. It has been observed that enhancing molecular flexibility can lead to enhancements in the rheological characteristics and a decrease in the filtration rate of fluids[42].

2.8. Fibers Influence the Cutting's Transport and Suspension Behavior in Horizontal Wells

The optimization of drilling fluid performance in horizontal and deviated wells necessitates careful consideration of cutting transport and suspension. This is particularly crucial due to the tendency of cuttings to accumulate at the lower side of the annulus, resulting in the formation of a bed. Problems like decreased hole cleaning, increased torque and drag, stuck pipes, and formation damage may result[43].

Fibers are among the additives that have the potential to impact the cutting transport and suspension characteristics in horizontal wells. Fibers can function as bridging agents, viscosifiers, and suspending agents, with their specific role being contingent upon their type, concentration, and size[12], [44]. Several research studies have examined the impact of fibers on the cutting transport and suspension in horizontal wells. Examples of such investigations include:

- Drilling cutting transport in a horizontal wellbore is modeled and simulated numerically. This investigation employed a computational fluid dynamic (CFD) and discrete element method (DEM) framework to simulate the fluid flow and cutting motion within a horizontal wellbore. The research revealed that incorporating fibers into the drilling fluid can enhance the efficiency of cutting transport, which is achieved by forming a network structure that effectively captures and hinders the settling of cuttings[45].
- Cutting Transport in Horizontal and Deviated Wells Using Coiled-Tube Drilling: Flow Patterns and Minimum Suspension Velocity. This research employed

experimental data and empirical correlations to examine the flow patterns and determine the minimum suspension velocity of various drilling fluids in horizontal and deviated wells. The study determined that incorporating fibers into the drilling fluid can effectively decrease the minimum suspension velocity, augmenting the fluid's apparent viscosity and yield stress[26].

2.9. Advantages and disadvantages of using fibrous fluids in horizontal well Cleanout

The process of horizontal well cleanout involves the removal of accumulated solids and debris from the wellbore, which can negatively impact the well's productivity and integrity. Fibrous fluids refer to a specific category of drilling fluids that incorporate fibers as supplementary components. These fibers augment the efficacy of hole cleaning by establishing a network structure that effectively captures and transports solid particles[46].

Table 2. Advantages and disadvantages of using fibrous fluid in horizontal well cleanout.

Advantages	Disadvantages
Enhancing the conveyance and suspension of cuttings in horizontal and inclined wellbore configurations by reducing the settling velocity of cuttings[47].	May not exhibit a discernible enhancement in the case of high-viscosity fluids, which already have commendable efficacy in hole cleaning[48].
Maximize the hole-cleaning effectiveness of low-viscosity fluids by increasing their apparent viscosity and yield stress[48].	Improve pumping power and reduce flow rate by increasing the friction pressure in the annulus[47].
Mitigate the occurrence of formation damage and enhance the stability of the wellbore by minimizing the loss of fluid and the production of filter cake[47].	may be incompatible with additives or forms, affecting performance and rheology[47].

2.10. Gap Analysis

Several crucial aspects of drilling fluids have not been adequately addressed in contemporary and historical studies. In order to investigate the effectiveness of fibrous fluids in the process of hole cleaning in horizontal and inclined well configurations, Elgaddafi conducted a study in 2020[47]. The study was undertaken to examine the impact of fiber on suspensions of Xanthan gum during the cleanout procedure. However, there remains a dearth of theoretical and experimental advancements in comprehending the characteristics and behavior of fibrous cleanout fluid. Moreover, recent research has not yielded an alternative formulation for Fibrous Cleanout Fluid (FCF) specifically designed for use in horizontal wells. A stability test for formulations based on fluid catalytic cracking (FCF) has not been developed to examine the impact of a viscosifying polymer.

Additionally, no numerical models currently can forecast the cleanout performance of various FCFs and suggest the optimal operational conditions for using FCFs. A performance test for FCF using pilot-scale studies to replicate industrial conditions was not conducted. Furthermore, a comprehensive understanding of the impact of various aspect ratio fibers on enhancing mud-cutting carrying capacity and cutting transportation is currently lacking.

CHAPTER 3: THE EFFECT OF FIBERS ON THE CUTTINGS CARRYING CAPACITY OF CARBOXYL METHYLCELLULOSE (CMC)-BASED POLYMERIC FLUIDS: PILOT SCALE TESTING

3.1.Introduction

The drilling process utilizes mud as a working fluid, accounting for 15-18% of the total drilling operation cost[49]. Drilling fluids are made to perform various tasks that call for various performance qualities, such as removal of cuttings wellbore physical stability, drill bit lubrication and cooling, and control of filtration loss[50]–[52]. Drilling fluids' functionality and efficiency are determined mainly by their properties, including but not limited to their interdependent rheological and hydraulic properties. Interdependence frequently encourages operational complexity[53]. Hole cleaning (cuttings removal) in deviated and horizontal wells continues to be a complex problem despite the development and ongoing intensive research on drilling fluids from academia and industry[54], [55]. Inadequate hole cleaning or cuttings transportation can cause excessive drag and torque, reduced penetration (ROP) rate bit wear, and fractures caused by gradual blockage, which increases fluid loss and lost circulation[52]. Poor hole cleaning issues can increase the drilling operational cost and non-productive time (NPT) or, in severe cases, force the abandonment of the wellbore due to technical difficulties[56].

Over time, drilling fluids have evolved to meet various needs and requirements, increasing in cost and complexity. To better select and use the right fluid for a given operation, there is a need to understand the characteristics of drilling fluid better. Cuttings are produced at the drill bit as drilling progresses; after production, rock shavings mix with fluid to form a solid-liquid system, where various forces act on the shavings and the area around them[26]. A particle suspended in a moving fluid is subject to axial hydrodynamic drag, lateral lift force, upward buoyancy, and downward gravity throughout the transport process. When the magnitude of the net upward forces is less than the downward forces, drilled cuttings will gather on the low side of the wellbore and produce stationary cutting beds within the annulus[57]–[59]. Due to their significant effects on the forces acting on the cuttings, drilling fluid properties are essential for efficient cutting transport[60]–[63]. Drilling fluid properties must be sufficient under low shear rate conditions to avoid bed formation and cuttings sedimentation specifically.

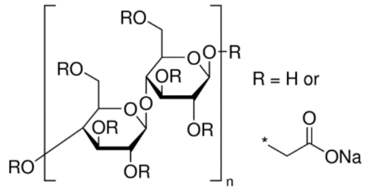
Water-based mud (WBM) enhancement research has made significant strides recently. Various additives are being researched to enhance these fluids' rheological properties and carrying capacity. For instance, it is thought that natural fibers, synthetic fibers, and polymeric beads can improve the transport of cuttings by creating hydrodynamic interference between the cuttings and additives[64]–[68]. Ahmed and Takach examined the effectiveness of fibers in horizontal and deviated wells in 2009[68]. Their findings demonstrated that fibers may prevent particles from settling. Cuttings deposition is hampered by the drag forces that fiber increases on the particles[69]. The density of the base suspension or mud charge can be increased by incorporating fiber particles, which ultimately increases the carrying capacity of the cuttings[12]. Since low-viscosity suspensions can't evenly suspend fibers for long, two distinct layers, an upper fiber layer, and a lower suspension layer, clearly separate and form[70]. Since the functionality of fibrous suspension depends on its stability, fibrous fluids must be prepared with fibers whose specific gravities are very close to those of the base fluid to prevent fiber separation brought on by density differences[11]. Numerous studies have also shown that wellbore angle (vertical, deviated, and horizontal) affects cuttings transportation performance. Since a single wellbore can acquire all types of inclinations, a practical application calls for efficient cutting transportation at all inclinations[71]–[74]. Few pilot-scale studies have been conducted on the cleaning effectiveness of fibrous fluids, particularly in vertical configurations and large cuttings. Additionally, this work investigates how well polypropylene low aspect ratio fibers clean. This experimental study aims to determine whether fibers with various aspect ratios can increase the cutting-carrying capacity of polymeric fluid systems.

3.2.Experimental Setup and Methods

3.2.1. Materials

The synthetic fibers used in this investigation were white virgin polypropylene monofilament fibers (FORTA Super-Sweep® Fiber), with a specific gravity of 0.91 and an average melting point of 172 C. We used fibers with dimensions of 100 µm in diameter and 3 and 12 mm in length (with respect to aspect ratios of 30 and 120). Carboxymethyl Cellulose (CMC) polymer was used to create fluids with various water content concentrations. Tap water was used to prepare each suspension. In place of actual cuttings, inert glass beads with a size range of 1 to 6 mm were used. The characteristics and source of each material, where applicable, are summarized in **Table 3**.

Table 3. Materials characteristics and properties

Name	Characteristics	Source	Structure/Shape
Carboxy Methyl Cellulose Sodium (CMC)	CAS No.: 9004-32-4 Molecular Weight: 242 g/mol Purity: 99.5% (min)	Arshine pharmaceutical co. Ltd, Hunan, China	

Name	Characteristics	Source	Structure/Shape
Fibers	Specific Gravity: 0.9 Length: 3.175 mm, 12.7 mm Diameter: 100 µm Environmental effect: LC50 value of 1 million, Safe	FORTA Super-Sweep, Pennsylvania, USA	Composition: Virgin Polypropylene Structuer: Monofilament fibers
Glass Beads (Cuttings)	Composition: Borosilicate Diameter: 1,3, & 6 mm Specific Gravity*: 2.4, 2.3, 2.5, for 1,3, and 6 mm, respectively.	ISOLAB GmbH, Wertheim, Germany (3 & 6 mm) YIWU SANJIA Electronic Commerce Co., Ltd. Zhejiang, China (1 mm)	Shape: Spherical Reactivity: inert Color: White-transparent

3.2.2. Fluid Preparation and Formation

In a mixing tank, weighted amounts of polymer were gradually added to water. The tank was filled with polymer powder while mixing at 600 rpm. A prolonged mixing period of 1-3 hours at a faster rotational speed (600-1200 rpm) was then performed after the initial mixing of 30 minutes. Depending on the polymer's concentration and ability to disperse, different mixing times and levels of shearing were used. The suspensions were allowed to hydrate for 24 hours while the mixing speed was kept at its ideal level to ensure efficient mixing and prevent lump formation and intensive mixing, which can cause air bubbles to be introduced into the suspension.

After hydration, the polymeric suspension was stirred for 10 minutes to ensure homogeneity. The polymeric mixture was mixed at 4000-6000 rpm for 2 minutes while adding fibers. The fiber clumps were manually broken up with a spatula to ensure good fiber dispersion before being added to the polymer suspension. In **Table 4**, the test matrix is displayed. The ambient temperature (20 °C) was used for all experiments.

Table 4. Test Matrix

#	Polymer Concentration (wt.%)	Fiber Concentration (wt.%)	Fiber length (mm)	RPM	Reynold Number	Taylor Number
1	0% CMC	Fiber-free	-	0	0	0
2	0% CMC	0.02% fiber	12	0	0	0
3	0% CMC	0.06% fiber	12	0	0	0
4	0.747% CMC	Fiber-free	-	0,20,55	0,24,81	0,33,110
5	0.747% CMC	0.02% fiber	3 &12	0,20,55	0,24,81	0,33,110
6	0.747% CMC	0.06% fiber	3 &12	0,20,55	0,24,81	0,33,110
7	1.1% CMC	Fiber-free	-	55	31	42
8	1.1% CMC	0.04% fiber	12	55	31	42
9	1.1% CMC	0.08% fiber	12	55	31	42

Fiber stability is known as the capacity of fibers to disperse within a solution uniformly over an extended period. Polymeric suspensions are anticipated to display good stability by preventing the segregation of fiber particles. For 80% fiber stability, CMC suspensions with more than 0.4 wt% polymer concentration are advised[11]. Additionally, CMC suspensions combined with fibers and up to 0.8 wt% polymer concentration could increase cuttings carrying capacity[12].

