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Pilot-scale study on the suspension of drill cuttings: Effect of fiber and fluid characteristics

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ABSTRACT

Drilling operation smoothness is essential to minimize drilling non-productive time (NPT). Inadequate cuttings transport can result in cuttings bed build-up in the wellbore low side, jeopardizing the whole drilling operation. Modifying base fluid properties can prevent the associated risks with poor hole cleaning. Fiber sweeps enhanced hole-cleaning performance and increased cuttings transport to the surface with a negligible increase in fluid viscosity. This experimental investigation examines the effect of fibers on the cuttings carrying capacity of carboxyl methylcellulose (CMC) based polymeric fluids. The carrying capacity of the fluids is assessed by measuring the suspended and deposited cuttings/solids concentrations after a predefined quiescent period. Synthetic monofilament fiber of 0.9 specific gravity, 100 μm diameter, and two different lengths (3 and 12 mm) were used. Polymer concentrations were 0.747 and 1.1 wt %, while fiber concentration was varied from 0.00 to 0.08 wt%. The investigation was performed using a vertically configured annular test section (150 cm long) with a rotating inner shaft speed. Experimental results indicate that increasing fiber or/and polymer concentrations significantly improved cuttings carrying capacity of the fluids in suspending fine (1 mm) particles.

In most cases, the carrying capacity of the fluids in suspending coarse cuttings (3 and 6 mm particles) was slightly improved with the addition of polymer and fiber. Although the rotation of the inner shaft substantially reduced the deposition of fine particles but did not prevent the settling of coarse cuttings. In addition, short fibers demonstrated better performance than long ones in improving the carrying capacity of the fluids. Utilizing long and short mixed fibers at a specific proportion improved the cuttings carrying capacity of the fluid better than unmixed fiber.

1. Introduction

The drilling process utilizes mud as a working fluid, accounting for 15–18% of the total drilling operation cost (Rohan et al., 2021). Drilling fluids are designed to have versatile functions which require different performance characteristics, including filtration loss control, drill bit lubrication and cooling, wellbore physical stability, and cuttings removal (Bloys et al., 1994; Caenn and Chillingar, 1996; Xiaofeng et al., 2013). The functionality and effectiveness of drilling fluids mainly depend on their properties, including, and not limited to, rheological and hydraulic properties, which are interdependent. Often, interdependency promotes operational complexity (Nguyen and Rahman, 1998). Despite the advancement and ongoing intensive research on drilling fluids from academia and industry, hole cleaning (cuttings removal) remains a challenging problem in deviated and horizontal wells (Mahmoud et al., 2020; Pedrosa et al., 2021). Ineffective hole cleaning or cuttings transport can result in excessive drag and torque, reduced rate of penetration (ROP), bit wearing, and induced fractures due to gradual blockage, which increases fluid loss and lost circulation (Xiaofeng et al., 2013). Problems associated with poor hole cleaning significantly improve the drilling operational cost and non-productive time (NPT) or, in extreme cases, result in wellbore abandoning due to the technical complexities (Hopkins and Leicksenring, 1995).

Drilling fluids are becoming more expensive and complex overtime to meet various factors and requirements. There is a need to improve the understanding of drilling fluid characteristics related to selecting and

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using suitable fluid for a specific operation. Cuttings are generated at the drill bit with the progress of the drilling process; after generation, rock cuttings mix with the fluid forming solid-liquid system, where different forces act on the cuttings and their vicinity (Kelessidis and Mpandelis, 2003). The primary forces acting on a particle suspended in a moving fluid throughout the transport process are axial hydrodynamic drag and lateral lift force, upward buoyancy, and the downward gravity force. Drilled cuttings will accumulate on the low-side of the wellbore, producing stationary cuttings beds within the annulus when the magnitude of the net upward forces is less than the downward forces (Cho et al., 2000; Fang, 1993; Ramadan et al., 2001). The drilling fluid properties are the key for effective cuttings transport because they significantly influence the forces acting on the cuttings (Hemphill, 2010; JieNian et al., 2010; Wisniowski, 2017; Yan et al., 2014). More specifically, drilling fluid properties must be adequate under low shear rate conditions to prevent or hinder cuttings sedimentation and avert bed formation.

Recently, research in water-based mud (WBM) enhancement has achieved significant progress. Numerous additives are investigated to improve these fluids' rheological characteristics and carrying capacity. For instance, natural fibers, synthetic fibers, and polymeric beads are considered to enhance the cuttings transport through the development of hydrodynamic interference between cuttings and additives (Ahmed and Takach, 2009; Lihui et al., 2010; Movahedi et al., 2017; Qingling et al., 2018; Song et al., 2016). Ahmed and Takach (2009) investigated the effectiveness of fibers in horizontal and deviated wells. Their results showed that fibers could hinder particles from settling. The presence of fiber improves the drag forces on the particles, hindering cuttings deposition (Elgaddafi et al., 2016). The use of fiber particles can be incorporated with base suspension/mud charge density, which ultimately enhances the cuttings carrying capacity (Mahmoud et al., 2021). Low-viscosity suspensions cannot homogenously suspend fibers for an extended time, resulting in clear separation and formation of two layers: an upper fiber layer and a lower suspension layer (George et al., 2012). The stability of fibrous suspension is essential for their functionality; therefore, fibrous fluids must be prepared with fibers that have a specific gravity that is very close to the base fluid to prevent fiber separation driven by density difference (Alhajabdalla et al., 2021). Additionally, numerous research has found that wellbore angle (vertical, deviated, and horizontal) affects cuttings transportation performance, the practical application requires efficient cutting transportation at all inclinations as a single wellbore can acquire all types of inclinations (Mohammadsalehi and Malekzadeh, 2012; Ogunrinde and Dosunmu, 2012; Onuoha et al., 2015; Peden et al., 1990). Existing pilot-scale studies related to fibrous fluids cleaning performance are minimal, specifically in a vertical configuration and large cuttings. Furthermore, this work researches the cleaning performance of polypropylene low aspect ratio fibers. This experimental study aims to investigate fiber of different aspect ratio effectiveness in improving the cuttings carrying capacity of polymeric fluid systems.

