Assessment of Viscoelastic Properties of Drilling Fluids and their Impact on Hole Cleaning Capacity in Horizontal Directional Drilling

by

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Abstract

Trenchless construction technologies are a group of construction methods that use strategies to minimize or eliminate surface excavation. Horizontal directional drilling (HDD) is one commonly used trenchless method and can be used HDD to install underground pipelines and conduits. Additionally, HDD is the preferred method when crossing water courses because it reduces the environmental damage that can be caused by conventional construction methods. During the HDD process, especially while drilling the pilot bore, a large volume of cuttings is produced. Efficient transportation of these cuttings to the surface—commonly known as the hole cleaning—is essential for the successful completion of the project. Inappropriate hole cleaning conditions can lead to several problems that may cause the failure of the HDD project.

Researchers have studied hole cleaning process in the oil and gas industry as well as in HDD in the past years, and there is a general consensus that annular velocity, i.e., the velocity of the drilling fluid in the annulus of the borehole, is the factor that most influences hole cleaning performance in both vertical and directional drilling. Nevertheless, maintaining a high annular velocity is not feasible in HDD projects due to the impossibility of having rig equipment that keeps a turbulent regime. Moreover, in cases where high annular velocity is reached, this may cause erosion and hole enlargement. Other factors that influence the hole cleaning process, such as the nature of the cuttings produced and operational parameters, might be difficult to control. Those factors are determined by formation characteristics, equipment facilities in the field,

borehole trajectory design, and project budget. Therefore, the effect of the rheological properties of drilling fluid on hole cleaning capacity was chosen as the major focus of this study. In particular, the elastic properties of the drilling fluid are studied, which are seldom included in the hole cleaning assessment.

The experimental program consisted of conducting rheological tests on water-based drilling fluids using an oscillatory rheometer (DSR). The drilling fluid additives investigated included partially hydrolyzed polyacrylamide (HPAM, two different grades) and sodium bentonite. The Bingham-Plastic model, Power-Law model, and Herschel-Bulkey model were applied to characterize the drilling fluids. The viscoelastic behavior of each sample according to its concentration and molecular weight has been determined, as well connecting the viscoelastic properties of the drilling fluid and indicators of hole cleaning capacity.

The major findings based on experiments with HPAM can be summarized as follows. First, the solution that gave the best hole cleaning performance had a molecular weight of 8 million Dalton at the highest concentration investigated (0.1%). Second, in most solutions, elastic behavior dominated over viscous behavior. Third, viscosity benefits hole cleaning while elasticity lowers the hole cleaning performance. The experiments with bentonite as a drilling fluid additive indicate that increasing the bentonite concentration increases the elastic and viscous component and improves hole cleaning performance. In addition, increasing the bentonite concentration causes the rheological parameters (such as the yield point (YP), the plastic viscosity (PV), the yield stress (τ_y), and so on) to increase, and flattens the velocity profile, which is also beneficial for the hole cleaning performance. The main conclusion of this study is that viscosity and elasticity each play a role in drilling fluid and both parameters should be included for an accurate assessment of hole cleaning performance.

Preface

This thesis is the original, unpublished, independent work of the author, Paula Lizeth Rodriguez Leon.

All the work presented in this thesis was conducted in the Asphalt Lab and the Concrete Lab located at the Natural Resources Engineering Facility at the University of Alberta.

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Table of Contents

List of Tables

List of Figures

Chapter 1: INTRODUCTION

1.1. Background

Trenchless construction technologies are a group of methods used for installation and rehabilitation of underground infrastructure with minimal impact on the surface. Among those methods, horizontal directional drilling (HDD) is a technique used to install underground utilities and pipelines under water (Allouche et al., 2000). The three main phases in an HDD installation include drilling the pilot bore, reaming, and pullback. The pilot bore consists of drilling the soil following the designed trajectory. The aim of the reaming process is to enlarge the borehole to a specific diameter. Finally, the product pipe is connected to the drill head and pulled back into the borehole until the full length of the pipe is installed (Woodroffe & Ariaratnam, 2008; Zeng et al., 2018). In the first two phases of an HDD installation (drilling and reaming), large volumes of cuttings are produced and the efficient transportation of these cuttings to the surface, commonly known as hole cleaning, is essential for the successful completion of an HDD project. Inappropriate hole cleaning can lead to various problems, including blockage of the annulus area: this increases drilling torque, drag forces, and annular pressure, as well as raising the risk of hydro fracture. The consequences of inappropriate hole cleaning may include failure of the project (Hemphil et al., 1993; Shu et al., 2015).

The process of hole cleaning in drilling has been studied by the petroleum industry for more than half a century. However, problems still exist in many drilling operations. The unique characteristics of HDD, including large annular diameter and low annular velocity, which are caused by limited pressure capacity in the field, make the hole cleaning process even more difficult in this case. The flow annular velocity has been identified as the most effective parameter in hole cleaning performance (Azar & Sanchez, 1997; Iyoho, 1980; Pilehvari et al., 1999). Nevertheless, for the low annular flow velocity conditions in HDD, this parameter can not be exploited fully to solve hole cleaning issues.

Another consideration is the rheological characteristics of the drilling fluid. Tomren et al. (1986) claimed that the higher the ratio of yield point to plastic viscosity (*YP/PV*) or the lower *n* value of PL model provide better cuttings transport. It was also found that high value of *YP* and *YP/PV* are more pronounced at low annular fluid velocity. Pilehvari et al. (1999) mentioned that high viscosity fluid in laminar flow conditions can provide hole cleaning performance as good as low viscosity fluid in turbulent flow, due to the rotation of the drill pipe in the latter technique. Powell et al. (1991) pointed out that gel behavior helps determine the suspension capacity in polymer-containing fluids. Similarly, Zamora et al. (1993) claimed that elasticity improves the hole cleaning in the laminar regime.

According to previous studies, both the viscosity and the elasticity behavior of a drilling fluid play a significant role on the cutting transportation process in HDD. Therefore, a deeper review of the effect of drilling fluid rheology (i.e., viscosity and elastic properties) into the hole cleaning process is necessary.

1.2. Research Objectives

The general objective of this study is to analyze the impact of viscous and elastic properties on hole cleaning performance in HDD.

The additives investigated for the drilling fluid solutions include HPAM and bentonite. A dynamic shear stress rheometer (DSR) from Anton Paar was used to characterize the solutions.

The specific objectives of this thesis are as follows:

- To study the influence of the molecular weight of HPAM on the viscoelastic properties of solutions,
- To investigate the viscoelastic properties of drilling fluid solutions with the variation in additive concentration (for HPAM and bentonite),
- To identify the rheological model that best describes the behavior of the solutions (Bingham-Plastic (BP), Power-Law (PL), and Herschel Bulkley (HB) models), and
- To determine the most suitable indicator for determining the rheological model that best fits the rheological behavior of the drilling fluid solution.

1.3. Methodology

A comprehensive review of features and constructions phases in HDD was conducted, as well as identification of the main challenges using these techniques. Among all the challenges associated with HDD, transportation of drilled cuttings to the surface by the drilling fluid has been selected as the main subject of study. A literature review of the variables affecting cuttings transportation in the oil and gas industry, as well as in HDD, was conducted. Then, the variables that have the most influence on cuttings transportation, and therefore in hole cleaning performance, were analyzed, as well as the parameters that are more feasible to modify in the field. As a result of this process, the rheological properties of the drilling fluid were identified as being most important to investigate.

The experimental program consisted of rheological tests using an oscillatory rheometer (DSR). Water-based drilling fluids were mixed using partially hydrolyzed polyacrylamide (HPAM) of two different grades and sodium bentonite. The viscoelastic behavior of each sample is discussed according to concentration and molecular weight. Based on these experiments, the parameters for three different rheological models (Bingham-Plastic, Power-Law, and Herschel-Bulkey models) were determined. After careful analysis, the model that best describes the tendency of the measured data was chosen. Finally, a connection between the viscous and elastic properties of the drilling fluid and conventional hole cleaning index were considered. Restrictions, such as the frictional pressure loss, were also included in the previous analysis.

1.4. Outline of Thesis

This thesis has the following structure:

Chapter 1: Introduction

The introduction provides an overview of the research topic, including a short summary of the background, the objectives, the methodology used, and the structure of this thesis.