In vertical and slightly inclined boreholes, increasing fluid viscosity enhances cuttings lifting performance[75]. Alternately, increasing fluid viscosity can have a negative impact on the hole-cleaning procedure of horizontal wells[76]. This variation in cutting transport mechanisms between inclined and horizontal wellbores, which depends on the flow regime and forces acting on the cutting particles, may be related to this difference. Turbulence tends to increase the carrying capacity of drilling fluids due to its disruptive action. Therefore, experiments were carried out at low Reynolds and Taylor numbers to reduce the impact of turbulence and the secondary flow on our carrying capacity measurements. For a concentric annulus with inner pipe rotation, the Reynolds number is written as follows:

$$Re = \frac{\rho\omega r_i(r_o - r_i)}{\mu_{eff}} \quad 2$$

where r_i and r_o are the inner and outer radii of the pipe, respectively, and ρ is the fluid density and angular velocity. The effective viscosity μ_{eff}, which is determined for a power-law fluid from the wall shear rate ($\dot{\gamma}_w$), is calculated as follows:

$$\mu_{eff} = k\dot{\gamma}_w^{n-1} \quad 3$$

where n is the fluid behavior index, and k is the flow consistency index. According to Lockett et al. (1993)[77], the generalized Taylor number for the annular flow of non-Newtonian fluids with a rotating inner pipe is as follows:

$$T_a = r_i(r_o - r_i)^3\left(\frac{\rho\omega}{\mu_{eff}}\right)^2 \quad 4$$

The wall shear rate of rotational flows can be determined by applying the narrow slot approximation as:

$$\dot{\gamma}_w = \frac{\omega r_i}{(r_o - r_i)} \quad 5$$

3.2.3. Experimental Setup

Figure 3 presents a schematic illustration of the experimental configuration. The apparatus includes a rotating shaft in the fully transparent test section, a fluid preparation and collection tank, a separation sieve, and a transfer pump. The height and diameter of the test section are 150 and 19.5 cm, respectively. A concentric annulus is created in the test section by a 9-cm rotating shaft powered by a 1-HP electric motor with a maximum speed of 900 RPM capacity. The rotating shaft's bottom end is attached to a 10 cm-long piece of uneven terrain. The total volume of the test section is 0.0354 m3 (35.4 L). A manual drain valve manages the discharge at the test section's base. Clear acrylic tubes were used for the test section and piping, allowing for visual inspection of the fiber-particle interaction.

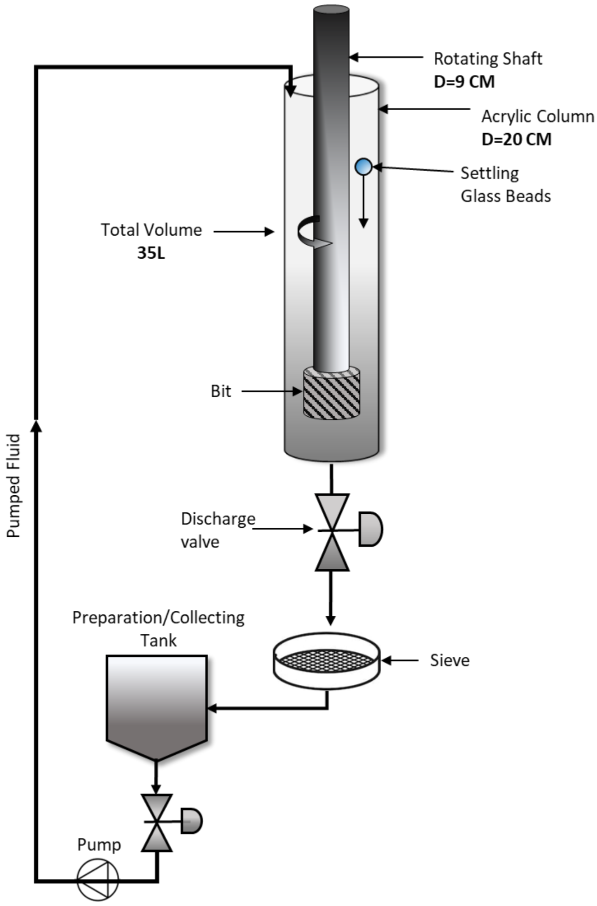


Figure 3. Schematic of the test section

3.2.4. Pilot-Scale Test Procedure

Different fiber and polymer concentrations, cutting sizes, and shaft rotation speeds were used in the experiments. **Figure 4** displays a block diagram that depicts the experimental process. Preparing the test fluid, as described in Section 3.2, was the first step in the experiment. After the preparation, a representative sample was taken to use a rheometer to measure the rheological properties. The mixing tank was then gradually filled with fibers as it was stirred at a speed of 5500 RPM. To ensure that the fiber particles were evenly distributed, the agitation was kept up for 5 minutes. A centrifugal pump was then used to pump the combined solution into the test section. 750 RPM was applied to the inner shaft during the transfer process. Glass beads of the required size and quantity (354 g) were then injected to create a 1% (wt.) solid suspension after the shaft speed had been adjusted. For 2.5 minutes, the fluid was allowed to remain below the prescribed shaft rotation speed. Finally, cuttings within the suspension in the test section are separated before the bottom 20% of the suspension is discharged. To speed up the drying process, an oven with a temperature of 100 (°C) was used to dry the cuttings. **Equations 6** and **7** were used to weigh the dried cuttings to calculate the deposited and suspended cuttings concentrations.

$$\text{Deposited cutting concentration (DCC)} = \frac{\text{Weight of cuttings from the bottom 20\%}}{\text{Weight of total injected cuttings}} \text{x} 100 \qquad 6$$

$$\text{Suspended cuttings concentration (SCC)} = 100 - \text{DCC} \qquad 7$$

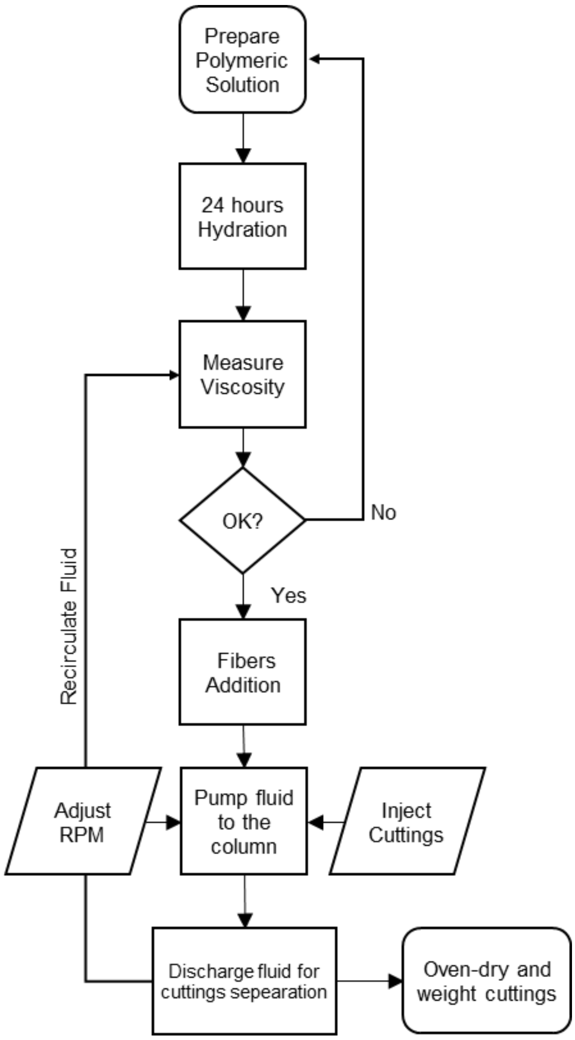


Figure 4. Flow chart of the experimental procedure

3.2.5. Rheological Tests

Most of the test fluids are categorized as non-Newtonian fluids with significant yield stress and shear-thinning behavior. According to the yielding behavior, these fluids must first experience a certain level of shear stress before they can begin to flow. Given these characteristics, non-Newtonian fluids appear to be the best option for suspending rock shavings and lowering pressure losses at high flow rates.

The flow behavior of test fluids was evaluated using a rheometer. The method described in Section 3.3.2 was followed in preparing the polymeric suspensions of CMC. An Anton Paar Modular Compact Rheometer (MCR) 302 Rheometer was used for the experiments, which used Couette cells with diameters and lengths of 24 and 30, respectively. The measurements were made with a shear rate ranging from 0.01 to 100 1/s at 20 1.0 °C room temperature. Various rheological models have been used to illustrate the non-Newtonian behavior of test fluids.

The non-Newtonian behavior of shear-thinning fluids can be modeled using a variety of rheological theories. The relationship between shear stress and shear rate in most of the drilling and completion fluids is described by the generalized Herschel-Bulkley model $\tau = \tau_o + k\dot{\gamma}^n$[69]. This model is created by incorporating the shear stress necessary to start the flow into the power-law model $\tau = k\dot{\gamma}^n$, where is the shear stress, k is the fluid consistency index, $\dot{\gamma}$ is the shear rate, n is the fluid behavior index, and τ_0 is the yield stress. For non-Newtonian fluids, the apparent viscosity (η_{app}) can be calculated using the formula: $\eta_{app} = \tau/\dot{\gamma}$.

3.3.Results

3.3.1. Rheology Test

3.3.1.1.Effects of Polymer Concentration

The polymer's impact on the base fluid's rheological characteristics was investigated through rheology tests. The Herschel-Bulkley model regression line and the power-law (Ostwald) line are shown alongside the flow curve of polymeric suspensions in **Figure 5**. Due to technical restrictions on the rheometer, the shear rate was restricted to 1-100 1/s. The flow curves show how the fluids behave when thinned by shear. Over the entire range of shear rates, the apparent fluid viscosity increased with an increase in polymer concentration from 0.747 to 1.1%. Both concentrations of polymeric suspensions exhibit significant shear thinning. The model parameters from Ostwald and Herschel-Bulkley (**Table 5)** confirm shear-thinning strengthening with the polymer concentration. High-shear rate data points are used to calculate the flow consistency coefficient and behavior index. The linearized Herschel-Bulkley equation based on low-shear rate data points yields the yield stress term of the Herschel-Bulkley model from its y-intercept.

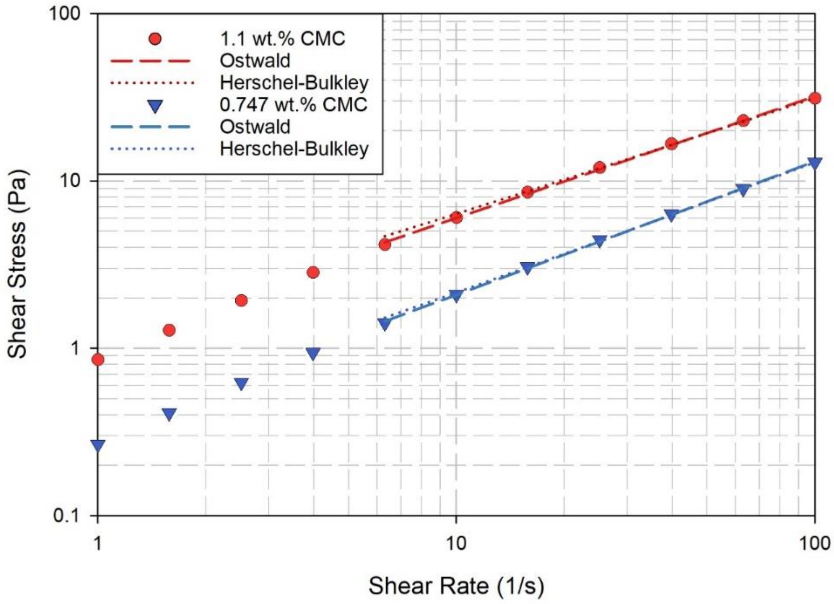


Figure 5. Flow behavior of fiber-free polymeric suspensions

Table 5. Ostwald & Herschel-Bulkley model parameters

CMC (wt.%)	Ostwald				Herschel-Bulkley				
	n	k (Pa.s)^n	RMS	R^2	n	k (Pa.s)^n	τ_0 (Pa)	RMS	R^2
0.747	0.80	0.334	0.088	0.99	0.79	0.339	0.069	0.098	0.99
1.1	0.73	1.132	0.34	0.99	0.71	1.187	0.305	0.444	0.99

3.3.1.2.Effects of Shear Degradation and Aging

Throughout the 6-day experimentation period, fluid samples were taken every day before the test to investigate suspension stability and shear degradation. Samples from the mixing tank were taken to assess the rheological property changes brought on by repeated mixing, sharing, pumping, and aging during the testing period. **Figure 6** represents the 6-day rheological measurement of the samples. Overall, five samples were tested; four samples were obtained over the course of four consecutive days, and the final sample was obtained following two days of storage. The test fluid used for the experimental runs was the same batch from which all samples were drawn. The suspension's rheological properties over a period of four consecutive experimental days were found to be barely affected by storage and use, according to the results. A fresh batch of test fluid was made and given 24 hours to hydrate after four days of experimental runs to reduce the experimental error.