2. Experimental setup and methods

2.1. Materials

White virgin polypropylene monofilament synthetic fibers (FORTA Super-Sweep® Fiber), with a specific gravity of 0.91 and an average melting point of 172 °C, were used in this investigation. Fibers of 100 μm diameter and 3 and 12 mm length (aspect ratio of 30 and 120 respectively) were used. Various concentrations of water-based fluids were prepared using Carboxymethyl Cellulose (CMC) polymer. All suspensions were prepared using tap water. Spherical glass beads, ranging in size from 1 to 6 mm, were used as an inert alternative to real cuttings. Table 1 summarizes the characteristics and source of each material where applicable.

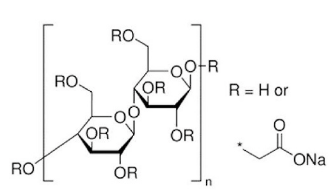
2.2. Fluid preparation and formulation

Predetermined amounts of polymer were weighted and steadily added to water in a mixing tank. The powdered polymer was added to the tank while mixing at 600 rpm. The mixing was continued for 30 min, then followed by a prolonged 1–3 h mixing at a higher rotation speed (600–1200 rpm). The mixing time and shearing intensity were varied depending on the dispersing ability and concentration of the polymer. The suspensions were left to hydrate for 24 h, and mixing speed was maintained at an optimum value, ensuring efficient mixing while minimizing lump formation and intensive mixing, which can introduce air bubbles into the suspension.

Following hydration, polymeric suspension underwent 10 min of agitation to ensure homogeneity. Subsequently, fibers were added to the polymeric mixture while mixing at 4000–6000 rpm for 2 min. The clumps of fibers were separated manually using a spatula before their addition to the polymer suspension to ensure good fiber dispersion. The test matrix is represented in Table 2. All experiments were conducted at ambient temperature (20 °C).

Fiber stability could be defined as the ability of fibers to disperse within a solution homogenously for an extended time. Polymeric suspensions are expected to exhibit good stability by preventing fiber particles from segregation. CMC suspensions with more than 0.4 wt% polymer concentration are recommended for 80% fiber stability

Table 1
Materials characteristics and properties.

Name	Characteristics	Structure/Shape	Source
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
Fibers	Specific Gravity: 0.9 Length: 3.175 mm, 12.7 mm Diameter: 100 μm Environmental effect: LC_{50} value of 1 million, Safe	Composition: Virgin Polypropylene Structuer: Monofilament fibers	FORTA Super-Sweep, Pennsylvania, USA
Glass Beads (Cuttings)	Composition: Borosilicate Diameter: 1,3, & 6 mm Specific Gravity[a]: 2.4, 2.3, 2.5, for 1,3, and 6 mm respectively.	Shape: Spherical Reactivity: inert Color: White-transparent	ISOLAB GmbH, Wertheim, Germany (3 & 6 mm) YIWU SANJIA Electronic Commerce Co., Ltd. Zhejiang, China (1 mm)

[a] Estimated values.

Table 2
Test matrix.

#	Polymer Concentration (wt.%)	Fiber Concentration (wt.%)	Fiber length (mm)	RPM	Reynold Number	Taylor Number
1	Water (0% CMC)	Fiber-free	–	0	0	0
2	Water (0% CMC)	0.02% fiber	12	0	0	0
3	Water (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

(Alhajabdalla et al., 2021). Furthermore, CMC suspensions with a polymer concentration of up to 0.8 wt% could enhance cuttings carrying capacity in conjunction with fibers (Mahmoud et al., 2021).

Increasing fluid viscosity improves cuttings lifting ability in vertical and slightly inclined boreholes (Ford et al., 1990). Alternatively, the hole-cleaning process of horizontal wells can be adversely affected by increasing fluid viscosity (Kelessidis et al. (2007). This difference could be associated with the variation in the cutting transport mechanisms in inclined and horizontal wellbores, which are dependent on the flow regime and the forces acting on the cutting particles. Due to its disruptive action, turbulence tends to enhance the carrying capacity of drilling fluids. Therefore, to limit the effects of turbulence and the secondary flow on our carrying capacity measurements, experiments were conducted at low Reynolds and Taylor numbers. The Reynolds number for a concentric annulus with inner pipe rotation is expressed as:

$$Re = \frac{\rho \omega r_i (r_o - r_i)}{\mu_{eff}} \tag{1}$$

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

$$\mu_{eff} = k \dot{\gamma}_w^{n-1} \tag{2}$$

where k is the flow consistency index, and n is the fluid behavior index. The generalized Taylor number for the annular flow of non-Newtonian fluids with a rotating inner pipe is given by (Lockett et al., 1993):