Chapter 2: Literature Review

A review of the features, processes, and main challenges in HDD is presented. The factors affecting the hole cleaning process in the oil and gas industry, as well as in HDD are introduced. Finally, a review of the effect of the rheological properties of drilling fluid on hole cleaning performance is discussed.

Chapter 3: Rheological and viscoelastic properties of horizontal directional drilling fluids and their impact on hole cleaning performance

This chapter focuses on analyzing the impact of the viscosity and the elastic properties of drilling fluid on cuttings transportation in HDD. Water-based drilling fluids were tested using an oscillatory dynamic shear rheometer (DSR), and flow curves and frequency sweep tests were acquired. The additives used in the experiments were partially HPAM (two different grades) and sodium bentonite. First, an assessment of the rheological properties of drilling fluids containing HPAM and sodium bentonite was done. Second, the rheological model that best fits the measured data was evaluated. Finally, an analysis of the association of hole cleaning indicators and viscosity properties, as well as elastic features, were performed.

Chapter 4: Conclusion and future research

In this chapter, the most important results of this research work are summarized and recommendations for future studies are presented.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

Trenchless construction technologies are a group of methods used for installing, repairing, and renewing underground infrastructure. Trenchless methods use strategies that minimize or eliminate the need for surface excavation. HDD is a trenchless method employed to install underground pipelines and conduits with minimal impact at the surface. This method has seen fast growth since 1980 due to many advantages, over conventional open excavation, including less damage to the environment, lower societal costs in urban areas (e.g., decrease in traffic delays and business activities), and minimal damage to surrounding infrastructure (Ma & Najafi, 2008). HDD originated in the oil and gas industry but has been adopted for civil engineering applications. Drilling in the oil and gas and HDD industries shares similar features and challenges. One of these challenges encountered in both industries is hole cleaning, which is defined as the process to transport drilled cuttings from the wellbore to the surface. Nevertheless, hole cleaning is more difficult in HDD due to the large diameter of the annulus, as well as the low annular velocity due to the limit on pump capacity in the field (Zeng et al., 2018).

Based on oil and gas research, it has been concluded that the main factors affecting cuttings transport (and therefore hole cleaning) are annular velocity, hole inclination, and the rheological properties of drilling fluid (Iyoho, 1980). A high annular velocity is not feasible on HDD projects, due to the impossibility of having rig equipment that maintains drilling fluid in a turbulent regime. Moreover, high annular velocity might also cause erosion and hole enlargement (Bayer Hans-Joachim, 2005). The hole inclination is established according to the formation features and the crossing obstacles, such as watercourse and utilities conduits. Thus, it is more feasible to modify the rheological properties of the drilling fluid to improve hole cleaning performance.

Although the best-known rheological properties in the drilling fluid industry are plastic viscosity (*PV*) and yield point (*YP*) based on the Bingham Plastic Model, the elastic component is a key element that is seldom considered. The elasticity is one aspect of the rheological properties of a drilling fluid and can be measured using parameters such as gel strength and relaxation time. The rarity of the application of the elastic component of a drilling fluid in industry (as well as in the research community) can be attributed to a lack of understanding of its impact on the hole cleaning process (Powell et al., 2007; Werner et al., 2017).

When evaluating carrying capacity and cuttings transport in directional and horizontal drilling, the elastic component of the drilling should be given attention, because it influences the dynamics and interactions of the fluid and cuttings particles. Powell et al. (2007) studied the characteristics of biopolymer-containing fluids and their influence on rheology and fluid performance and concluded that elasticity enhances the carrying capacity of the biopolymer fluid. Similarly, Beck et al. (1993) claimed that the elastic component improves hole cleaning, and therefore cuttings transport, under laminar flow conditions. In addition, Sayindla et al. (2017) and Werner et al. (2017) reported that oil-based fluids have better cuttings transport capacity than water-based fluids, even though both fluids are close in viscosity. The results from these previous studies indicate that elastic component plays a significant role in hole cleaning. Thus, both the elastic and viscous properties of a drilling fluid should be included in an accurate assessment of cuttings transport capability. Despite these studies that indicate that the elastic component influences cuttings transportation, there are few studies in the literature that discuss either the individual or combined effects of viscous and elastic properties of drilling fluid on hole cleaning (Werner et al., 2017).

Throughout this chapter, a review of features, processes, and main challenges in HDD will be considered. Then, factors affecting the hole cleaning process in the oil and gas industry (as well as HDD) will be introduced. Finally, a detailed review of the rheological properties of drilling fluid will be presented.

2.2. Horizontal Directional Drilling

Horizontal directional drilling (HDD) is the fastest growing construction technique among underground trenchless methods. Since its first application in 1971—which consisted of the installation of 185 m of steel pipe (10 cm in diameter) across the Pajaro River in California—HDD has seen a rapid growth (Allouche et al., 2000). For instance, in North America, there were only 12 HDD rigs available in 1984, and by 1995 there were 2,000 rigs operating (Kirby et al., 1996). The applications of HDD include utility installations and rehabilitation of water mains, gravity sewers, natural gas pipelines, and telecommunications. HDD is also the method of choice for crossing buried elements and underground obstacles (Allouche et al., 2000; Ma & Najafi, 2008).

2.2.1. HDD Procedure

For HDD, the installation process can be divided in three main phases: drilling the pilot bore, reaming, and pullback. The main equipment used for HDD include a rig for drilling, a drill head (selected according to the type of soil or rock being drilled), and a set of reamers (used to enlarge the borehole until it reaches the required diameter). The schematic of these three phases is shown in **Figure 1**, and a brief description of each construction phase is given in the following paragraphs.

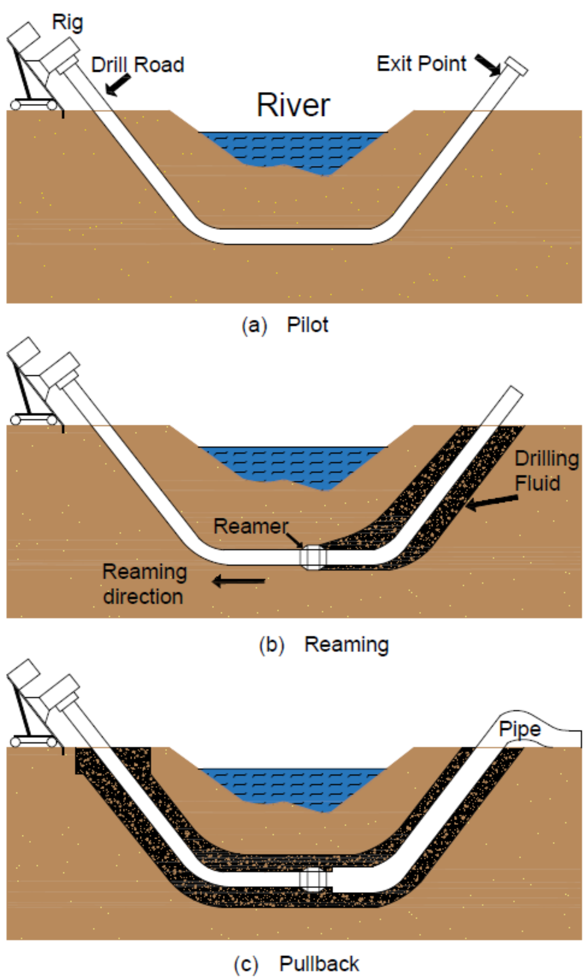

Figure 1. Horizontal directional drilling process. Adapted from Zeng et al. (2018)

Drilling the pilot bore is the first phase of an HDD installation. Before starting the drilling process, a borehole trajectory should be established, including the entry and exit locations. The entry angle and the exit angle should be kept the same, with a value around 8-16°. However, in cases of large pipe diameters, angles of up to 20° have been used. The rig is located at the entry location and the drill head is introduced into the surface to create the bore. A curved trajectory is followed until the desired depth is achieved. Later, the drilling head follows an approximately horizontal trajectory, and finally the drilling head is gradually steered until it reaches the planned exit (Woodroffe & Ariaratnam, 2008; Zeng et al., 2018)

Reaming consists of the enlargement of the borehole after the pilot stage. At the exit, the drilling head is removed and replaced with a reamer (a large sharp rotary cutting tool). The reaming process may be conducted in multiple passes using reamers of increasing diameter. Once the borehole has reached the required diameter, the pipe is attached to the reamer at the exit location and then pullback is done to install the product pipe (Woodroffe and Ariaratnam 2008; Zeng et al. 2018).