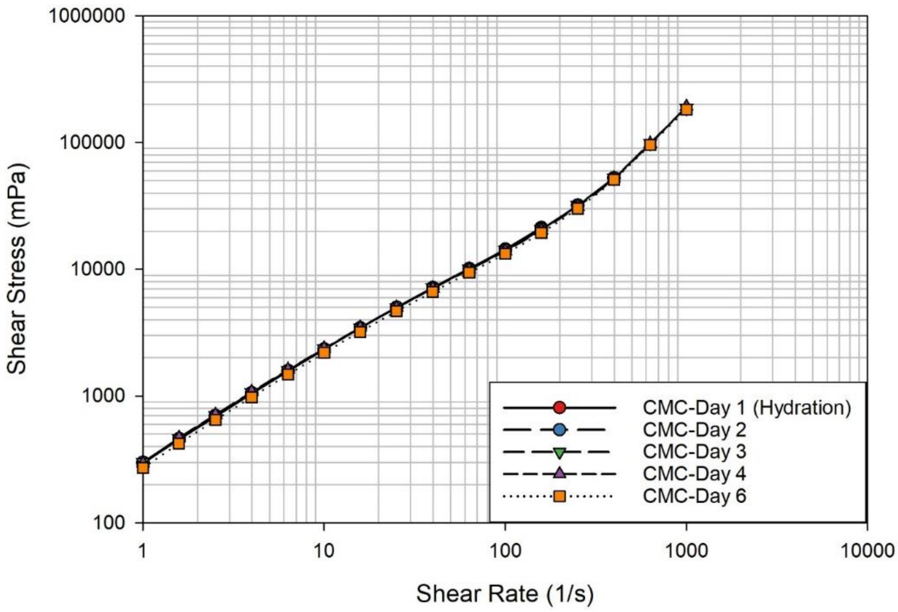


Figure 6. Rheological characteristics 0.747% CMC suspension over 6 days of experimentation

3.3.2. Effects of Polymer and Fiber Concentrations

The ability of fibers to improve the carrying capacity of fluids was tested in various base fluids. A moderate increase in suspended cuttings concentration (SCC) following the tests **Figure 7-a** shows that when water was used as the base fluid, increasing fiber concentration did not significantly affect the fluids' ability to carry solids. Water could not produce a homogeneous suspension of fibers, as demonstrated by the visual observation of the particle sedimentation process. The main cause of the limited performance of fiber in water may be fiber separation [11]. The addition of polymer helped to stabilize the homogeneous fiber suspension, demonstrating the role of fiber in increasing the fluid's ability to carry solids **Figure 7-b**. Fiber addition significantly influenced solid particles' settling time (1 mm). The SCC went from 5% to 18% with the addition of fibers up to 0.06%.

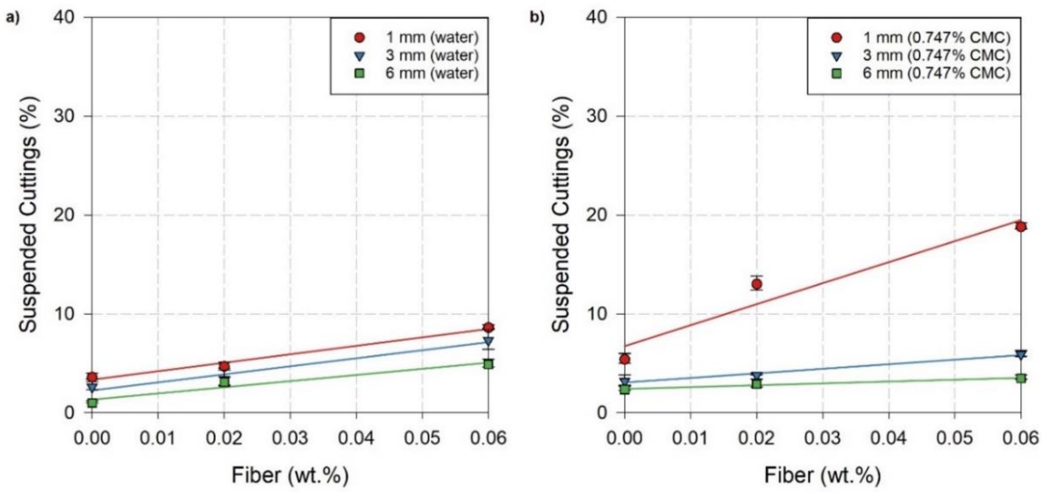


Figure 7. Cuttings suspension against fiber concentration and cuttings size: a) Water; b) 0.747% CMC, 0 RPM, and using 12 mm fibers

The addition of fiber resulted in a slight improvement in SCC for Coarse particles (3 and 6 mm). Their SCC comparison between base fluids with and without fibers reveals a slight increase in carrying capacity due to the fibers. The fiber effect was more pronounced for fine (1 mm) particles when 0.749% polymer concentration was used.

Figure 8 shows the impact of increasing polymer concentration from 0.747 to 1.1% while the shaft rotates (at 55 RPM) on the fluid's carrying capacity. Figures 5a and 6a show that without fiber, the increase in polymer concentration and shaft rotation caused the SCC of 1-mm solids to rise from 4% to 17%. Additional progress in SCC was seen after fiber was added. In a 0.747% polymer suspension, a gradual increase in fiber concentration from 0 to 0.06% improved the SCC of 1-mm solids from 17 to 31.6% (an 85% improvement). A 1.1% polymer suspension improved the SCC from 38.9% to 52.9% (a 36% increase). Due to the rise in fiber and polymer concentrations, the SCC of the coarse cuttings (3 and 6 mm) slightly improved. These findings show that the polymer concentration affects how much the SCC improves due to fiber addition. The effect of fiber addition on the SCC was more noticeable at low polymer concentrations (0.747%). When the viscous drag is insufficient because of the restricted fluid viscosity, this observation can be explained by considering the predominating role of the fiber drag (i.e., mechanical, and hydrodynamic drag forces associated with the fiber network formation in the fluid)[78].

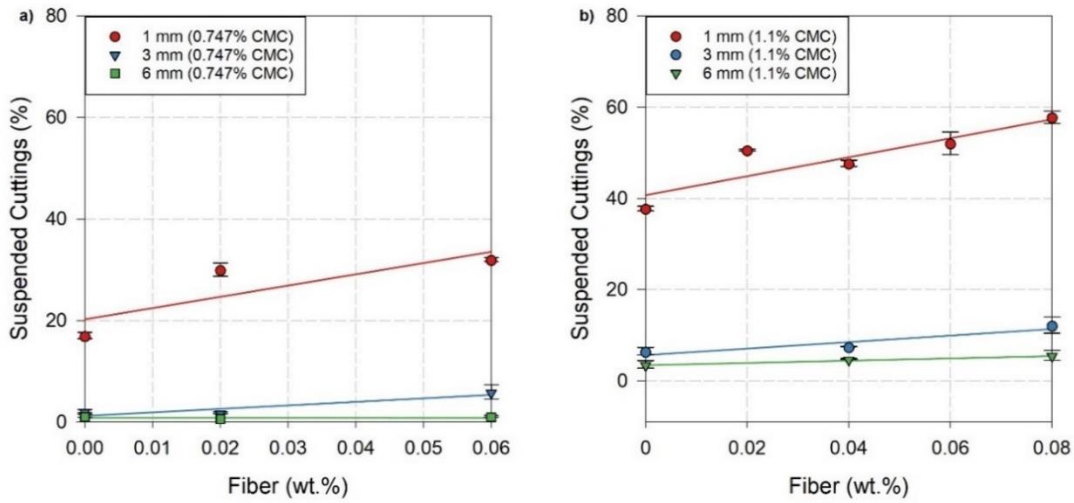


Figure 8. Cuttings concentration vs. fiber concentration at 55 RPM and using 12 mm fibers for different cuttings sizes and polymer concentrations: a) 0.747% CMC; b) 1.1% CMC

3.3.3. Effect of Inner Pipe Rotation

Numerous variables, including formation type, hole size, bit rotation speed, weight on the bit, and bit type, can affect the penetration rate (or wellbore drilling speed)[79]. Therefore, in the absence of a downhole motor, the rate of penetration (ROP) is directly influenced by the drill string rotation speed. **Figure 9** illustrates the impact of drill string rotational speed on fiber performance in enhancing fluid carrying capacity (i.e., increasing SCC). Two different behaviors were seen for coarse (3 & 6 mm) and fine (1 mm) cuttings with pipe rotation. The SCC of coarse cuttings was primarily slightly reduced when rotation speed was increased at a particular fiber concentration. Despite this, the pipe rotation had a favorable impact on the SCC of fine cuttings. Regardless of the fiber concentration, these contradictory observations happened. The existence of settling enhancing and hampered phenomena occurring under dynamic conditions could explain the contradiction.

On the one hand, the shaft's rotation could make the fluid appear less viscous by raising the shear rate that results from it ($\dot{\gamma}_R$). The base fluids exhibit a strong shear-thinning behavior, which causes the reduction in apparent viscosity to be more pronounced. The resultant shear rate for sedimentation in a Couette flow field can be calculated as follows: $\dot{\gamma}_R = \sqrt{\dot{\gamma}_s^2 + \dot{\gamma}_r^2}$, where $\dot{\gamma}_s$ and $\dot{\gamma}_r$ are the settling and rotational shear rates, respectively. The settling is made worse by reducing viscosity, which reduces viscous drag. On the other hand, the pipe's rotation may cause turbulence and secondary flows that result in diffusion mechanisms and slow the rate at which the particles settle. Even though experiments were carried out at low Taylor and Reynolds numbers, the rotating shaft's vibration likely caused turbulence to form, negating the apparent viscosity reduction. Fine particle dispersion in fluids can be accomplished effectively through diffusion[58]. However, as the particle size increases, it loses its effectiveness. The current findings imply that for fine (1 mm) particles, the effect of diffusion predominated over the impact of apparent viscosity reduction, whereas this was not the case for coarse (3 & 6 mm) particles.

Regardless of the inner shaft rotation, there was little impact of fiber on the SCC of 6-mm cuttings. The SCC of 3 mm cuttings significantly increased when the fiber concentration was raised to 0.06%. No matter how quickly the shaft rotated, the effect of fiber in the case of 1 mm cuttings consistently increased their SCC.