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

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

$$\dot{\gamma}_w = \frac{\omega r_i}{(r_o - r_i)} \tag{4}$$

2.3. Experimental setup

A schematic representation of the experimental setup is illustrated in Fig. 1. The setup consists of a fully transparent test section with a rotating shaft, fluid preparation and collection tank, separation sieve, and transfer pump. The test section height and diameter are 150 and 19.5 cm, respectively. A 9-cm rotating shaft which is driven by a 1-HP electric motor that has a maximum speed of 900 RPM capacity is positioned in the test section to form a concentric annulus. A 10-cm bit of irregular surface is attached to the bottom end of the rotating shaft. The total test section volume is 0.0354 m^3 (35.4 L). A manual drain valve controls the discharge located at the bottom of the test section. The test section and piping were made of clear acrylic tubes, permitting visual observation of the fiber-particle interaction.

2.4. Pilot-scale test procedure

The experiments were carried out under different fiber and polymer concentrations, cutting sizes, and shaft rotation speeds. A block diagram that shows the experimental procedure is presented in Fig. 2. The experiment started by preparing the test fluid, as explained in Section 3.2. Following the preparation, a representative sample was collected to perform rheological measurement using a rheometer. Fibers were then gradually added to the mixing tank while agitating at 5500 RPM speed. The agitation was maintained for 5 min to ensure good dispersion of the fiber particles. Then, the mixed solution was transferred into the test section using a centrifugal pump. The inner shaft was rotated 750 RPM during the transfer process. Afterward, the shaft speed was adjusted and glass beads of the desired size and amount (354 g) were injected to form a 1% (wt.) solid suspension. The fluid was allowed to remain under the specified shaft rotation speed for 2.5 min. Finally, the bottom 20% of the suspension in the test section is discharged, and cuttings within that suspension are separated. Cuttings were placed in an oven to dry, the

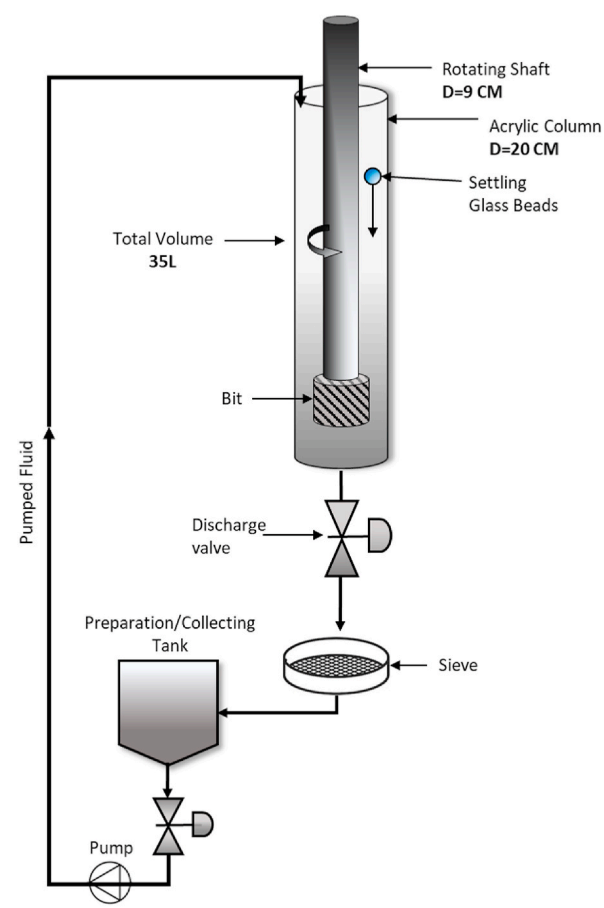


Fig. 1. Schematic of the test section.