2.2.2. Drilling in HDD

In the three main phases of an HDD installation, the main activity is the drilling operation, where the drilling fluid is commonly known as “the blood of the process” (Shu et al., 2015). Therefore, drilling fluid is considered as the major factor affecting the success of an HDD project. The functions of the drilling fluid include, but are not limited to, the following: (1) transporting cuttings from the hole; (2) lubrication of drilling tools and pipe; (3) maintaining borehole stability; and (4) cooling down the drilling equipment.

Among these functions, hole cleaning is the most important, since inappropriate removal of cuttings can lead to the pipe getting stuck, which sometimes results in the failure of the project (Shu et al., 2015).

2.3. Hole Cleaning in Drilling Industry

Throughout this section, a review of the main findings related to cuttings transport and hole cleaning in the oil and gas industry is given. First, the studies focused on analyzing the hole cleaning process in vertical wellbores, and it took over 30 years of research in the literature to completely understand the phenomena. Academics determined that good hole cleaning performance in a vertical wellbore can be achieved by exploiting adequate annular velocity and the suspension capacity of drilling fluid (Baker Hughes, 2006).

In the 1980s, academics started to be interested in the problem of hole cleaning in inclined and horizontal wellbores. Many authors pointed out that the hole cleaning performance in inclined hole sections is completely different than in vertical wellbores, due mainly to the effect of gravity. In the inclined sections, gravity is a disadvantage to the hole cleaning process because it acts on the cuttings and cause them to settle in the borehole, and therefore, form a cuttings bed. This fact makes the transport of cuttings in inclined and horizontal wellbores more difficult (Adari et al., 2000; Baker Hughes, 2006). For a general review of the main findings related to hole cleaning in vertical wellbore, as well as inclined and horizontal sections, please refer to Sections 2.3.1 and Sections 2.3.2 respectively.

2.3.1. Cuttings transport in vertical wellbores

Effective cuttings transportation and hole cleaning are the main operational concerns in the oil and gas industry because these factors have a direct influence on the time and cost of drilling projects (Becker et al., 1991). If a well hole-cleaning plan is not established, the drilled cuttings settle down in the lower side of the well and can cause serious operational problems such as stuck drill pipes, premature bit wear, slow drilling, formation fracturing, and high torque (Becker et al., 1991; Nazari & Hareland, 2010).

Since 1940, extensive experimental studies have been carried out to investigate the impact of different parameters on hole cleaning. One of the earliest studies related to hole cleaning in vertical wellbores was conducted by Pigott (1941). This study involved calculation of the cutting settling velocity based on Stokes and Rittinger laws (for laminar and turbulent flow, respectively). Pigott (1941) determined that high annular velocity and drilling fluid density are essential factors in the capacity of the drilling fluid to carry the cuttings to the surface.

In the early 1970s, more parameters were considered in hole cleaning research in vertical wells or near-vertical wellbores. Chien (1972) investigated the rotary drilling operations and developed analytical relationships to select an appropriate annular velocity, including penetration rate, hole size, and drilling fluid properties. This study also included the influence of non-Newtonian viscosity on settling velocity. It was concluded that for each case or situation, where drilling factors can vary extensively, there is an optimal annular velocity. Later, experimental studies were carried out by Sifferman et al. (1974) to analyze cuttings transport in a vertical annulus. Sifferman et al. (1974) concluded that annular velocity and the rheological properties of drilling fluid are the most important parameters in the hole cleaning process.

In summary, hole cleaning in vertical wellbores is basically defined as overcoming the cuttings settling velocity by exploiting the annular velocity and carrying ability of the drilling fluid. By the end of the 1970s, several correlations had been developed to calculate the cuttings settling velocity, and the issue with cuttings transport in vertical wellbores were fairly well understood (Azar & Sanchez, 1997). Also, experimental data has resulted in recommendations to keep the concentration of cuttings below 5%. Higher concentrations of cuttings can lead to trouble during operations (Baker Hughes, 2006).

2.3.2. High inclined sections and horizontal wellbores

In the early 1980s, experimental research was performed to study hole cleaning in directional drilling, including high inclined sections and horizontal wellbores. Iyoho (1980) concluded that the main parameters affecting cuttings transport (and therefore hole cleaning) include annular velocity, hole inclination, the rheological properties of the drilling fluid. This study particularly pointed out that higher annular velocities are required for effective hole cleaning in directional drilling compared to vertical wells. Furthermore, the results showed that — within the same flow regime — high viscosity drilling fluids result in better cuttings transport than low viscosity drilling fluids.

Tomren et al. (1986) expanded the study of Iyoho, finding that cuttings buildup or bed formation is critical for hole inclination angles of 40°-50°. This study reported that bed formation is almost certain at hole inclination angles greater than 60°, but that bed does not slide down. Similarly, Brown et al. (1989) reported that the cuttings transportation is dramatic for hole inclination angles of 50°-60°. This study also pointed out that below angles of 50°, for a turbulent flow regime, water shows better hole cleaning performance than a polymer-containing drilling fluid.

Okrajni and Azar (1986) focused particularly on the effect of the rheological properties of drilling fluid on hole cleaning in directional drilling. This research indicated that, within a turbulent flow regime, cuttings transport is generally not affected by the rheological properties of the drilling fluid. However, in laminar flow regimes, it was observed that cuttings buildup is lower for higher yield point/plastic viscosity (*YP/PV*) ratios throughout the total range of hole inclination angles. Later, Becker et al (1991) included more parameters in the investigation of the impact of rheological properties of drilling fluid on hole cleaning performance in directional drilling. Power-law exponent, consistency index, dial readings at different shear rates, effective viscosity, and gel strength were studied. The results agreed with the findings presented by Okrajni and Azar (1986). Additionally, Becker et al (1991) concluded that low shear rate parameters, which include 3 rev/min Fann and 6 rev/min Fann V-G meter dial reading, as well as initial gel strength, correlate better with hole cleaning performance.

Investigation of hole cleaning and drilling factors continued in the 1990s. A study conducted by Sifferman and Becker (1992) showed that annular velocity and drilling fluid density are the main variables that influence cuttings bed formation. In addition, the same authors reported that cuttings accumulated more easily in oil-based drilling fluids than in water-based drilling fluids.

Another approach was taken by Gabignet and Sobey (1989), who proposed a two-layer model for cuttings transport in wells with a high hole inclination angle. Gabignet and Sobey (1989) reported that the main mechanisms for cuttings transport are saltation (when forces exerted by the drilling fluid on a cuttings particle cause it to be lifted into the fluid stream) and sliding (when the cuttings built up in the bed overcome the particle friction at the surface and move).

Similarly, Ford et al. (1990) investigated the main cuttings transport mechanisms in directional drilling. Their results showed that cuttings were removed by two distinct mechanisms: rolling/sliding and suspension, which are defined as follows. The rolling/sliding mechanism refers to when cuttings move on the lower side of the hole, whereas Suspension occurs when the cuttings are suspended in the drilling fluid. Additionally, the authors determined the minimum annular velocity required to initiate cuttings transport for each of the cuttings mechanisms they established.

Numerous experimental and numerical studies have been conducted to create models that predict hole cleaning performance. Some of these are (Campos, 1995; Cho et al., 2002;

Doron et al., 1987; Ford et al., 1996; Gillies & Shook, 2000; Jalukar, 1993; Kamp & Rivero, 1999; Larsen et al., 1997; Martins & Costapinto Santana, 1992; Nguyen & Rahman, 1998). However, the focus of this current study is not modeling hole cleaning performance, and the above references are included for readers who are interested in these studies.