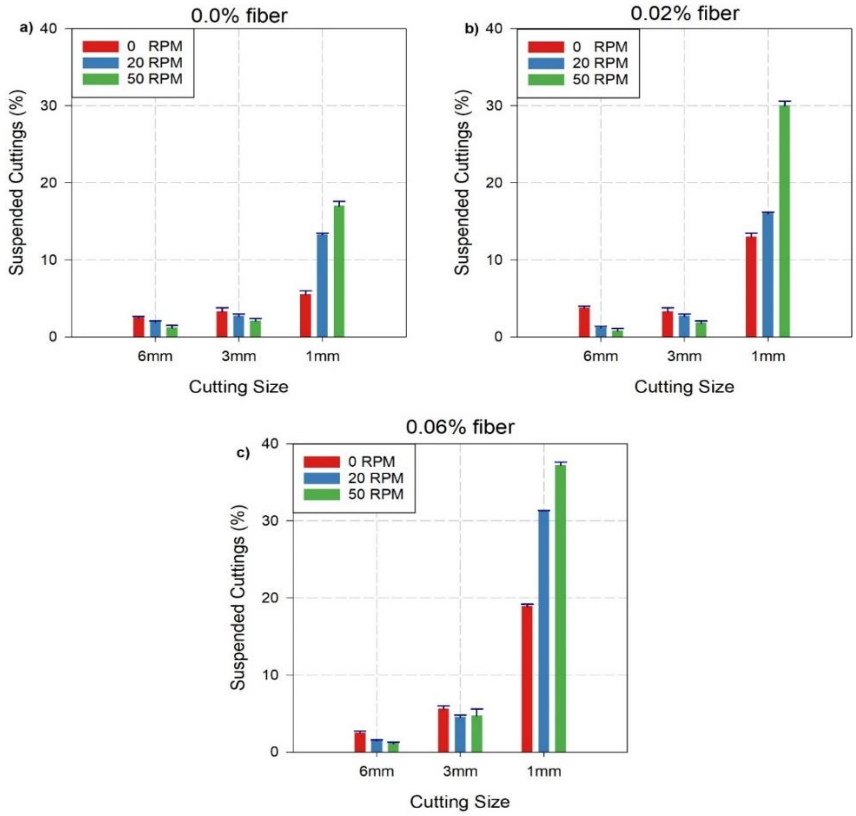


Figure 9. Suspended cuttings concentration vs. cuttings size using 0.747% polymer concentration, different cuttings sizes (1, 3, and 6 mm) and rotation speeds (0, 20, and 50 RPM), and for various fiber concentrations: a) 0.0% fiber; b) 0.02% fiber; c) 0.06% fiber

3.3.4. Effect of Fiber Length

The carrying capacity of fluids should be affected differently by fibers with the same diameter but different lengths. Short fibers have a limited capacity for network formation, whereas long fibers have robust fiber-to-fiber interactions and the potential to form a structured network[11]. However, the smooth operation of downhole tools can be jeopardized by long fibers, as evidenced by laboratory and field observations **Figure 10**. These problems have recently motivated researchers to examine the incorporation of long and short fibers at various mixing ratios to increase the fibers' applicability. To investigate this, short (3 mm) and long (12 mm) fibers were mixed at different fractions, ranging from 0 to 100 wt.%.

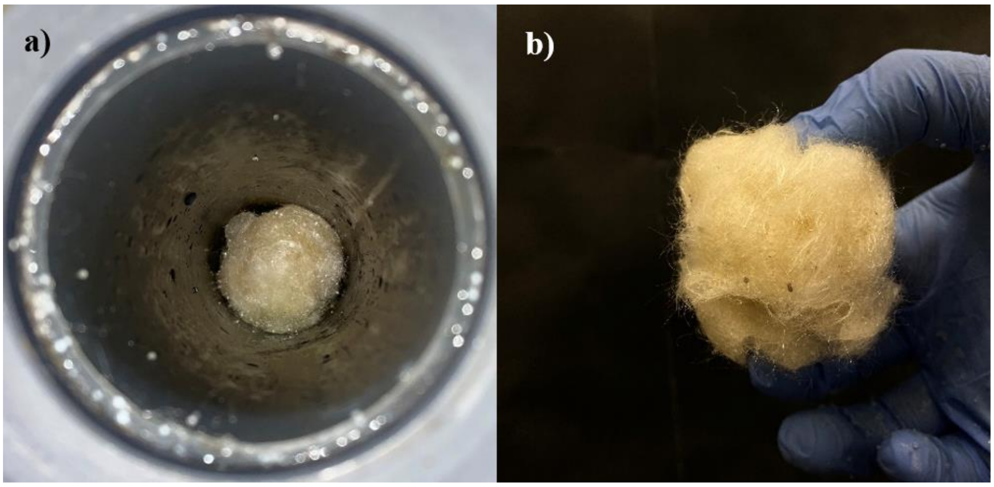


Figure 10. Fiber cluster blocking system pipes; a) fibers inside the pipe; b) extracted fibers

Figure 11 shows how mixing long and short fibers affects SCC. Compared to the right-end, the left-end represents 0% long fiber and 100% short fiber. The SCC of 3 mm cuttings did not significantly improve when mixing short and long fibers. However, in the case of 1 mm cuttings, the SCCs obtained using mixed fiber were significantly higher than those obtained using unmixed fiber. The fiber particle length impacts the propensity for networks to form. Short fibers make up four times as much fiber as long fibers, giving them a greater boost in bouncy force for the same amount of fiber. The advantages of long fibers over short fibers, which are absent in short fibers, include establishing long-range fiber-fiber interactions. To create a fiber network with a large number of fiber particles and at the same time have long-range fiber-fiber interactions, fibers of different lengths are mixed. As a result, pipeline blockage issues brought on by long fiber entanglements could be avoided without affecting the effectiveness of cuttings transport. There was a slight improvement in SSC from 20.4% to 34.3% when the mass fraction of the long fiber was maintained between 50% and 75%, despite the fact that the effect of fiber mixing on the SCC of 1 mm cuttings was minimal.

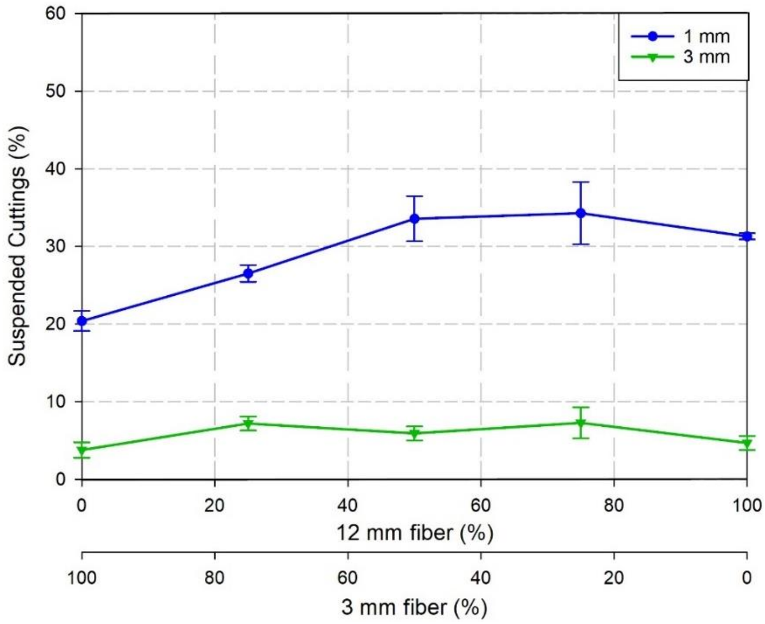


Figure 11. SCC vs. fiber mass fraction in 0.747% polymer suspension at 0.06 wt.% fiber, and 55 RPM

3.4.Conclusion

The cutting carrying capacity of fibrous polymeric suspensions was thoroughly investigated in a pilot unit with a vertical annular test section with a rotating inner shaft simulating the drill string. Experimental parameters, including fiber concentration, polymer concentration, cuttings size, shaft rotation speed, and fiber length were changed to investigate their effects on the carrying capacity of test fluids. The investigation's findings allow for the following conclusions to be drawn:

- Water had a poor cutting carrying capacity because it couldn't keep the fibers in the network structure. However, the formation of a reasonably stable fiber network was significantly improved by adding a small amount (0.747 & 1.1 wt%) of viscosifying polymer.
- The addition of fiber and/or polymer had a minimal impact on the SCC of coarse cuttings (3 and 6 mm), showing a marginal response to the changes in operational conditions.
- The SCC of fine (1 mm) cuttings increased noticeably (by about 20%), according to the results, when the polymer concentration was raised from 0.747% to 1.1% in the absence of fiber. The SCC went up another 20%, adding up to 0.08% fiber.
- The SCC of fine cuttings increased as a result of shaft rotation. Contrarily, the SCC of coarse cuttings (3 and 6 mm) was primarily negatively impacted by pipe rotation; however, the changes were minimal.
- The mixing of short and long fibers improved the SCC of both fine (1 mm) and coarse (3 mm) cuttings. The longer fiber outperformed the shorter one in terms of increasing the fluid's carrying capacity when there was no mixing. The outcome demonstrates that mixing short and long fibers at specific ratios can increase cutting carrying capacity at a fixed fiber concentration (0.06%). Incorporating shorter fibers is also advantageous for preventing valve and pipeline blockages.

CHAPTER 4: THE EFFECT OF POLYMER CONCENTRATION, FIBER CONCENTRATION, AND CUTTING SIZE ON CUTTING TERMINAL VELOCITY: A PARAMETRIC STUDY

4.1. Introduction

The development of additives for drilling fluids remains a significant challenge in improving the efficiency and effectiveness of drilling operations[80]. The circulation of drilling fluid, also known as drilling mud, within the borehole is employed to enhance the efficiency and cost-effectiveness of drilling operations[81]–[83]. The drilling mud comprises concentrated fluids that may be synthetic, oil-based, or water-based. It is formulated with heavy minerals and chemical additives injected into the drilling pipe to achieve specific objectives[84], [85].

Drilling fluids play a vital role in various essential functions, such as facilitating the transportation of cuttings to the surface, ensuring well control, providing cooling and lubrication, and assisting in bearing a portion of the weight of the drill bit and drill pipe[69], [86]–[89]. The drilling of the well impacts the trajectory of the cutting's transportation. During the drilling process of wells,68 cuttings are transferred from the borehole to the surface to facilitate the drilling of horizontal, build-up, and vertical sections. Cuttings rapidly undergo sedimentation within the drilling fluid upon cessation of drilling operations, particularly during specific circumstances such as establishing a connection between the drill pipe segments. The settling velocity impacts the cutting concentration in the vertical portion and the thickness of the cutting bed in the deviated sections[90], [91]. The probability of cuttings settling and burying the drill bit within the wellbore is heightened when the settling velocity is exceptionally high. This is due to the forming of a cutting bed plug in the deviated sections of the well[68], [74], [92], [93]. Efficient wellbore cleaning is of utmost importance in horizontal and deviated wells. Implementing specific measures can mitigate challenges such as stuck pipe occurrences, lost circulation incidents, high torque, drag issues, and the loss of control pertaining to equivalent circulation density (ECD). Finally, it can potentially reduce the expenses associated with drilling operations.

Wellbore cleanout operations are extensively employed in horizontal and highly inclined wells. The process frequently entails intricate and expensive procedures due to various operational parameters. Certain wellbore sections may remain unclear if the cleaning process is improperly executed. Solid materials within the wellbore give rise to various operational challenges, such as pipe entrapment, circulation loss, drilling setbacks, instability of the borehole, contamination of the drilling fluid, and impairment of the productive formation[94], [95]. One commonly employed approach for enhancing the efficiency of hole cleanout operations involves the utilization of viscous pills or gelled sweeps. These substances, explicitly formulated for wellbore cleanout, are characterized by their high viscosity. Despite the effectiveness of gelled sweeps in cleaning vertical wellbores, their performance is significantly reduced in a well's highly deviated and horizontal sections. The horizontal configuration of their particle lifting capability exhibits a low level. Consequently, they exhibit an inability to suspend particles that have been deposited effectively.