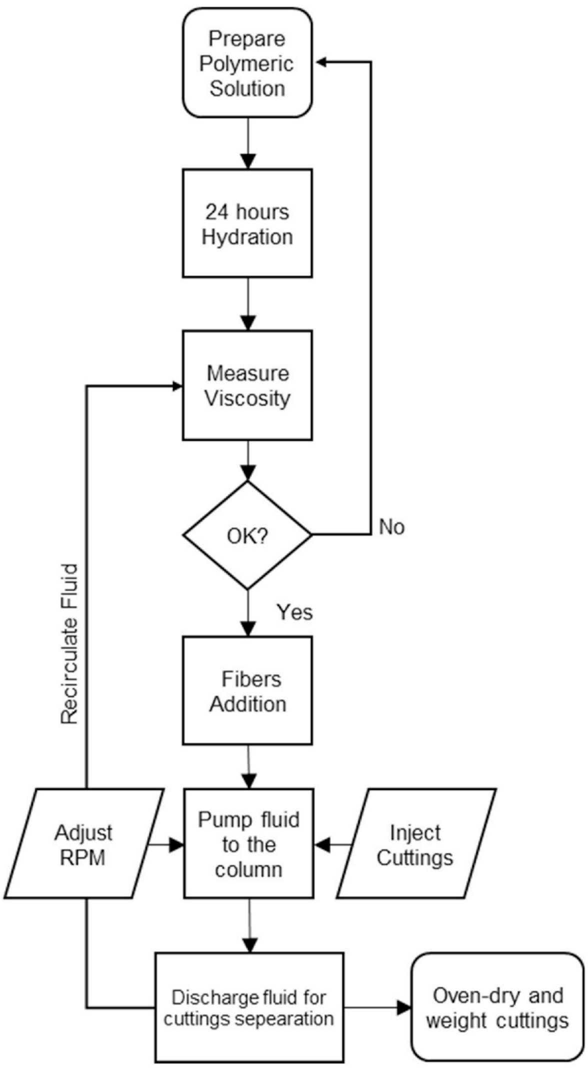


Fig. 2. Flow chart of the experimental procedure.

oven temperature was maintained at 100 °C to facilitate the drying process. The dried cuttings were weighted to determine the deposited and suspended cuttings concentrations using Eqs. (5) and (6), respectively.

$$\text{Deposited cutting concentration (DCC)} = \frac{\text{Weight of cuttings from bottom 20\%}}{\text{Weight of total injected cuttings}} \text{ x100} \tag{5}$$

$$\text{Suspended cuttings concentration (SCC)} = 100 - \text{DCC} \tag{6}$$

2.5. Rheological tests

The majority of the test fluids are classified as non-Newtonian fluids with considerable shear-thinning behavior and yield stress. The yielding behavior implies that these fluids must first undergo a certain amount of shear stress before they can start flowing. Given these characteristics, non-Newtonian fluids seem to be an ideal choice for suspending rock cuttings and reducing pressure losses at high flow rates.

A rheometer was used to assess the flow behavior of test fluids. The polymeric suspensions of CMC were prepared as per the procedure outlined in Section 3.2. Experiments were carried out using an Anton Paar Modular Compact Rheometer (MCR) 302 Rheometer utilizing a Couette cell with 24 and 30 mm diameter and length, respectively. The measurements were conducted at room temperature of 20 ± 1.0 °C, and the shear rate ranged from 0.01 to 100 1/s. The non-Newtonian behavior of test fluids has been demonstrated using a variety of rheological models.

Several rheological models can describe the non-Newtonian behavior of shear-thinning fluids. The generalized Herschel-Bulkley model ($\tau = \tau_o + k\dot{\gamma}^n$) describes the relationship between shear stress and shear rate in most drilling and completion fluids (Elgaddafi et al., 2016; Kelessidis et al., 2006). This model is developed from the power-law model ($\tau = k\dot{\gamma}^n$) by taking into account the shear stress required to initiate the flow, where τ is the shear stress, k is the fluid consistency index, $\dot{\gamma}$ is the shear rate, n is the fluid behavior index, and τ_o is yield stress. The apparent viscosity (η_{app}) for non-Newtonian fluids can be determined as: $\eta_{app} = \tau/\dot{\gamma}$.

3. Results

3.1. Rheology test

3.1.1. Effect of polymer concentration

Rheology tests were performed to investigate the influence of polymer on base fluid rheological characteristics. Fig. 3 illustrates the flow curve of polymeric suspensions and power-law (Ostwald) and Herschel-Bulkley model regression lines. The shear rate was limited in the range of 1–100 1/s due to the rheometer technical limitations. The flow curves demonstrate the shear-thinning behavior of the fluids. An increase in polymer concentration from 0.747 to 1.1% increased the apparent fluid viscosity across the entire range of shear rates. Polymeric suspensions of both concentrations have shown strong shear thinning. Ostwald and Herschel-Bulkley model parameters (Table 3) confirm the enhancement of shear-thinning with the polymer concentration. High-shear rate data points are used to obtain flow consistency coefficient and flow behavior index. The yield stress term of the Herschel-Bulkley model is obtained from the y-intercept of a linearized Herschel-Bulkley equation based on low-shear rate data points.

3.1.2. Effects of shear degradation and aging

Fluid samples were collected every day before the test during the 6-days experimentation period to investigate suspension stability and shear degradation. The samples were taken from the mixing tank to evaluate the rheological property changes that have occurred during the testing period due to repeated mixing, sharing, pumping, and aging. Fig. 4 represents the 6-days rheological measurement of the samples. Five samples were tested in total, four samples were taken in four consecutive days, and the fifth sample was collected after two days of storage. All samples were taken from the same batch of test fluid used for experimental runs. Results show that storage and usage of the suspension had a negligible effect on the rheological properties over 4 consecutive experimental days. As a result, following four days of experimental runs, a new batch of test fluid was prepared and allowed to hydrate for 24-h to minimize the experimental error.