In 2007, Bilgesu et al. (2007) proposed a method to classify the variables affecting cuttings transport, and therefore hole cleaning. The variables were divided into three main groups: drilling fluid factors, cutting features, and operational parameters. The variables in the first group are related to drilling fluid characteristics, including the rheological properties of drilling fluid, annular velocity, and fluid density. The second group (cuttings features) comprises cuttings density, shape, and concentration, as well as rate of penetration (ROP). The third group (operational parameters) includes inclination angle, pipe rotation, and annular eccentricity. The current study uses this classification (Bilgesu et al., 2007). In the following sections, the variables in each group—drilling fluid factors, cuttings features, and operational parameters—will be discussed in greater detail, with a focus on how each variable influences cuttings transport in HDD.

2.4. Variables Affecting Cuttings Transport

2.4.1. Factors related to Drilling Fluid

Rheological Properties of Drilling Fluid

Rheology has been described as the study of the fluid flow and deformation, including the elasticity, plasticity, and viscosity of fluids (Baumert et al., 2005; Orodu et al., 2018). From the drilling literature, the apparent viscosity, sometimes called effective viscosity, is frequently considered to be the only parameter to measure the rheological properties of the drilling fluid. However, other factors are also required to describe the behavior of a drilling fluid (Bird et al., 1987; Dealy & Wang, 2013). Plastic viscosity (*PV*), yield point (*YP*), and gel strength are also among the main rheological properties relevant to hole cleaning capacity (Agwu et al., 2021). Due to the complexity and length of the discussion of the rheological properties of drilling fluid, this is explained in detail in Section 2.5. The influence of rheological parameters in cuttings transport in HDD is also discussed in that section.

Annular Velocity

Regardless of the number of factors that have been shown to influence hole cleaning, annular velocity has been established as the factor that dominates cuttings transport in vertical and directional drilling (Azar & Sanchez, 1997; Pigott, 1941; Tomren et al., 1986). Some studies point out that the turbulent flow regime (which is obtained under conditions of high annular velocity) might be more effective in terms of cuttings transport than a laminar flow regime (which is associated with low annular velocity) (Okrajni & Azar, 1986; Tomren et al., 1986). This theory is also supported by (Yuejin Luo, (1988) who attributed the better performance of turbulent flow regime to the eddies and swirls that are created in this regime, and to a flatter velocity profile. A turbulent flow regime is obtained under conditions of high annular velocity. However, a maximum limit for annular velocity exists and depends on (1) the capacity of the existing rig in the field, (2) the equivalent circulating density accepted, and (3) the risk of fracturing the formation (Azar & Sanchez, 1997). Therefore, it may be impractical or impossible to maintain a turbulent flow regime in some wells, especially in HDD, which possesses unique features such as large borehole size, limited pump capacity, and high risk of hydro fracture. Design of HDD projects should be done assuming a low annular velocity in laminar flow regime (Deng, 2018).

Density

The main function of the density of drilling fluid is correlated to wellbore formation stability rather than to the hole cleaning process. Wellbore stability is stablished by preventing the influx of external fluid into the annulus, and it can be achieved by balancing the formation pressure. Wellbore stability highly depends on the depth and the properties of the formation, as well as the drilling fluid density. A high-density drilling fluid might help in cuttings suspension and, therefore, the hole cleaning process. However, high density fluids may increase the capacity of the pump needed, and therefore, rise the total cost of the operation (Azar & Sanchez, 1997).

2.4.2. Factors related to Cuttings Features

Size, Shape and Density of Cuttings

The main characteristics of cuttings are size, the shape and density. These aspects of cuttings produced depend on parameters such as bit type, annular velocity, drilling fluid properties, and wellbore geometry(Walker & Li, 2000). Therefore, it is difficult to control the main characteristics of the cuttings. In inclined wellbores, it has been reported that small cuttings are difficult to transport. However, if the fluid has certain rheological properties (i.e., viscosity), and pipe rotation is also implemented, smaller cuttings appear to be transported by suspension (Azar & Sanchez, 1997).

Rate of Penetration

The quantity of drilled cuttings produced per unit time in a wellbore is related to the rate of penetration (ROP). A high ROP results in more cuttings being generated, which could lead to drilling problems such as pipe sticking and excessive torque. To overcome these problems, a higher annular velocity of drilling fluid is required to clean the hole (Nazari & Hareland, 2010; Sifferman & Becker, 1992); however, this is not feasible in HDD projects due to the limited pump capacity in the field, and the increased risk of hydro fracture with higher annular velocity. On the other hand, low ROP may have a positive impact on hole cleaning; however, in this case, drilling time is extended, which increases the project cost (Azar & Sanchez, 1997). Pigott (1941) has suggested maintaining a maximum cuttings concentration of 5% (by volume) in vertical wellbores. However, Iyoho (1980) reported that 5% was too conservative, due to the higher production of cuttings expected during the drilling process, especially in inclined and horizontal wellbores. Recent research in HDD pointed out that the maximum threshold in fine sand formation is 30-35% of solid volumetric fraction (Yi Su, 2020).

2.4.3. Operational Parameters

Inclination Angle

The inclination angle has a significant impact on hole cleaning (Tomren et al., 1986). Therefore, several experimental studies have been carried out with the aim to analyze the influence of hole inclination into cuttings transport. According to (Becker& Azar, 1985; Okrajni & and Azar, (1986), and Tomren et al., (1986), a cutting bed is not only formed, but also slides downwards along the wall when the critical angle of hole inclination is between 35 and 55 degrees. The hole inclination angle is defined according to the bore path design, and it is selected according to the geological conditions and company objectives (Yuejin Luo, 1988). Thus, hole inclination angle is a parameter that is uncontrollable in the field.

Inner pipe rotation

The inner pipe rotation has been described as a string vibration that induces a tangential component of the annular velocity, which may cause turbulence in the surrounding area (Yuejin Luo, 1988). Pipe rotation leads to better hole cleaning performance (Hall et al., 1950; Hopkin, 1967; Okrajni & Azar, 1986; Thomas & Becker, 1982; Williams & Bruce, 1951; ZEIDLER HU, 1972). In addition, other findings have been established by some authors. For instance, Williams and Bruce (1951) reported that the positive effect of pipe rotation on hole cleaning is more significant in the laminar flow regime than in the turbulent flow regime. Also, Thomas and Becker (1982) pointed out that the influence of pipe rotation on cuttings transport is almost negligible at higher annular velocities. Another approach was made by Yuejin Luo (1988), who claimed that in a high incline wellbore, where a cutting bed has been created on the invert of the annulus, the rotation of the drill pipe can bring some benefits such as the induction of mechanical forces on the destruction of cuttings bed. Similar results were found by Zeng et al (2018), who confirmed the positive contribution of drill pipe rotation in cuttings transport in the HDD reaming process.

Eccentricity

Eccentricity refers to the drill string position into the annulus, in other words, the distance between the center of the string and the center of the borehole. A negative eccentricity occurs when the string is closer to the crown, and positive eccentricity occurs when the string is closer to the invert. In high inclined wells, the string tends to lay down in the bottom side of the pipe due to gravity. This is the worst scenario since lower velocity is expected in the gap below the string where most cuttings are deposited. The eccentricity of the string plays an important role in hole cleaning process. However, eccentricity is another uncontrollable factor because is determined by the well-bore trajectory design, and therefore, its impact on cuttings transport is unavoidable (Azar & Sanchez, 1997).

Based upon the studies shown in Section 2.3, a conclusion might be drawn. Some of the factors that influence the hole cleaning process, such as cuttings features, and operational parameters may be difficult to control. Those factors are defined based on the formation characteristics, equipment facilities in the field, borehole trajectory design, and project budget. Therefore, they will not be considered in the current study. The annular velocity has been defined as the factor that dominates the cuttings transport in vertical and directional drilling (Azar & Sanchez, 1997; Pigott, 1941; Tomren et al., 1986). However, maintaining a high annular velocity is not feasible in HDD projects due to the impossibility of having rig equipment that keeps a turbulent regime. Moreover, in cases where high annular velocity is reached, it may cause erosion and hole enlargement. To overcome this limitation, it is desirable to improve the rheological properties (i.e., viscosity, elasticity and so on) of drilling fluids to improve carrying capacity, and to keep the frictional pressure loss as low as possible (Baker Hughes, 2006).