In recent years, numerous studies have investigated the utilization of drilling fluids containing fibrous materials to improve the effectiveness of wellbore cleaning and the suspension of cuttings during drilling operations[11], [12], [34], [48]. The efficacy of fiber-containing sweep fluids in removing drill cuttings from wells that possess horizontal and highly inclined orientations has been demonstrated through field experiments[69]. Based on empirical research, the transportation of cuttings is subject to various factors, including cutting parameters, fluid parameters, operational factors, and formation parameters[63]. T fluid flow rate and rheology are particularly crucial, as they are closely monitored and controlled[75]. The flow regime and rheological characteristics of the drilling fluid are critical in cleaning wells. The incorporation of fiber into drilling fluids reduces the settling velocity of cuttings, thereby enabling the suspension of cuttings that are smaller than a predetermined threshold determined by the properties of the base fluid and the amount of fiber present. This study aims to determine the optimal parameters for the settling velocity of drilling cuttings in a water-based fluid containing fibrous Carboxymethyl Cellulose (CMC). The Box-Behnken Design (BBD) is employed with four factors and three replicates to generate statistical models that optimize the cutting terminal velocity and identify its stability regions. An investigation was conducted to determine the terminal velocity of a water-based fluid containing cellulose microcrystals (CMC). The study involved varying three parameters: cutting size, fiber concentration, and fiber length. Additionally, the fluid was tested at three different concentrations. The experiments were conducted and recorded using a cylindrical column, a high-speed video camera, photography lightning, and a personal computer.

4.2.Experimental Setup and Methods

4.2.1. Materials

FORTA Super-Sweep Fiber, a white polypropylene monofilament synthetic fiber with a specific gravity of 0.91 and an average melting point of 172 o C was used for this study. These fibers come in two different types and have dimensions of 100 m in diameter and 3 and 12 mm in length (respectively, with aspect ratios of 30 and 120). Carboxymethyl cellulose (CMC) polymer concentrations were used as base fluids. In order to simulate the actual drilling cuttings, inert glass beads ranging from 1 to 6 mm were used. The sources and properties of each material are listed in **Table 3**.

4.2.2. Fiber Stability Test

Fibers are frequently used as a fluid additive in the oil and gas industry to improve hydraulic fracturing effectiveness, reduce fluid filtration loss, and improve hole-cleaning performance. A small amount of fiber is frequently dispersed in the base fluid to achieve the desired results without making the base fluid more viscous. Fiber dispersion must be kept constant to be useful, which can be challenging in wellbore environments. A deeper understanding of fiber suspension or stability in base fluids is needed to effectively use fibers in drilling and completion operations[11]. Numerous studies have proven the effectiveness of fibrous drilling sweeps in horizontal and severely deviated wells. Drilling fluids with a trace amount of flexible monofilament fiber added to them (concentrations less than 0.06 wt%) hardly changes their rheological properties. However, the rheological characteristics of drilling fluids containing fibers at concentrations higher than 0.09 weight percent change. For example, adding 0.4 weight percent of fiber to hydroxypropyl guar gel caused the fluid's viscosity to increase by three times[69], [78], [96], [97]. An experimental study on spherical glass bead particles found that a small amount (0.02 to 0.04 weight percent) of fiber reduced the particle settling velocity by about 50% when added to a dispersion of Xanthan gum at a concentration of 0.35%. Earlier studies chose a fiber concentration range between 0.02 and 0.1%w for easier fluid processing and pumping slow down settling[78].

4.2.3. Design of Experimental

The experimental design statistical technique, BBD, is used to evaluate multi-variable systems, investigate the interaction effects of three variables, and improve the responsiveness of multi-variable processes. The main advantage of the BBD methodology is that it needs fewer experimental trials to analyze various factors than other approaches[112].

The base CMC concentration, fiber concentration, and cutting size were the three factors that this study looked at in water-based polymeric fluids with fiber lengths of 12 and 3 mm **Table 6**. The BBD method required 45 sets of experimental trials for each fiber length **Table 7**. Two fiber lengths were used in 96 experimental trials overall. The experimental runs were randomized while keeping the settings constant to minimize bias and error.

Table 6. Limits of the studied parameters for two lengths of fibers: 3 and 12 mm

Factors	Factor levels			
	Symbol	low (-1)	Central (0)	High (+1)
Cutting size (mm)	A	1	3.5	6
Fiber (wt%)	B	0.02	0.06	0.1
CMC (wt%)	C	0.5	0.75	1

Table 7. Three-Factor Box-Behnken Experimental Design for 3 mm fiber

Run No.	Cutting size (mm) (A)	Fiber (wt%) (B)	CMC (wt%) (C)	Run No.	Cutting size (mm) (A)	Fiber (wt%) (B)	CMC (wt%) (C)
1	1	-1	0	24	0	0	0
2	0	1	-1	25	-1	-1	0
3	-1	0	-1	26	0	1	-1
4	1	0	-1	27	-1	0	1
5	1	0	-1	28	1	1	0
6	-1	-1	0	29	0	-1	1
7	-1	0	-1	30	-1	1	0
8	-1	1	0	31	1	0	1
9	0	1	1	32	0	-1	-1
10	0	0	0	33	0	-1	-1
11	1	1	0	34	1	1	0
12	0	0	0	35	1	-1	0
13	-1	-1	0	36	-1	1	0
14	0	0	0	37	0	1	1
15	1	0	1	38	0	-1	1

Run No.	Cutting size (mm) (A)	Fiber (wt%) (B)	CMC (wt%) (C)	Run No.	Cutting size (mm) (A)	Fiber (wt%) (B)	CMC (wt%) (C)
16	0	0	0	39	1	0	1
17	1	-1	0	40	0	0	0
18	0	-1	1	41	0	0	0
19	0	-1	-1	42	-1	0	1
20	0	1	1	43	0	1	-1
21	-1	0	1	44	1	0	-1
22	0	0	0	45	-1	0	-1
23	0	0	0				

The surface method box-Benhken design generated a model of a second-order polynomial equation, and it was discovered to fit a second-order polynomial with a regression coefficient of 0.99. As a function of CMC concentration, fiber concentration, and cutting size, the variables' interactions with terminal velocity **Equation 8**.

$$V = n_0 + n_1A - n_2B - n_3C + n_4A^2 - n_5B^2 + n_6C^2 - n_7A \times B - n_8A \times C + n_9B \times C \quad 8$$

A, B, and C are the three independent variables of the model; A stands for cutting size; B for fiber concentration; C for polymer concentration; V stands for response variable; n0 is a model constant variable; n1, n2, and n3 are linear coefficients; n4, n5, and n6 stand for quadratic effects; and n7, n8, and n9 stand for interaction effects of the model **Table 8**. The P-value indicates Model-independent variables' significance, where a P-value of 0.05 or less indicates that the variable is significant.

Table 8. P-values and Regression Coefficients

Term	3 mm length fiber V_1		12 mm length fiber V_2	
	$n\ value$	P- value	$n\ value$	P- value
n_0	4.405	0.000	4.106	0.000
n_1A	1.038	0.000	0.849	0.000

Term	3 mm length fiber V_1		12 mm length fiber V_2	
	$n\ value$	P- value		$n\ value$
n_2B	10.77	0.000	13.63	0.000
n_3C	12.03	0.000	11.15	0.000
n_4A^2	0.071	0.000	0.071	0.000
n_5B^2	35.50	0.283	35.50	0.283
n_6C^2	7.433	0.000	7.433	0.000
$n_7A \times B$	1.537	0.001	1.537	0.001
$n_8A \times C$	1.178	0.000	1.178	0.000
$n_9B \times C$	21.83	0.000	21.83	0.000

4.2.4. Experimental Procedure

Fifty liters of tap water were mixed with the necessary amount of CMC polymer. To avoid any aggregation, guarantee quick mixing, and ensure the production of homogeneous CMC fluid, the CMC was added gradually while being stirred at an increasing progressively stirring speed of up to 600 rpm for three hours. The CMC mixture was then allowed to hydrate for 24 hours. The following day, 3 liters of CMC fluid test samples were made by dividing the mixed CMC into various containers. To prevent coagulation and guarantee a homogeneous mixture formation, the required amounts of fiber were gradually added to the samples in accordance with the experiment's design. The necessary mixture of fibrous-CMC fluid was poured into a 53 cm tall cylindrical column to measure the suspension settling.

To analyze the experiment's results, a photography setup made up of lighting, a high-speed video camera (FASTCAM SA3, Photron, Japan), which can take up to 2000 pictures per second and a computer were used **Figure 12**. One at a time, particles were let loose from the column's top, and photography lighting was used to track their motion as captured on camera. With the help of Photron FASTCAM Viewer software 4 (PFV4), which was made available by Photron, the PC was used to operate the video camera and record the tracking profiles. The terminal velocity is computed using the motion of the recording particle.

It is worth mentioning that the standard classical equation for particle terminal velocity cannot be accommodated directly in these measurements. Because using a different aspect ratio of fibers hinders the particles during the settling process and invalidates the concept of the classical terminal velocity formula. In addition, the classical formula is not applicable because the fluids tested in this are all non-Newtonian, and the viscosity is a function of shear rate.

Tracker (a free video analysis and modeling tool from Open-Source Physics, OSP) tracks the suspension cuttings independently by measuring the displacement in the vertical and horizontal axes over time and generating multiple variables like velocity and acceleration. Using the software, the settling time is determined from the particle trajectory. The required experiment video record must be uploaded to the tracker application before the X and Y axes are defined and the column length is set. The number of frames per second must also be set. Then, to aid the program in tracking the object accurately and with few errors, we define the object by including its area inside the tracking circle.