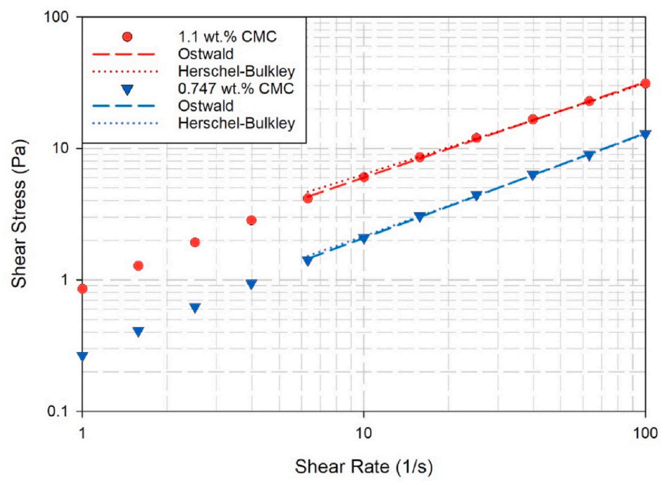


Fig. 3. Flow behavior of fiber-free polymeric suspensions.

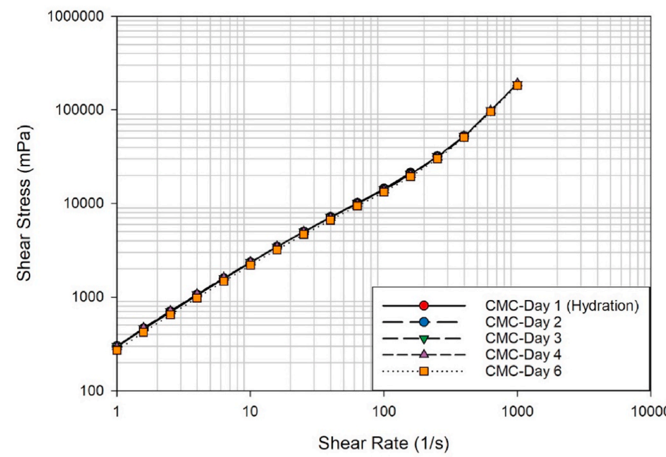


Fig. 4. Rheological characteristics 0.747% CMC suspension over 6-days of experimentation.

3.2. Effects of polymer and fiber concentrations

The ability of fibers in improving the carrying capacity of fluids was tested in various base fluids. When water was used as the base fluid, increasing fiber concentration did not strongly affect the solids carrying capacity of the fluids, as indicated by a moderate increase in suspended cuttings concentration (SCC) after the tests (Fig. 5a). The visual observation of the particle sedimentation process showed that water could not create homogeneous fiber suspension. The separation of fiber could be the main reason for the limited performance of fiber in water (Alhajabdalla et al., 2021). The introduction of polymer assisted the stabilization of homogeneous fiber suspension, subsequently showing the impact of fiber in improving the solids carrying capacity of the fluid (Fig. 5b). The fiber addition had a substantial effect on the settling of fine (1 mm) solid particles. Adding fibers up to 0.06% increased the SCC from 5% to 18%.

Coarse particles (3 and 6 mm) exhibited slight improvement in SCC with the fiber addition. Comparison of their SCC for fiber-free and fibrous base fluids shows a slight improvement in carrying capacity because of adding the fibers. For fine (1 mm) particles, the effect of fiber was more pronounced with the use of 0.749% polymer concentration.

The effect of increasing polymer concentration from 0.747 to 1.1% in the presence of shaft rotation (55 RPM) on the carrying capacity of the fluid is illustrated in Fig. 6. In the absence of fiber, the SCC of 1-mm solids increased from 4% to 17% (Figs. 5a and 6a) due to the increase in polymer concentration and the rotation of the shaft. With the addition of fiber, further improvement in SCC was observed. The gradual increase in fiber concentration from 0 to 0.06% in 0.747% polymer suspension enhanced the SCC of 1-mm solids from 17 to 31.6% (85% improvement) while in 1.1% polymer suspension the SCC enhancement was from 38.9 to 52.9% (36% increase). The SCC of the coarse cuttings (3 and 6 mm) slightly improved due to the increase in fiber and polymer concentrations. These observations reflect that the improvement of the SCC due to fiber addition is dependent on the polymer concentration. At low polymer concentrations (0.747%), the impact of fiber addition on the SCC was more pronounced. This observation could be explained by considering the dominating effect of the fiber drag (i.e. mechanical and hydrodynamic drag forces associated with the formation of fiber network in the fluid) when the viscous drag is inadequate due to the limited fluid viscosity (Elgaddafi et al., 2012).

3.3. Effect of inner pipe rotation

Wellbore drilling speed (rate of penetration) can vary depending on multiple factors such as formation type, hole size, bit rotation speed, weight on the bit, and bit type (Sikes Jr., 1936). Hence, in the absence of a downhole motor, the drill string rotation speed directly affects the rate of penetration (ROP). The effect of drill string rotational speed on the performance of fiber in improving the carrying capacity of the fluids (i.e. increasing SCC) is demonstrated in Fig. 7. Two different behaviors were observed for coarse (3 & 6 mm) and fine (1 mm) cuttings with pipe rotation. Predominantly, increasing the rotation speed at a given fiber concentration slightly decreased the SCC of coarse cuttings. Despite this, the SCC of fine cuttings was positively affected by the pipe rotation. These contradicting observations occurred regardless of the fiber concentration. A possible explanation for the contradiction could be the presence of settling hindering and enhancing phenomena occurring under dynamic conditions. On the one hand, the rotation of the shaft could reduce the apparent viscosity of the fluid by increasing the resultant shear rate ($\dot{\gamma}_R$). The reduction in apparent viscosity is more pronounced because of the strong shear-thinning behavior of the base fluids. For sedimentation occurring in a Couette flow field, the resultant shear rate can be related to the settling shear rate as: $\dot{\gamma}_R = \sqrt{\dot{\gamma}_s^2 + \dot{\gamma}_r^2}$, where $\dot{\gamma}_s$ and $\dot{\gamma}_r$ are the settling and rotational shear rates, respectively. The reduction in viscosity decreases the viscous drag and exacerbates the settling. On the other hand, the rotation of the pipe can induce turbulence and secondary flows that generate diffusion mechanisms, which can reduce the sedimentation rate of the particles. Even though experiments were conducted at low Taylor and Reynolds numbers, the vibration of the rotating shaft likely resulted in the formation of turbulence that counteracted the effect of apparent viscosity reduction. Diffusion is an effective mechanism in dispersing fine particles in fluids (Ramadan et al., 2001). However, it is effectiveness significantly reduces as the particle size increases. The current results suggest the effect of