2.5. Drilling Fluid Features and Rheology

2.5.1. Drilling Fluid Composition

In an HDD installation the main activity is the drilling fluid operation, where the drilling fluid is a vital component in the procedure (Shu et al., 2015). Drilling fluid is a mixture of base fluid (e.g., water, oil, or gas-based fluid) with different additives such as clays, polymers, and sodium chloride. The selection of the additive components depends on many factors such as temperature, formation features, drilling depth, and cuttings transport. The classification of drilling fluids is made according to its base; water-based, oil based, and gas based. Water-based fluids are the most common type in the industry. This mixture is an environment-friendly mud, easy to mix, and cost-effective, but is very sensible to use in high temperatures (Wiśniowski et al., 2017; Yan et al., 2010). In water-based fluids, the bentonite additive is the basic component (Allahvirdizadeh et al., 2016). Oil-based fluids can resolve many problems of water-based drilling fluids, such as instability at high temperatures as well as lubricity. However, the toxicity of oil-based fluids for the environment is a big concern. For the gas-based fluid, the most common components used are air and foam. This kind of drilling fluid is regularly use for underbalanced drilling in which a wellbore is drilled by keeping the wellbore pressure less than the formation (Wiśniowski et al., 2017; Yan et al., 2010).

Water-base fluids is the preferable mixture in HDD projects, with a bentonite concentration of 5% (*Non-Toxic Drilling Mud: Part of the HDD Process - Enbridge Inc.*, n.d.). Besides the use of bentonite, natural and synthetic polymers can also be added to the drilling fluid as rheology modifiers, shale inhibitors, and fluid loss control. Some common polymers that are used in water-based fluids are xanthan gum, diutan gum, polyacrylates, polyacrylamide, hydrolyzed polyacrylamide, partially hydrolyzed polyacrylamide, amphoteric cellulose, polyanionic cellulose, and carboxymethyl cellulose (Ahmad et al., 2018).

In polymer science, it has been extensively accepted that the size and structure of the polymer molecules strongly influence the rheological properties of the mixture (Bird et al., 1977). In particular, the average molecular weight significantly impacts the zero-shear rate viscosity, and relaxation time of polymer-containing drilling fluid (Ferry, 1980). The molecular weight distribution, also called polydispersity or molar mass distribution, influences the relaxation time and the extensional viscosity (Liu et al., 1998;

Shaw & Tuminello, 1994). Moreover, Plank (1992) stated that high molecular weight polymers in water-based fluids may improve rheological properties and filtration loss control compared to low molecular weight polymers in the field drilling industry.

2.5.2. Rheological models

A rheological model is considered as the mathematical equation between shear rate and shear stress (Wiśniowski et al., 2020). Most drilling fluids are complex due to their no-Newtonian behavior. However, it does not exist a model that exactly fits the shear stress data over all ranges of shear rates. The rheological model is chosen according to the application, and that model is a close approximation of the real behavior in that applied shear rate (Baker Hughes, 2006). The Bingham plastic model, the power-law model, and the Herschel-Bulkley model are the common models to describe the behavior of drilling fluids in HDD (Ariaratnam & Beljan, 2005). In Figure 2, a graphical comparison between the models can be seen.

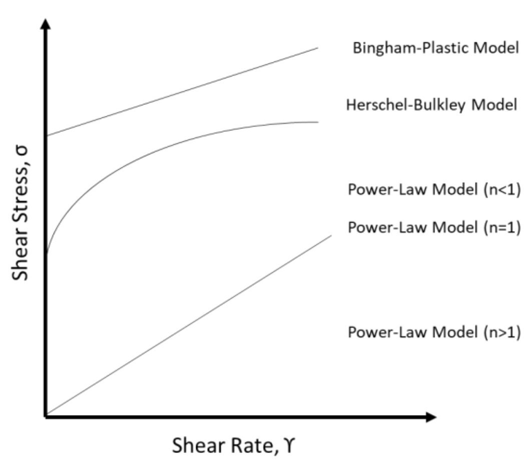

Figure 2 Shear stress-shear rate relationship of the three rheological models. Adapted from Deng (2018)

The Bingham Plastic Model (BP)

This model considers a linear relationship between the shear rate and the shear stress. It can be mathematic describe as seen in Equation 2-1.

$$\boldsymbol{\sigma = YP + PV\gamma} \qquad 2\text{-}1$$

YP is the yield point (Pa), and it represents the minimum stress required to initiate the drilling fluid moving.

PV is the plastic viscosity (Pa.s), and represents the rate of change of stress in an increased unit of shear rate. It is also an indicator of the amount, size, shape, and distribution of cuttings (Idress & Hasan, 2020).

Hemphil et al. (1993) claimed that the BP model is suitable for high shear rate applications and is inadequate for low shear rate ranges. The area of interest for drilling fluids in HDD projects is low shear rate ranges. Thus, the current method should be reviewed and used with caution (Baumert et al., 2005; Deng, 2018).

The Power Law Model (PL)

This model assumes the shear thinning behavior, but it does not consider the viscoelastic properties, which is observed with the yield stress absence (Baumert et al., 2005; Deng, 2018). It is defined by the following expression:

$$\sigma = k\gamma^n \qquad 2\text{-}2$$

k (CP) is the consistency index. It is an analogous to Newtonian viscosity, which represents the relation of shear stress to shear rate (Becker et al., 1991).

n is the flow behavior index, and it is an indicator of the relationship between the viscosity and the shear rate of drilling fluids. Either if the drilling fluid has a shear-thickening behavior ($n > 1$) or has a shear-thinning behavior ($n < 1$). Moreover, it is a measurement of the annular velocity profile. For lower values of n, the velocity profile is flatter, and for higher values of n, the velocity profile is more pointed (Becker et al., 1991; Okrajni & Azar, 1986).

The Herschel-Bulkley Model (HB)

This model is defined as the combination between the power-law model and the Bingham plastic model, which includes the yield stress characteristics. The Herschel-Bulkley model (HB) is considered as the most accurate model, among BP and PL models. It represents the behavior of non-Newtonian drilling fluids (Baumert et al., 2005; Deng, 2018). The mathematical equation that defines the current model is as follows:

$$\sigma = \tau_y + k\gamma^n \qquad \text{2-3}$$

Here τ_y is the yield stress, the same as *YP* in Bingham plastic model, which refers to the stress required to start the drilling fluid movement. *K* and *n* are the same parameters defined as in Power-Law model, but only in concept. The values, *n* and *K*, calculated with PL model are significantly different from those calculated with HB model (American Petroleum Institute, 2010).

To calculate the three parameters of the present model, the standard API RP 13D recommends two different procedures, the measurement method, and the numerical method.

2.5.3. Rheological Parameters of Drilling Fluids

The rheological properties that will be discussed in this section are the following: Viscosity (i.e., plastic viscosity and effective viscosity), yield point, flow behavior index, fluid consistency index, and elasticity (i.e., gel strength and relaxation time).

Viscosity

Viscosity is described as the fluid resistance to move or deform (Balhoff et al., 2011; Baumert et al., 2005), and it can be calculated as the ratio of viscous shear stress σ (N/m^2) to shear rate γ (1/s). On the one hand, when the stress is linearly related to the shear rate, the fluid is called Newtonian. On the other hand, fluids that does not keep a linear relationship between stress and shear rate are called No-Newtonian. Most drilling fluids in the industry are No-Newtonian (Baumert et al., 2005). Viscosity is known as an important property of drilling fluids, and it is essential for efficient hole cleaning (Powell et al., 2007; Zamora et al., 1993). There are two kinds of viscosity: plastic viscosity (PV) and apparent viscosity (AV).

Plastic viscosity (*PV*)

It is an indicator of the amount, size, shape, and distribution of cuttings. In addition, it is a measurement of the liquid phase viscosity (Idress & Hasan, 2020). A high plastic viscosity of drilling fluid is undesirable because it increases the energy required for pumping, and it also decreases the ROP, which increases the drilling process cost (Beck et al., 1995). The pumping capacity and the pressure drop are two factors that depend on viscosity (Shahsavani et al., 2018).