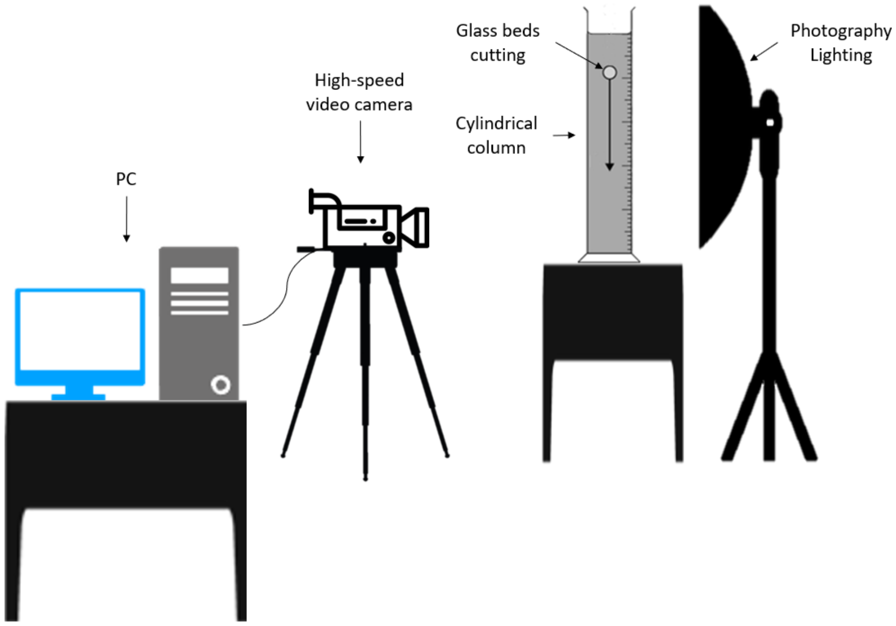


Figure 12. Experimental setup

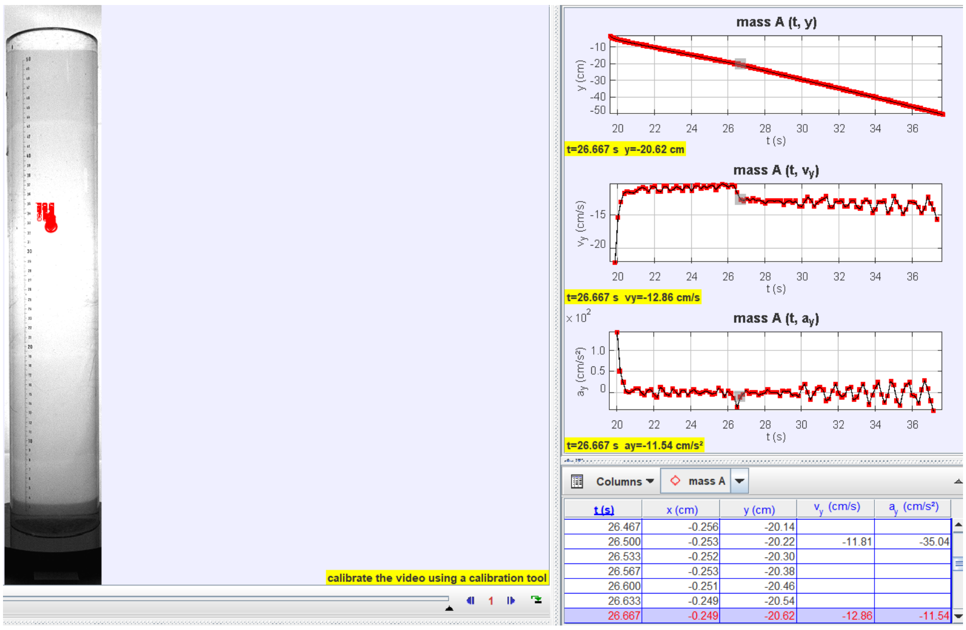


Figure 13. Experiment tracking and analysis using Tracker software

Five columns of data will be generated following tracking **Figure 13**. The experiment's response surface regression was made using BBD and an Excel sheet to define the terminal velocity for each trajectory **Figure 14**. **Equation 9** was used to calculate the terminal velocity at a steady state.

$$v_{Terminal} = \frac{|y - y_0|}{t - t_0} \quad 9$$

where y0 is the initial displacement of the particle in cm at time t0 in seconds, and y is the displacement of the particle in cm at any given time t in seconds. Each fiber length produced a regression equation for cutting size, fiber weight percentage, and CMC weight percentage. Using the Sigma Plot program, the 3 mm and 12 mm fiber length regression equations were used to plot 3D figures for interaction between design parameters.

Box-Behnken Design

WORKSHEET 1

Box-Behnken Design

Design Summary

Factors:	4	Replicates:	3
Base runs:	30	Total runs:	90
Base blocks:	1	Total blocks:	1

Center points: 18

	C1	C2	C3	C4	C5	C6	C7	C8-T	C9	C10-T
	StdOrder	RunOrder	PtType	Blocks	Cutting Size	Fiber con%	Soultion con%	Fiber lenght	Terminal V	
1	32	1	2	1	6.0	0.02	0.7495	3 mm	2.56542	Missing
2	85	2	2	1	3.5	0.10	0.4990	12 mm	0.85980	Missing
3	60	3	0	1	3.5	0.06	0.7495	12 mm	0.44811	Missing
4	70	4	2	1	3.5	0.10	0.4990	3 mm	1.88595	Missing
5	77	5	2	1	6.0	0.02	0.7495	12 mm	2.05071	Missing
6	76	6	2	1	1.0	0.02	0.7495	12 mm	0.08431	Missing
7	87	7	2	1	3.5	0.10	1.0000	12 mm	0.13768	Missing
8	26	8	2	1	3.5	0.02	1.0000	12 mm	0.26935	Missing
9	18	9	2	1	1.0	0.10	0.7495	12 mm	0.03759	Missing
10	35	10	2	1	1.0	0.06	0.4990	3 mm	0.29709	Missing
11	66	11	2	1	6.0	0.06	0.4990	3 mm	5.20634	Missing
12	36	12	2	1	6.0	0.06	0.4990	3 mm	5.23919	Missing
13	61	13	2	1	1.0	0.02	0.7495	3 mm	0.10863	Missing
14	30	14	0	1	3.5	0.06	0.7495	12 mm	0.46000	Missing

Figure 14. BBD design from Minitab

The rheological behavior of CMC is tested using a rheometer. The experiments used Couette cells with diameters and lengths of 24 and 30, respectively, and an Anton Paar Modular Compact Rheometer (MCR) 302. The measurements were made at room temperature (20 ± 1 °C), and the shear rate ranged from 0.01 to 100 s^{-1}.

4.3. Results and Discussion

4.3.1. Rheological Behavior

Rheological research is imperative to understand better the solids carrying capacity and hydrodynamics of the base CMC fluids. 1-100 s^{-1} was the maximum allowed shear rate. The apparent fluid viscosity increased with the increase in polymer concentration from 0.5 to 1 wt% across the entire range of shear rates. Significant shear thinning is present in polymeric suspensions at both concentrations.

The yield stress term is derived from the y-intercept of the linearized equation of (shear stress vs. shear rate plot) with the coefficient of determination R^2 based on the low-shear rate data extrapolation **Table 9**. A crucial element is yield stress, which measures the maximum tension a fluid can withstand before yielding[99], [100]. The power law model represents the linearized equation of the low shear rate data **Equation 10**.

$$\tau = \tau_0 + k\,\dot{\gamma} \qquad (10)$$

where τ_0 is the yield stress, k is the consistency index, and $\dot{\gamma}$ is the shear rate. The Cross model was also used to describe the rheological behavior of the CMC solution **Equation 11**.

$$\eta(\dot{\gamma}) = \frac{\eta_0 - \eta_\infty}{1 + (k\,\dot{\gamma})^n} + \eta_\infty \qquad (11)$$

where $\eta(\dot{\gamma})$ is viscosity as a function of shear rate, η_0, $\eta_\infty, k,$ and n are coefficients. The zero-shear viscosity η_0 is approached at very low shear rates, while the infinite shear viscosity η_∞ is approached at high shear rates.

Various concentrations of CMC solutions exhibit non-Newtonian behavior, as shown in **Figure 15**. Using a power law and cross model to fit the non-Newtonian behavior of the CMC solutions **Equation 11**, the findings are compiled in **Table 9**.

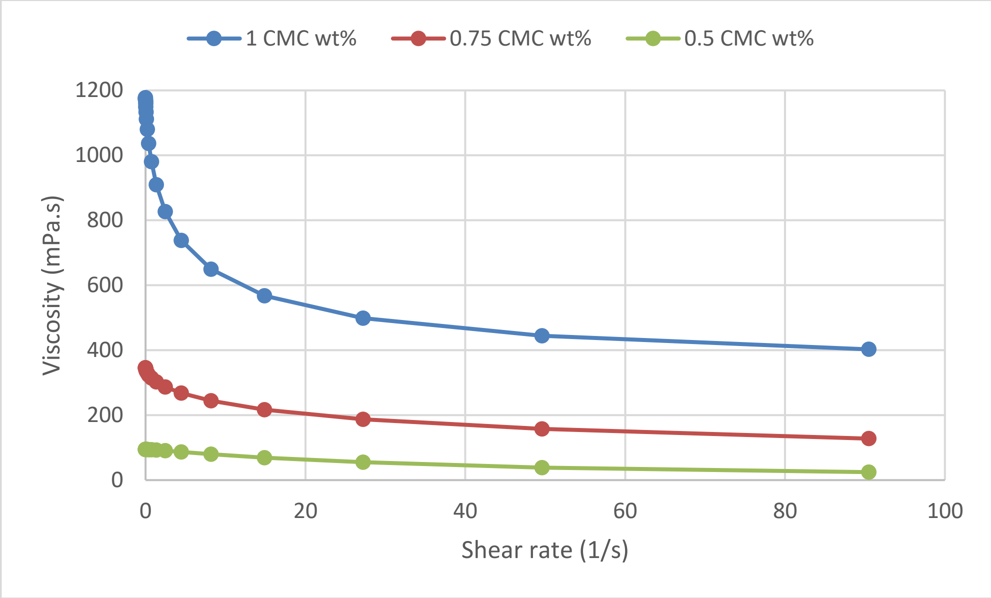


Figure 15. The viscosity of different CMC solutions vs. shear rate

Table 9. Power law and cross-model fitted data

CMC wt%	Power law			Cross-model			
	τ_0 (mPa)	k (mPa.s)	R^2	η_0 (mPa. s)	η_∞ (mPa. s)	n	k (mPa.s)
0.5	5.0	88.5	0.99	94.6	1.1×10^{-5}	1.1	0.03
0.75	37.8	273.1	0.99	346.9	3.2×10^{-5}	0.6	0.03
1	217.6	741.2	0.99	1180.9	3.1×10^{2}	0.7	0.2

4.3.2. Regression Modeling

Table 10. BBD terminal velocity response data for 3mm length fiber

Run Order	Cutting size (mm)	Fiber (wt%)	CMC (wt%)	Terminal V (cm/s)
1	6	0.02	0.75	2.565
2	3.5	0.1	0.5	1.886
3	1	0.06	0.5	0.297
4	6	0.06	0.5	5.206
5	6	0.06	0.5	5.239

Run Order	Cutting size (mm)	Fiber (wt%)	CMC (wt%)	Terminal V (cm/s)
6	1	0.02	0.75	0.109
7	1	0.06	0.5	0.291
8	1	0.1	0.75	0.067
9	3.5	0.1	1	0.256
10	3.5	0.06	0.75	0.809
11	6	0.1	0.75	2.140
12	3.5	0.06	0.75	0.805
13	1	0.02	0.75	0.109
14	3.5	0.06	0.75	0.805
15	6	0.06	1	1.933
16	3.5	0.06	0.75	0.807
17	6	0.02	0.75	2.565
18	3.5	0.02	1	0.305
19	3.5	0.02	0.5	2.680
20	3.5	0.1	1	0.257
21	1	0.06	1	0.060
22	3.5	0.06	0.75	0.803
23	3.5	0.06	0.75	0.814
24	3.5	0.06	0.75	0.799
25	1	0.02	0.75	0.109
26	3.5	0.1	0.5	1.903
27	1	0.06	1	0.064
28	6	0.1	0.75	1.960
29	3.5	0.02	1	0.297
30	1	0.1	0.75	0.069
31	6	0.06	1	2.067
32	3.5	0.02	0.5	2.565
33	3.5	0.02	0.5	2.622
34	6	0.1	0.75	2.050
35	6	0.02	0.75	2.433
36	1	0.1	0.75	0.068
37	3.5	0.1	1	0.255
38	3.5	0.02	1	0.312
39	6	0.06	1	1.950
40	3.5	0.06	0.75	0.813
41	3.5	0.06	0.75	0.807
42	1	0.06	1	0.065
43	3.5	0.1	0.5	1.868
44	6	0.06	0.5	5.223
45	1	0.06	0.5	0.294

The terminal velocity values from the experiment for the 3 mm length fiber are displayed in **Table 10**. A second-order polynomial regression model has investigated the relationship between the three parameters and the terminal velocities V_1 and V_2 for the 3 mm and 12 mm length fibers.