Table 3
Ostwald & Herschel-Bulkley model parameters.

CMC (wt.%)	Ostwald				Herschel-Bulkley				
	n	*k (Pa.s)^n*	*RMS*	R^2	*N*	*k (Pa.s)^n*	τ_o *(Pa)*	*RMS*	R^2
0.747	0.797	0.334	0.0875	0.999	0.789	0.339	0.0696	0.0988	0.999
1.1	0.726	1.132	0.343	0.999	0.709	1.187	0.305	0.444	0.999

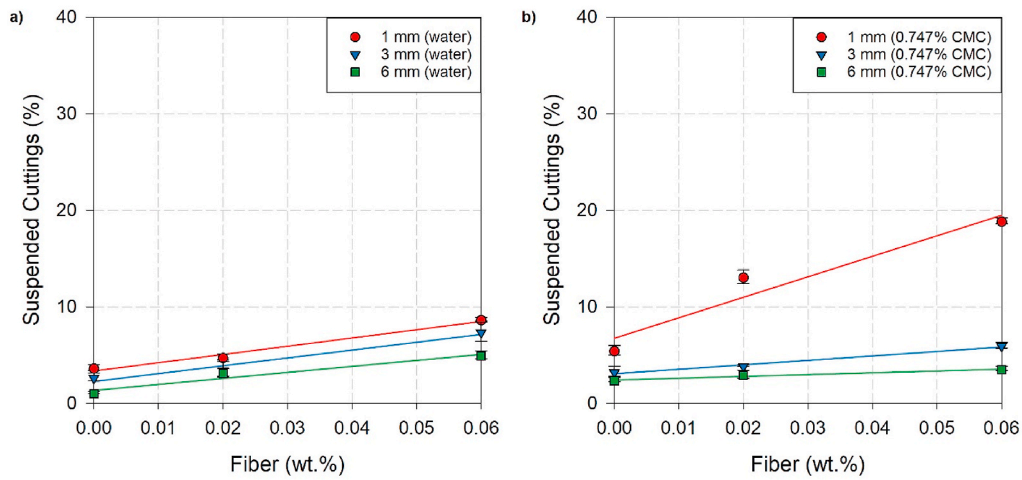


Fig. 5. Cuttings suspension against fiber concentration and cuttings size: a) Water; b) 0.747% CMC, 0 RPM, and using 12 mm fibers.

diffusion was dominating the impact of apparent viscosity reduction for fine (1 mm) particles, whereas this was the opposite in the case of coarse (3 & 6 mm) particles.

The effect of fiber on the SCC of 6-mm cuttings was insignificant regardless of the inner shaft rotation. A noticeable increase in the SCC of 3 mm cuttings was observed when fiber concentration was increased to 0.06%. In the case of 1 mm cuttings, the effect of fiber was consistent in increasing their SCC regardless of the rotation speed of the shaft.

3.4. Effect of fiber length

Fibers having the same diameter but distinct lengths are expected to affect the carrying capacity of fluids differently. Long fibers have strong fiber-fiber interactions and the potential for forming a structured network while short fibers exhibit limited network-formation ability (Alhajabdalla et al., 2021). However, laboratory and field observations have shown that long fibers can cause pipeline clogging (Fig. 8) in downhole tools, jeopardizing the smoothness of operation. These issues have recently generated motivation to improve the applicability of fibers through investigating the incorporation of long and short fibers at various mixing ratios. To investigate this, short (3 mm) and long (12 mm) fibers were mixed at various fractions, ranging from 0 to 100 wt %.

Fig. 9 demonstrates the effect of mixing long and short fibers on SCC. The left-end represents 0% of long fiber and 100% of short fiber and vice versa for the right-end. Mixing of short and long fibers did not show a substantial benefit in terms of improving the SCC of 3 mm cuttings. However, the SCCs obtained using mixed fiber were substantially higher than the ones obtained from using unmixed fiber in the case of 1 mm cuttings. The length of the fiber particles affects the network-formation tendency. For the same quantity of fiber, the number of short fibers is four times that of long fibers, thus having a greater uplifting bouncy force enhancement. However, it is important to note that long fibers have the benefits of establishing long-range fiber-fiber interactions that are absent in short fibers. Hence, mixing fibers with different length help create a fiber network with large numbers of fiber particles and at the same time having long-range fiber-fiber interactions. Consequently, pipeline blockage problems occurring due to long fiber entanglements could be avoided without compromising cuttings transport performance. Although the effect of fiber mixing on the SCC of 1 mm cuttings was limited, 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%.