Apparent viscosity (*AV*)

It is also called effective viscosity and is defined as the measurement of the viscosity under a specific shear rate at a fixed temperature (Huang et al., 2020). For every drilling fluid, a certain viscosity curve is obtained over a shear rate range. According to the tendency of the viscosity curve, a drilling fluid classification is given as follows. A shear thinning behavior, also called pseudoplastic fluid, refers to a mud which viscosity decreases at high shear rate. The opposite behavior, viscosity increases at shear rate, corresponds to a shear thickening fluid, also called dilatant fluid (Bird et al., 1977).

Yield point

The yield point (*YP*) represents the stress required to initiate the fluid movement (Abduo et al., 2016). A high value of *YP* improves the cuttings suspension, but increases frictional pressure drop and equivalent circulation density. Therefore, it is desirable to establish a certain *YP* value that allows the proper cuttings removal from the borehole, and keeps the pressure drop low (Agwu et al., 2021; Akpan et al., 2020).

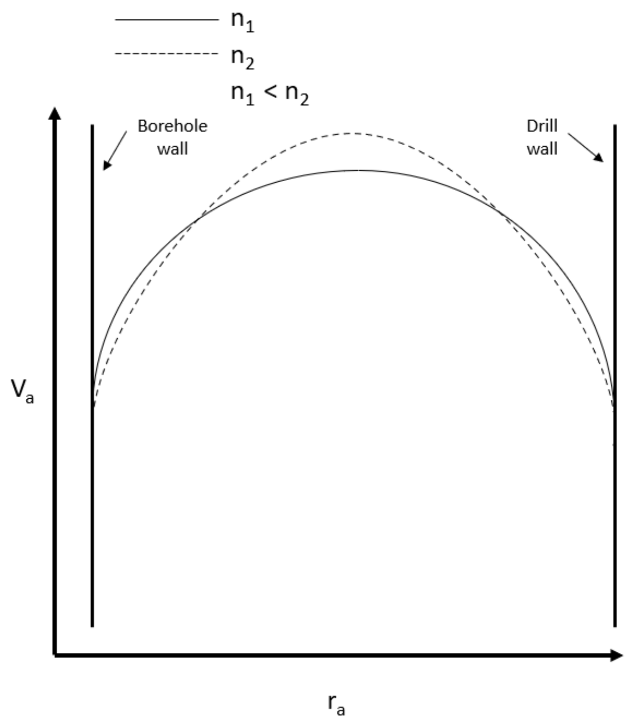

Figure 3. Effect of Parameter *n* on annular velocity profile. Adapted from Okrajni & Azar (1986)

The flow behavior index (n) and the fluid consistency index (*K*)

It is a parameter from the pseudoplastic model or power-law model. It is a measurement of the shear-thickening ($n > 1$) or shear-thinning ($n < 1$) of a drilling fluid. Moreover, it is an indicator of the velocity distribution profile when the rheology is varied, please refer to Figure 3. The velocity profile is more pointed for higher values of *n* and flatter for lower values. A flat velocity profile is desired for hole cleaning since it indicates the reduction of the percentage cross section area where particles settle down faster (Becker et al., 1991; Okrajni & Azar, 1986). The fluid consistency index (*k*) is an analogous to

Newtonian viscosity, which represents the relation of shear stress with shear rate (Becker et al., 1991). A high (k) value promotes an effective hole cleaning (Agwu et al., 2021)

Elasticity

The elastic property refers to the capacity of a material to deform immediately after the application of stress, and to recover to its original dimensions once the stress is released. An example of an elastic material is a rubber band (Balani et al., 2015). Many authors have related the elasticity with the drilling fluid capacity to suspend solids efficiently, and therefore, provide better hole cleaning. They have measured the elasticity through the gel behavior, the elastic modulus, and viscous modulus (Agwu et al., 2021; Akpan et al., 2020; Gomaa et al., 2015; Hirpa & Kuru, 2020; Powell et al., 2007)

Gel strength

It shows the ability of a drilling fluid to suspend solids in a dynamic or static condition. A drilling mud, with no gel strength, will not lift the cuttings despite its high viscosity (Akpan et al., 2020). Gel strength can be measured as the shear stress at low shear rates after the drilling fluid has remained static for a certain time (10 s, 10 min, and 30 min in the standard API procedure). Gel strength has been categorized as an important factor in cuttings transport, especially in horizontal wells, where greater values are required than in vertical wells to get a good cuttings performance (Baker Hughes 2006).

Elastic and Viscous Modulus

Most drilling fluid fluids show viscoelastic behavior, which implies a mix of viscous and elastic characteristics. A mixture is considered purely viscous when the deformation time is long upon the stress is applied. On the other hand, in a merely elastic mixture, the deformation is seen immediately or soon after the application of the stress. To understand the viscoelastic behavior better, an oscillation test is represented in Figure 4. In this test, sinusoidal stress is applied to the fluid, and the strain response is measured. Since the strain does not react at the same rate as the stress, a phase shift (δ) is created. The phase shift has a certain value according to its condition, as follows: (1) for purely elastic material, the δ is equal to zero, (2) for purely viscous material, the δ is equal to 90°, and (3) for a mixture equally elastic and viscous, the δ is equal to 45° (Franck, 1993).

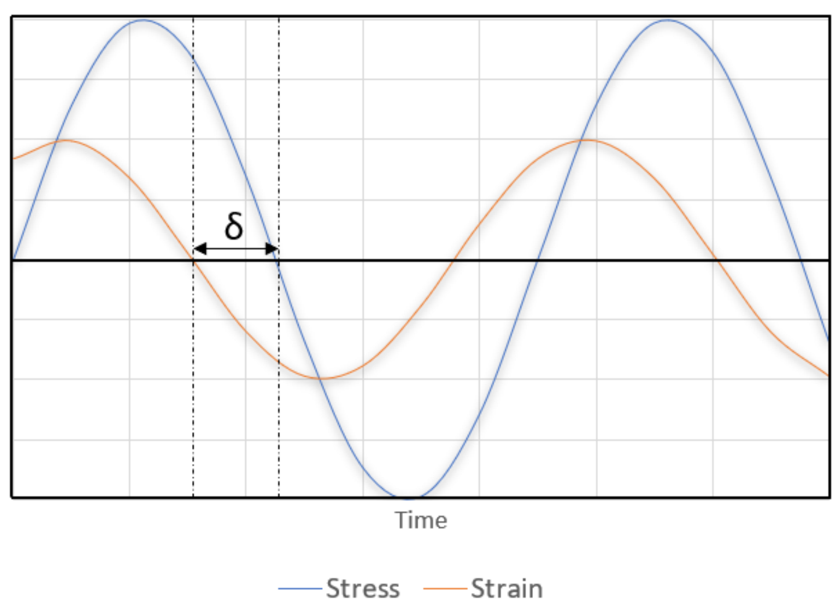

Figure 4 Stress and Strain signals during oscillation experiment. Adapted from Franck (1993)

The oscillatory experiment is also useful to determine the elastic and viscous modulus (G' and G'' respectively), which is defined as the ratio of the stress to strain. The elastic or storage modulus (G') relates to the capacity of the material to store energy elastically, and it is calculated when δ is less than 45 °. The viscous or loss modulus (G'') relates to the ability of the material to dissipate stress through heat, and it is calculated when δ is greater than 45°. When the phase angle δ is equal to 45 °, the elastic and viscous modulus are the same. That intersection is denominated as the relaxation time (λ) (Franck, 1993).