Equations 12 and **13** show the terminal velocity regression equation results for 3 mm and 12 mm, respectively.

$$V_1 = 4.405 + 1.0380\,A - 10.77\,B - 12.03\,C + 0.07129\,A^2 - 35.5\,B^2 + 7.433\,C^2 - 1.537\,A \times B - 1.1776\,A \times C + 21.83\,B \times C \quad 12$$

$$V_2 = 4.106 + 0.8494\,A - 13.63\,B - 11.15\,C + 0.07129\,A^2 - 35.5\,B^2 + 7.433\,C^2 - 1.537\,A \times B - 1.1776\,A \times C + 21.83\,B \times C \quad 13$$

The software produces the coefficients and their signs in equations 1,5 and 6. Positive coefficients exhibit synergistic effects, whereas negative coefficients have a negative impact on the stability response[101]. Therefore, terms with positive signs positively impact terminal velocity, whereas the ones with negative signs have the opposite effect. For instance, the quadratic terms A^2, C^2, B×C, and the linear term A in (**Equation 11**) all have positive signs, indicating that they influence the terminal velocity. The stability of the response decreases when other coefficients with negative signs, such as the first-order terms B and C, and second-order terms B^2, A×B, and C.

The probability P-value is used to evaluate the importance of coefficients and the effect of the combined terms of the interaction. P-values less than 0.05 show that a coefficient is more likely to affect the response significantly[102], [103]. The regression terms and accompanying p-values are displayed in **Table 9**. The V model indicates that every term is meaningful, except B^2, which may be excluded without changing the model's prediction. The coefficient of determination, or R^2, represents the proportion of variation in the dependent variable (V). The R^2 value indicates strong links between independent and dependent variables. Accordingly, the model correlation has strong fitting values, with an R^2 value of 0.97.

4.3.3. Model Validation

Models V_1 and V_2 show good model prediction versus experimental runs. The terminal velocity was predicted using **Equation 11** for 3 mm fibers and 5 for 12 mm fibers. The terminal velocities of the suspended particles, as observed and forecast, along with the corresponding error percentages, are listed in **Table 11**. Most points are within a 30% error margin in the results, demonstrating excellent agreement between experimental and anticipated values. The lowest error values for model V1 are displayed at point II, and the error rises rapidly as the fiber weight percent gets closer to the components' upper restrictions (+1). Model V_2 displays a higher error ratio than Model V_1 despite showing the same error increment with fiber weight percent. This may be due to the 12 mm fiber's propensity to form a structured network[12], which obstructs the path the suspended cuttings take and results in an unpredictable trend.

Table 11. Experimental value confirmation

	parameters				
	Fiber (wt%)	CMC (wt%)	Experimental value	Model prediction	Error%
3 mm fibers (V1)	0.02	0.5	2.62	2.58	1.5
	0.02	1	0.3	0.3	0
	0.06	0.75	0.81	0.86	6.2
	0.1	0.5	1.89	1.83	3.2
	0.1	1	0.26	0.41	57
12 mm fibers (V2)	0.02	0.5	2.02	1.99	1.5
	0.02	1	0.27	0.18	33
	0.06	0.75	0.46	0.4	13
	0.1	0.5	0.83	1.01	22
	0.1	1	0.14	0.06	57

4.3.4. Response Surface Analysis

The regression equations that forecasted the effect of cutting size, fiber (weight percentage) and CMC (weight percentage) on the cutting's terminal velocity were represented by 3D response surface plots. **Figure 16** displays the results of creating the response surface plots by varying two independent variables while holding the third independent variable constant.

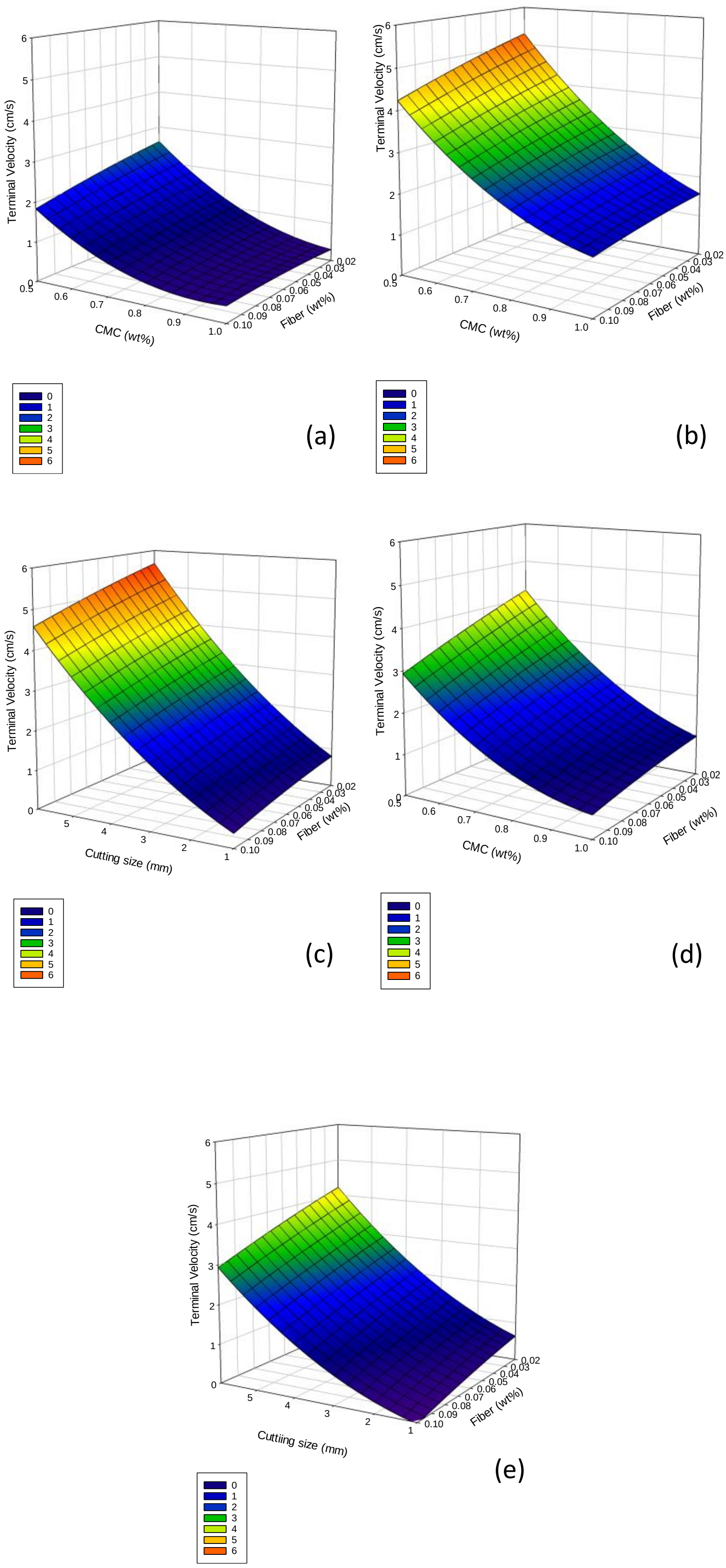


Figure 16. For 3 mm fibers, (a,b) show the effects of CMC wt.%, fiber wt.% for 3.5- and 6-mm cutting sizes, respectively, (c) shows the effects of cutting size and fiber

wt.% for 0.499 CMC wt.%. For 12 mm fiber, (d,e) shows the effects of CMC wt.% and fiber wt.%

The main goal of this study is to reduce the terminal velocity. The Pareto chart in **Figure 17** illustrates the importance of the interaction between independent and dependable factors on terminal velocity. The effects of fiber concentration and fiber length are negligible compared to the impact of cutting size and CMC concentration. Figure 17; decreasing cutting size or increasing polymer concentration significantly reduces terminal velocity. Although CMC concentration substantially affects the terminal velocity, cutting size has a more significant impact. The effect of reducing the terminal velocity with increasing CMC concentration is because of the relatively substantial change in the viscosity **Figure 15**. Another observation that can be drawn from **Figure 16** is that increasing cutting size has a different impact than increasing fiber length from 3 to 12 mm.

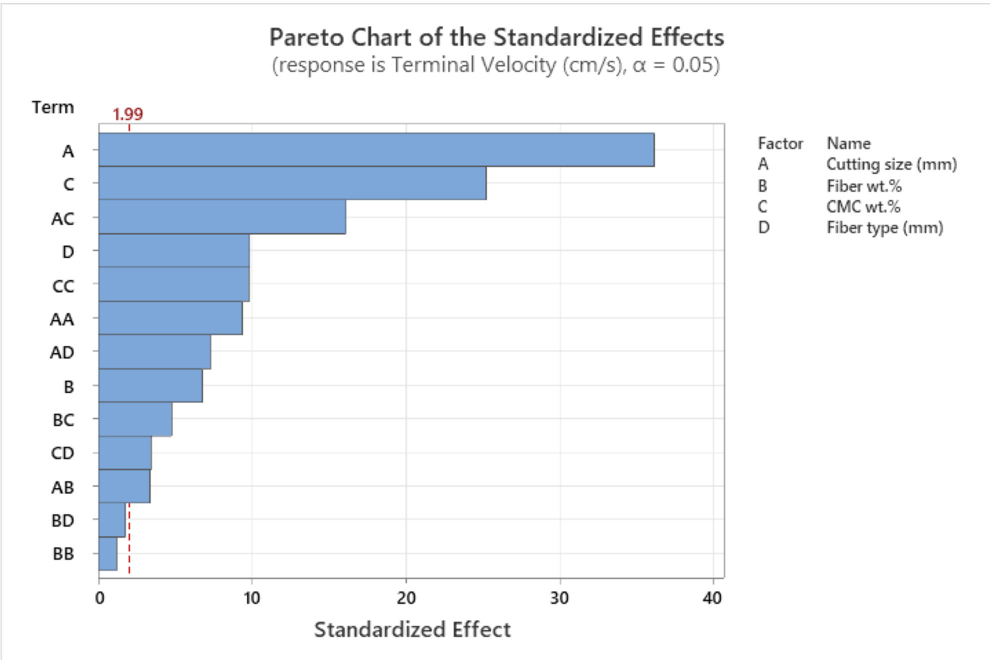
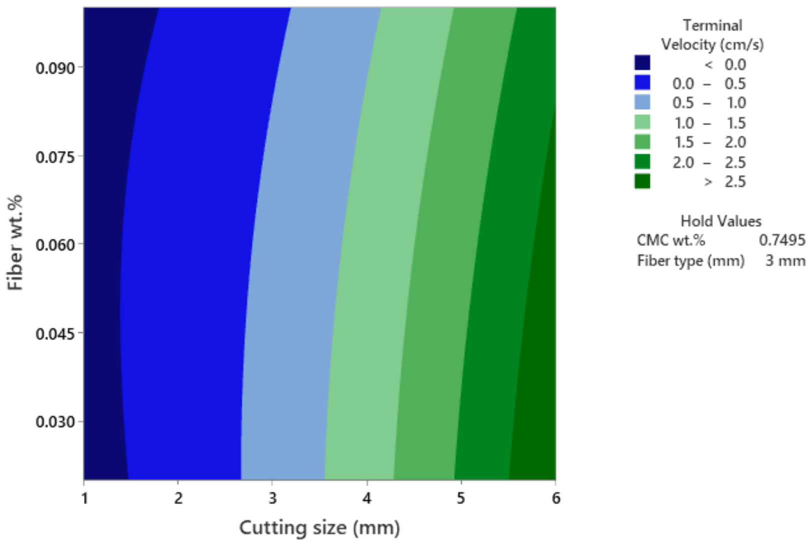
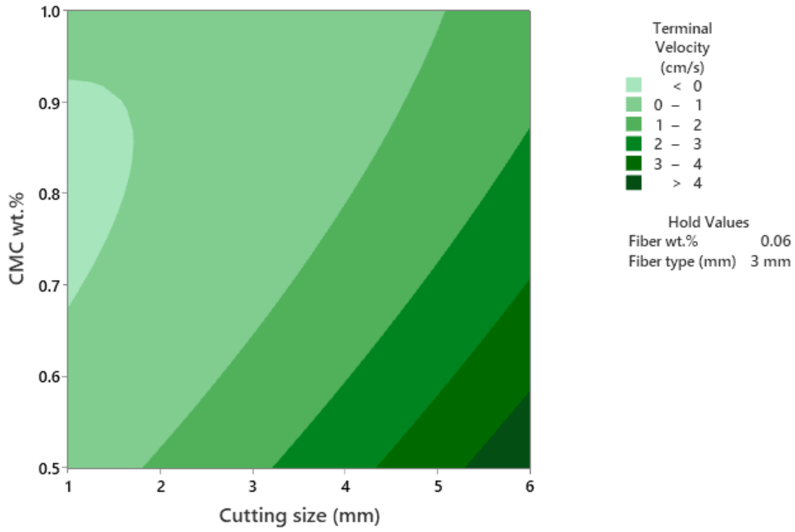


Figure 17. Pareto chart of the standardized effects

The combined effect of the two factors on the terminal velocity is also shown in **Figure 16**. It demonstrates unequivocally that the combination of CMC weight percentage and cutting size exhibits the most notable effects among other factors. The combination of fiber weight and fiber type and the duplication of fiber weight does not impact terminal velocity, while fiber weight and length do **Figure 17**.