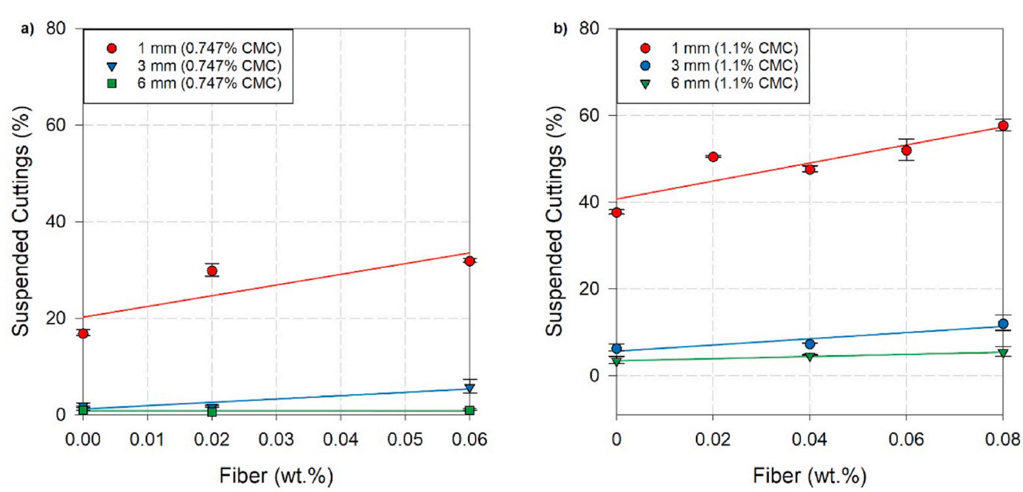


Fig. 6. Cuttings concentration vs. fiber concentration at 55 RPM, and using 12 mm fibers for different cuttings sizes and polymer concentrations: a) 0.747% CMC; b) 1.1% CMC.

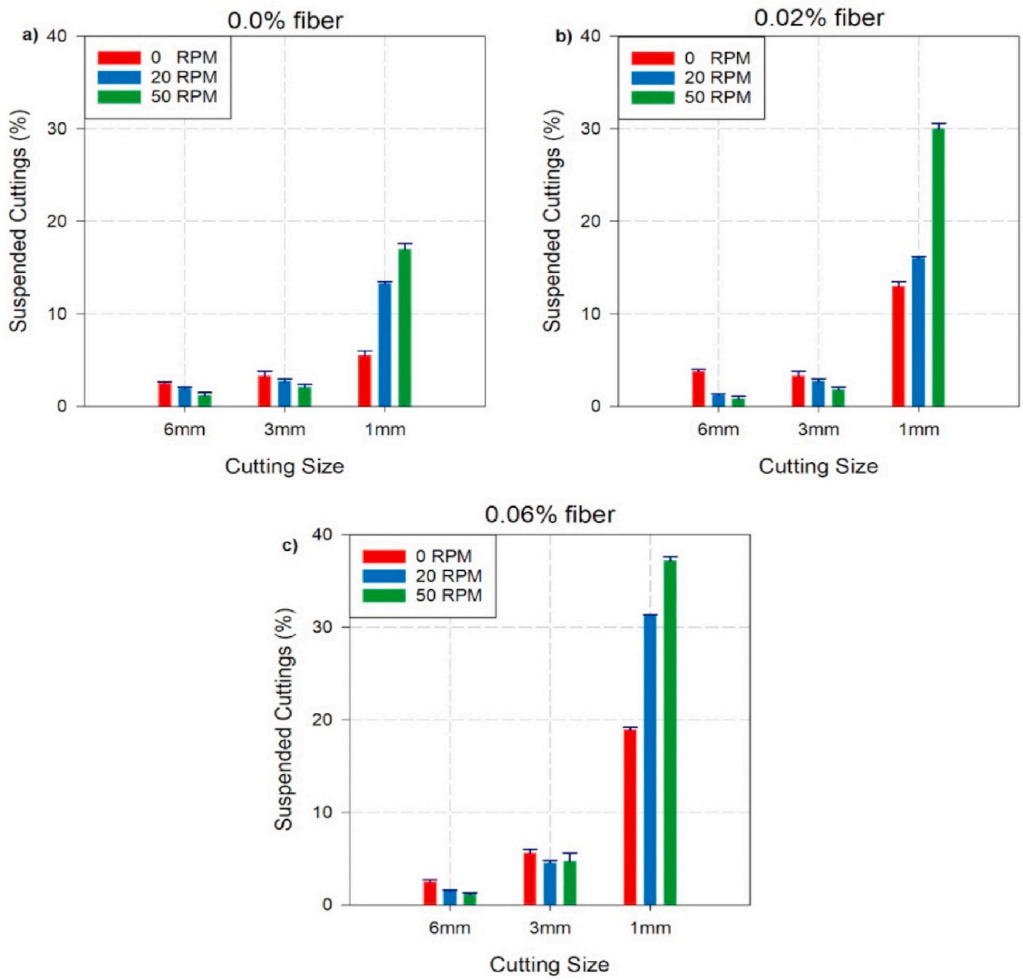


Fig. 7. Suspended cuttings concentration vs. cuttings size using 0.747% polymer concentration and different cuttings sizes and rotation speeds, and for various fiber concentrations: a) 0.0% fiber; b) 0.02% fiber; c) 0.06% fiber.