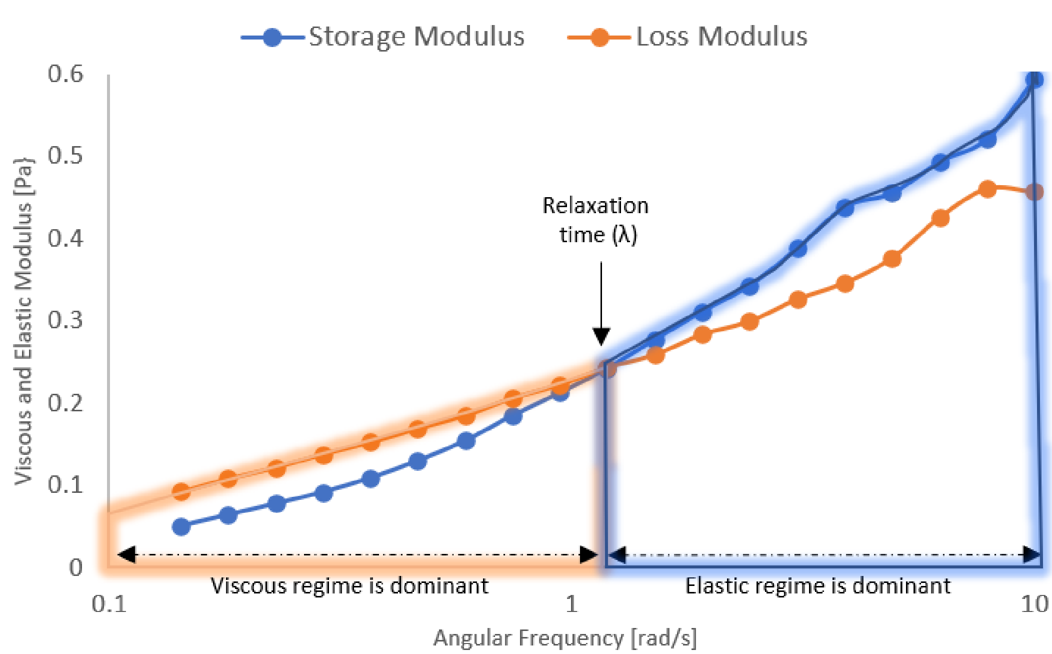

Figure 5 Typical G' and G'' curves as a function of frequency and/or shear. Adapted from Gomaa et al. (2015).

From Figure 5, the cross-over point can be identified and correspond to the relaxation time where viscous and elastic modulus are the same. Moreover, it defines the frequency or shear rate point at which the elastic component dominants over the viscous behavior (Gomaa et al., 2015). Some authors have used the relaxation time (λ) to compare drilling fluids. They claimed that fluids with longer relaxation time are more elastic. In other words, the mixture with higher λ is more dominated by elastic behavior over the shear rate range (Okesanya, Kuru, and Sun 2020; Arnipally and Kuru 2018; Arnipally, Bizhani, and Kuru 2018; Hirpa and Kuru 2020).

2.5.4. Hole Cleaning Capacity Indices

(Okrajni & Azar, 1986; Tomren et al., 1986) focused on the effect of rheological properties on the hole cleaning process. It was claimed that the parameters from BP model, the ratio of yield point to plastic viscosity (*YP/PV*) provides better cuttings transport, which agrees with the definition given in Section 2.4.2. Higher values of *YP* increase the suspension capacity of the fluid, and a lower value of *PV* is desired because is an indicator of the quantity of cuttings. Furthermore, Okrajni & Azar (1986) and Tomren et al. (1986) also argued that lower value of n (from the parameters of PL model) provides a flatter velocity profile, which is desired for cuttings transport under low annulus velocity.

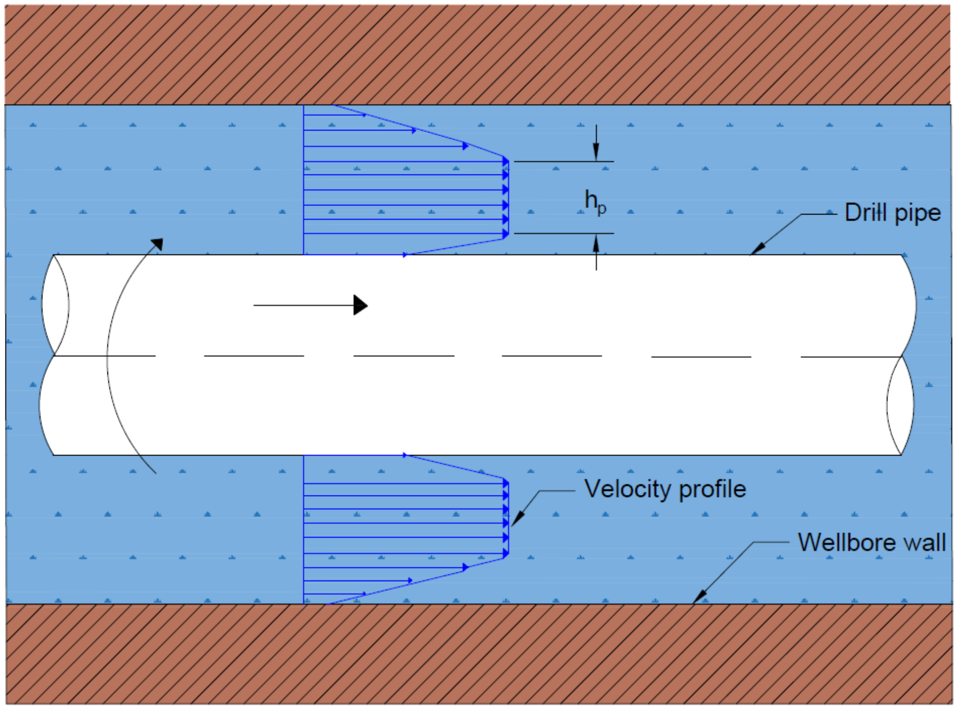

Figure 6 Velocity profile of flat laminar flow. Adapted from Shu et al. (2015)

The annular velocity profile for laminar flow of drilling fluids in HDD is illustrated in Figure 6, where an unsheared plug region of the velocity profile can be identified from the respective picture. In the unsheared plug region, the shear stress is less than the yield stress of the drilling fluid, which is an expected behaviour in yield stress fluids (Kelessidis et al., 2006; Zamora et al., 1993). The width of the unsheared plug region is known as the plug width (h_p), which is used to indicate the flatness of the annular velocity profile (Kelessidis et al., 2006).

Many authors have documented the benefit of a flattened annular velocity profile on a well cutting transport performance. Some of the benefits of a flattened annular velocity profile include but are not limited to the following: (1) low shear rate in this region may increase the viscosity, which helps in the carrying capacity of the drilling fluid; (2) the drilled cuttings near the borehole wall try to move where the viscosity is higher, and the velocity gradient is lower. That cuttings migration enhances the bed erosion; (3) A widen plug region (h_p) is achieved by increasing the degree of shear-thinning properties, which also lower the pressure loss, and therefore, increase the permitted pump rate to further improve the hole cleaning (Beck et al., 1993; Leising & Walton, 2002; Powell et al., 2007; Zamora et al., 1993).

For the prediction of the plug width (h_p), (Kelessidis et al., 2006) proposed a methodology based on HB model for non-Newtonian fluids in laminar flow. The equation 2-4 is used to calculate the h_p.

$$h_p = \frac{2\tau_y}{\Delta P} \quad \text{2-4}$$

Here τ_y is the yield stress (Pa), and ΔP is the annular frictional pressure loss (Pa/m). To compare the h_p with other drilling fluids conditions, a normalized plug width might be used. The equation 2-5 is commonly used for calculating the normalized plug width.

$$h = \frac{h_p}{H} * 100\% \quad \text{2-5}$$

h_p is the plug width (m) and H is the slot gap between the drill rod and the borehole wall (m).

Chapter 3: RHEOLOGICAL AND VISCOELASTIC PROPERTIES OF HORIZONTAL DIRECTIONAL DRILLING FLUIDS AND THEIR IMPACT ON HOLE CLEANING PERFORMANCE

3.1. Introduction

Trenchless construction techniques are a group of methods used for underground excavation with minimal disturbance on the surface. Among those methods, HDD has seen a fast growth since 1980 due to its many advantages over conventional drilling, such as less damage to the environment and lower social cost in urban zones (Ma & Najafi, 2008). The industry applications of HDD are installations and rehabilitation of utilities, including water mains, gravity sewer, natural gas, and telecommunications (Allouche et al., 2000; Ma & Najafi, 2008).

HDD is a technique that originated in the oil and gas industry but has been adapted to civil engineering applications. Therefore, drilling in oil and gas, and in HDD share some similarities and some challenges. One of the challenges that both industries face is the poor ability of the drilling fluid to transport cuttings from the wellbore to the surface, which is commonly known as the hole cleaning (Pilehvari et al., 1999). In horizontal and directional drilling as well as in HDD, the cuttings tend to settle down at the annulus and may form a bed if not removed efficiently. An insufficient cuttings removal is often responsible for stuck drill pipes, premature bit wear, slow drilling, formation fracturing and high torque (Larsen et al., 1997). Hole cleaning is a more difficult challenge in HDD than in horizontal and directional drilling due to its unique characteristics such as large annular diameter, and slow annular velocity that is caused by the limit of pressure capacity (Zeng et al., 2018).