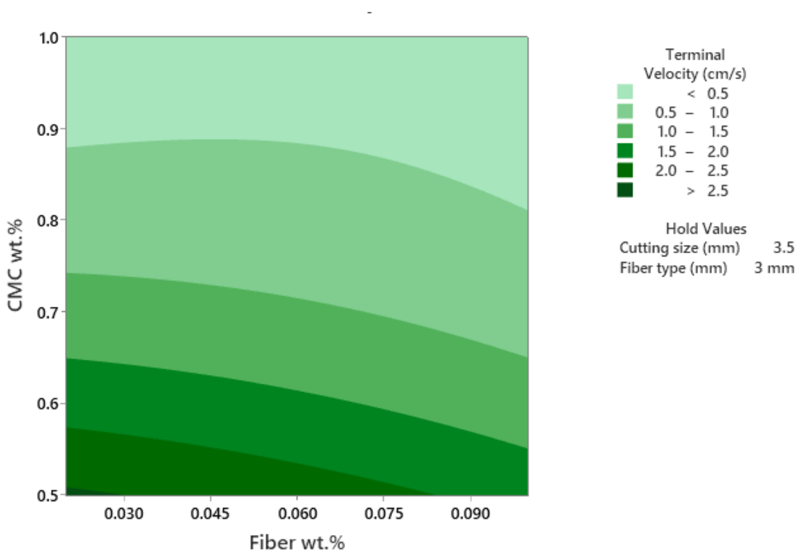


Figure 18. Contour plots for terminal velocity range for 3 mm fiber: a) Fiber wt.% vs. cutting size with constant 0.75 CMC wt%; b) CMC wt.% vs. cutting size with constant 0.06 fiber wt.%; c) CMC wt.% vs. Fiber wt.% with constant 3.5 mm cutting size

A perfect drilling fluid preparation factors ratio could be selected using contour plots in **Figure 18** within the zone where the cuttings terminal velocity is between 0 and 0.5 cm/s. **Figure 18-c** shows that the region where CMC wt.% is larger than 0.9 CMC wt.% and cutting size equal to or smaller than 3.5 mm could be set as a perfect preparation range. **Figure 18** also shows two other ranges, as shown in **a** and **b**. We conclude from contour plots that fiber wt.% has minor impacts on the terminal velocity, as drilling fluid preparation regions do not change with fiber wt.% **Figure 18 a** and **c**.

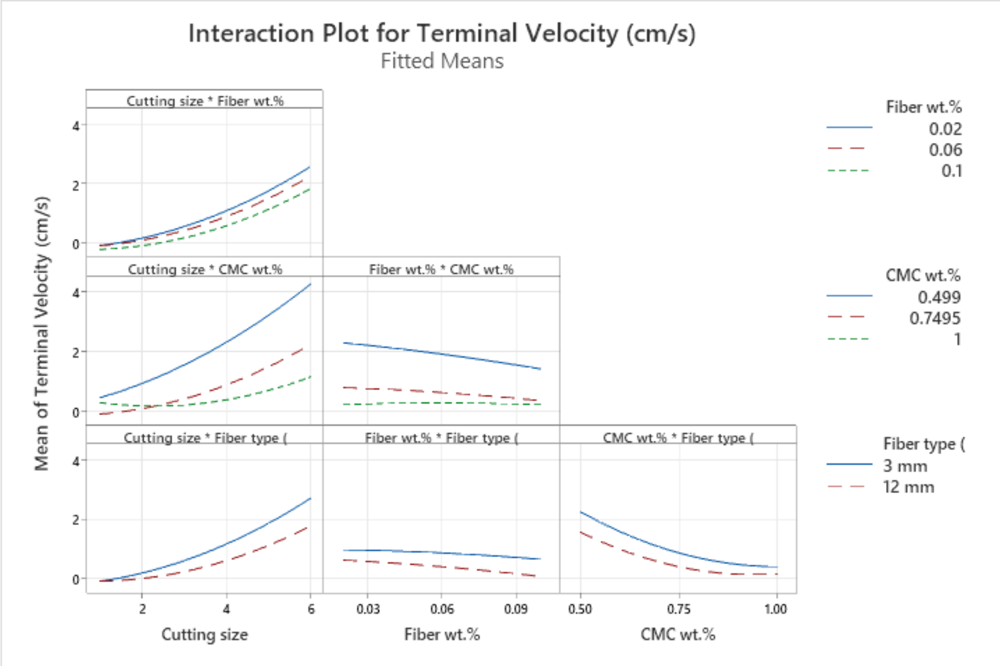


Figure 19. Design factors interaction plot

The interaction between design-independent variables and the cuttings' terminal velocity is shown in **Figure 19**. The mean terminal speed is high when cutting size interacts with other factors. This is particularly true when cutting size and CMC concentration interact. This demonstrates that cutting size, alone and in conjunction with CMC concentration, is the most crucial variable. You could use **Figure 17** to conclude the same result.

4.3.5. Response Surface Optimization

The desirability function is another method for examining the optimization response surface. The projected values of the response are transformed into the dimensionless scale d. The desirability function rang between d = 0 and d = 1, where d = 0 denotes unfavorable response values and d = 1 denotes a completely desirable response[104]. The optimization was complete when the terminal velocity was reduced.

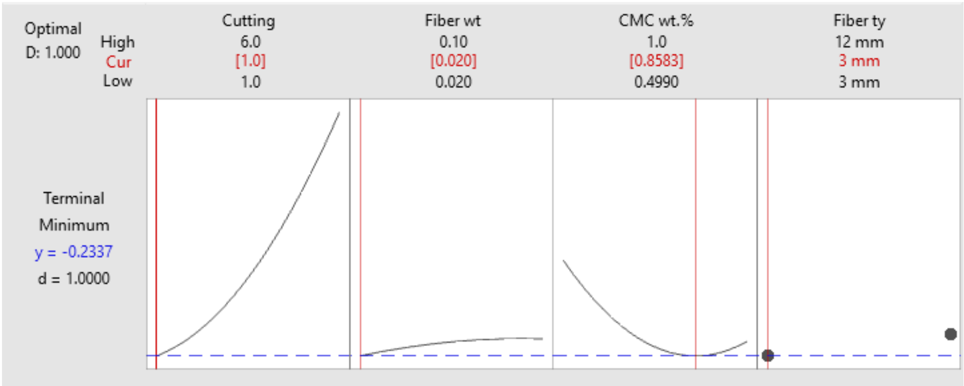


Figure 20.Optimization response

All desirability values were acceptable and met the desired minimum terminal velocity (d = 1). Response data show that cutting size dominates the final terminal velocity. **Figure 20** displays the parameters influencing the optimization of terminal velocity. For each factor, the chosen factor level is indicated vertically by a straight line, and the expected response value is shown horizontally by a dotted line.

4.4.Conclusions

In this study, we investigated the terminal velocity of drilling cuttings using the Box-Behnken design with three replicates to derive models of terminal velocity as a function of cutting size, CMC concentration, and fiber concentration. In a water-based drilling fluid with three CMC polymeric concentrations of 0.499, 0.7495, and 1 wt%, the terminal velocity was examined using three cutting sizes of 1, 3.5, and 6 mm, three fiber concentrations of 0.02, 0.06, and 0.1 wt%, and two fiber lengths of 3- and 12-mm. Models showed that cutting size and polymer concentration were the most significant factors affecting the terminal velocity.

The following is a summary of the main findings:

- Cutting size represents the most critical factor affecting the terminal velocity of the cuttings.
- Higher polymer concentrations improve fluid viscosity and decrease the

terminal velocity of cuttings. At low polymer concentrations, the effects of fiber concentration on fluid viscosity are more noticeable; increasing the fiber concentration increases fluid viscosity and creates networks that could hinder the settling. As a result, the impact of fiber concentration is correlated to polymer concentration.

- The combination of cutting size and CMC concentration results in a significant interaction.
- CMC fluids with a viscosity of 630.4 cP are sufficient to maintain a minimum terminal velocity of 0.234 cm/s, a cutting size of 1 mm, and a fiber concentration of 0.02 of 3 mm length fiber.

CHAPTER 5: CONCLUSIONS AND FUTURE PERSPECTIVES

5.1.Overall Conclusion

This study investigated the cutting carrying capacity of fibrous polymeric suspensions in a pilot unit, focusing on parameters such as fiber concentration, polymer concentration, cutting size, shaft rotation speed, and fiber length, and highlights the importance of understanding these factors in enhancing the carrying capacity of test fluids. The water's poor cutting carrying capacity was improved by adding a small amount of viscosifying polymer to improve the stability of the fiber network. The addition of fiber and/or polymer had minimal impact on the SCC of coarse cuttings (3 and 6 mm), showing a marginal response to changes in operational conditions. The SCC of fine cuttings increased by about 20% when the polymer concentration was raised from 0.747% to 1.1% in the absence of fiber. The SCC of coarse cuttings (3 and 6 mm) was primarily negatively impacted by pipe rotation, but the changes were minimal. The mixing of short and long fibers improved the SCC of both fine and coarse cuttings, with the longer fiber outperforming the shorter one in terms of increasing the fluid's carrying capacity when there was no mixing.

The terminal velocity of drilling cuttings was also examined using the Box-Behnken design with three replicates. The results showed that cutting size and polymer concentration were the most significant factors affecting the terminal velocity in a water-based drilling fluid with three CMC polymeric concentrations. The terminal velocity of cuttings is significantly influenced by cutting size and fiber concentration. Higher polymer concentrations improve fluid viscosity, while fiber concentration increases fluid viscosity and creates networks that hinder settling. The impact of fiber concentration is correlated to polymer concentration. The combination of cutting size and CMC concentration results in a significant interaction. CMC fluids with a viscosity of 630.4 cP are sufficient to maintain a minimum terminal velocity of 0.234 cm/s, with a cutting size of 1 mm.

5.2.Future Prospective

Despite the significant findings and contributions of this research in enhancing the comprehension of FCFs, it is imperative to acknowledge that particular perspectives should be incorporated in forthcoming studies. Future research objectives that should be addressed to improve the understanding of Fiber-based Cleanout Fluids (FCFs) include the evaluation of the efficacy of polymeric solutions as additives to drilling fluids. Specifically, the investigation should focus on utilizing various Molecular weight polyacrylamides (PAMs) with distinct charge types, such as anionic and non-ionic. Additionally, the impact of temperature and drill rotation speed on the stability and performance of drilling formulations should be examined. Furthermore, a comparative analysis between formulated fibrous Oil-Based Mud (OBM) and Water-Based Mud (WBM) should be conducted. Lastly, a comprehensive assessment of the environmental consequences of using fiber in drilling cleanout fluids is warranted.

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