4. Conclusions

The cutting carrying capacity of fibrous polymeric suspensions was extensively investigated in a pilot unit with a vertical annular test section that has a rotating inner shaft representing the drill string. Experimental parameters such as fiber concentration, polymer concentration, cuttings size, shaft rotation speed, and fiber length were varied to examine their impact on the carrying capacity of test fluids. Based on the findings of this investigation the following conclusions can be made:

- The suspended cuttings concentration (SCC) of coarse cuttings (3 and 6 mm) were not strongly affected by the addition of fiber and/or polymer, demonstrating marginal response to the changes occurring in operational conditions.

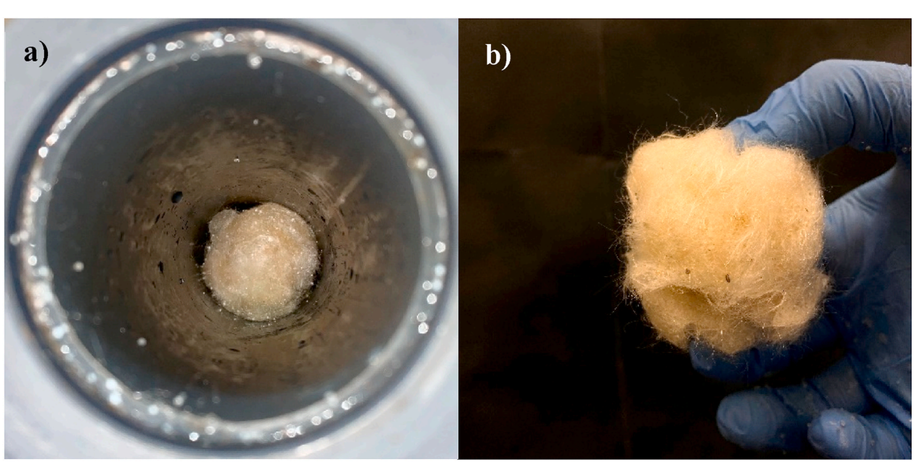


Fig. 8. Fiber cluster blocking system pipes; a) fibers inside the pipe; b) extracted fibers.

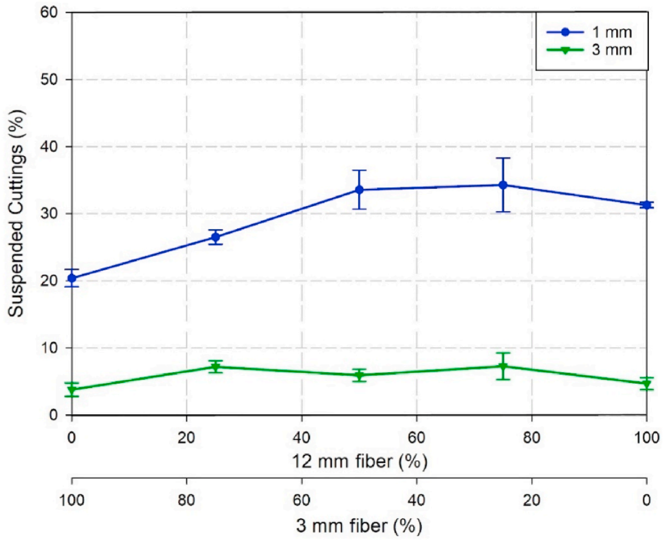


Fig. 9. SCC vs. fiber mass fraction in 0.747% polymer suspension at 0.06 wt% fiber, and 55 RPM.

- Results indicate that an increase in polymer concentration from 0.747% to 1.1% in the absence of fiber considerably increased (approximately 20%) the SCC of fine (1 mm) cuttings. The addition of up to 0.08% fiber further increased the SCC by another 20%.
- The shaft rotation increased the SCC of fine cuttings. In contrast, predominantly pipe rotation negatively affected the SCC of coarse cuttings (3 and 6 mm); however, the changes were negligible.
- Mixing of short and long fibers improved the SCC of both fine (1 mm) and coarse (3 mm) cuttings. Without mixing, the longer fiber performed better than, the shorter one in improving the carrying capacity of the fluid. The result shows that mixing short and long fibers at fixed fiber concentration (0.06%) at specific ratios can enhance cuttings carrying capacity.
- The incorporation of shorter fibers has shown to sustain similar cleaning performance of longer fibers, which is beneficial in avoiding pipeline/valves blockages in addition to lowering operational costs.

Author contributions

Husameldin Mahmoud: Conceptualization; Writing – original draft; Methodology; Formal analysis. Mohammed Alhajabdalla: Methodology; Formal analysis. Arafat A.A. Mohammed: Writing; Methodology. Mustafa S. Nasser: Conceptualization; Supervision; Funding acquisition; Project administration. Ibnelwaleed A. Hussein: Writing – review & editing; Funding acquisition. Ramadan Ahmed: Formal analysis, Writing – review & editing. Hamidreza Karami: Writing – review & editing Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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