The research community has studied the cuttings transportation and hole cleaning in vertical, horizontal, and directional drilling for several years. In 1940, experimental studies were conducted by Pigott (1941), who investigated the cuttings transportation in vertical wellbores. He pointed out that the most influential factor in cuttings transportation is the annular velocity. The same conclusion was made by Sifferman et al. (1974), who also investigated the cuttings transportation phenomena in vertical wellbores. Sifferman et al. (1974) also indicated that the rheological properties of drilling fluids play an important role in the hole cleaning performance in vertical drilling. Hole cleaning performance in vertical wellbore has been investigated extensively by many authors, and it has been concluded that a successful cuttings transportation can be obtained by overcoming the velocity of the particles with the main features of a drilling fluid, which includes annular velocity and rheology properties (Baker Hughes, 2006).

In directional and horizontal drilling, the cuttings transportation process is different compared to vertical drilling. In directional drilling, especially in horizontal drilling, the cuttings do not move opposite to the velocity direction of the fluid flow, so the capacity of the drilling fluid to lift particles is reduced (Sifferman & Becker, 1992). Thus, the hole cleaning process in directional wellbore, as well as in horizontal sections, is more challenging than in vertical sections, and cuttings transportation investigations should conduct a deeper study of the factors influencing hole cleaning.

Annular velocity in the annulus has been established as the factor that most influences the cuttings transportation in vertical and directional drilling (Azar & Sanchez, 1997; Pigott, 1941; Tomren et al., 1986). The desired annular velocity for each drilling case depends on the type of drilling fluid used and the characteristics of the formation. For instance, Brown et al. (1989) pointed out that below angles of 50°, within a turbulent flow regime, water shows a better hole cleaning performance than a polymer-containing drilling fluid. Theoretically, a high annular velocity, which refers to turbulent regime instead of laminar regime, is desired not only because the high velocity of the drilling fluid moves the particles faster, but also provides a flatter velocity profile that reduces the settling down of cuttings. However, high annular velocity may cause several problems. First, high annular velocity can generate erosion as well as hole enlargement to the formation. Second, maintaining a high annular velocity, especially in washed-out or reaming processes, becomes impossible with existing rigs in the field. Third, the capacity of the pump may not be enough to reach a turbulent flow. For these reasons, it may be necessary to evaluate and improve the rheological properties of drilling fluid, so a higher carrying capacity can be obtained (Baker Hughes, 2006; Deng, 2018)

Leising and Walton (2002) investigated the cuttings transport problems in coiled-tubing drilling, and it was concluded that high viscosity may provide good suspension to the cuttings, and thus, prevent the formation of cuttings bed. Zamora et al. (1993) also supported this finding. Okajni and Azar (1986) investigated the effect of the rheological properties of drilling fluid on hole cleaning in directional drilling. The results of this study showed that the rheological properties influence the cuttings transportation only when the fluid is in a laminar regime. In particular, it was observed that higher yield point/plastic viscosity (*YP/PV*) ratios in vertical, inclined, and horizontal sections show a less cuttings buildup in the annulus, and therefore, better hole cleaning performance. Becker et al. (1991) also investigated the hole cleaning process in directional drilling, and their findings agreed with Okajni and Azar (1986) results. In addition, Becker et al. (1991) correlated the low shear rate parameters, such as 3 RPM and 6 RPM, as well as gel strength with hole cleaning performance. Other authors also investigated the effect of low shear rate parameters. For instance, Beck et al. (1993) and Powell et al. (1991) correlated a good cuttings suspension, at both static and dynamic, with high low-shear rate characteristics such as low-shear-rate-viscosity (*LSRV*), true yield stress (*TYS*), and elasticity.

Most drilling fluids possess viscous, as well as elastic properties. These characteristics have been evaluated together as well as separately. A few studies have only focused on the elasticity itself. Powell et al. (1991) correlated gel behavior with elasticity, and their analysis shows that elasticity helps in suspension capacity in polymers fluids. Similarly, Zamora et al. (1993) claimed that elasticity improves the hole cleaning in the laminar regime. Gomaa et al. (2015) investigated the influence of viscoelastic properties of drilling fluids on proppant transportation in fracturing operations and conducted experiments with a couple of polymers with similar shear viscosity profiles, but different elasticities. This study reported that elasticity significantly affects the settling of particles, which is related to hole cleaning performance. Arnipally and Kuru (2017) also carried out experimental studies to investigate the influence of elasticity on cuttings settling. Their results also confirmed that fluid elasticity reduce the settling of particles.

The previous studies indicate that the elasticity component is an important parameter in cuttings transportation phenomena and should be included in the hole cleaning analysis of drilling fluids, so a more realistic assessment is obtained. Nevertheless, there are not many investigations in the literature about elasticity, or about viscosity and elasticity combined (Bizhani, 2017; Hirpa & Kuru, 2020). Bizhani (2017) claimed that this occurs due to the lack of understanding of those properties, and the absence of equipment in construction field to measure those characteristics, especially elasticity.

The limited knowledge about the effect of viscosity and elasticity components in drilling fluids on hole cleaning performance is not only in the oil and gas industry, but also in HDD applications. Thus, this current study is focused on analyzing the viscosity and the elastic components of drilling fluids on cuttings transportation in HDD. Water-based drilling fluids were tested in an oscillatory rheometer (DSR), and flow curves and frequency sweep tests were acquired. The additives used for the experiments are partially hydrolyzed polyacrylamide (HPAM) in two different grades, and sodium bentonite. First, an assessment of the rheological properties of the different drilling fluids was done. Second, an evaluation of the rheological model that best fits the measured data is discussed. Finally, an association of the hole cleaning indicators and the viscosity, as well as the elasticity, was performed and analyzed.

3.2. Rheological Models

The rheology is the study of flow features and how they influence the fluid movement. Shear stress is one of the flow features and is described as the force per unit area required to keep a specific fluid flow or a shear rate (American Petroleum Institute, 2010). Rheology models are used to mathematical describe the shear stress-shear rate relationship within a shear rate range (Wiśniowski et al., 2020). Many rheology models have been developed by researchers throughout the recent years, and the most popular for petroleum and HDD industries are Bingham Plastic Model (BP), Power-Law Model (PL), and Herschel-Bulkely Model (HB) (Ariaratnam & Beljan, 2005; Kelessidis et al., 2006). In the following section, a detailed description of the models will be given, including the methods to calculate the parameters of each one.

3.2.1. Bingham Plastic Model

This model assumes a Newtonian behavior, which means that shear stress (σ, lb/100 ft^2 or Pa) has a linear relationship with shear rate (ϒ, s^{-1} or RPM), thus viscosity is maintained constant. The two parameters that describe this current model are plastic viscosity (*PV*), and yield point (*YP*) (American Petroleum Institute, 2010). The BP model is mathematical represented as:

$$\boldsymbol{\sigma}\left(\frac{\boldsymbol{lb}}{\boldsymbol{100\,ft2}}\right) = \boldsymbol{YP} + \boldsymbol{PV\,\gamma} \qquad \text{3-1}$$

YP (lb/100 ft^2) is the yield point and represents the minimum force per unit square required to interrupt the static of a drilling fluid. PV (cP) is the plastic viscosity and describes the rate of change of stress in an increased unit of shear rate.

According to the standard API RP 13D, the parameters of Bingham Plastic Model can be calculated from API rotational viscometer reading at θ_{300}, shear stress at 300 rpm, and θ_{600}, shear stress at 600 rpm, as follows:

$$PV\ (cP) = \theta_{600} - \theta_{300} \qquad \text{3-2}$$

$$YP\ (\frac{lb}{100\ ft2}) = \theta_{300} - PV \qquad \text{3-3}$$

Equations 3-2 and 3-3 should only be used when the shear stress is given in dial reading (deflection), which is the unit used by API rotational viscometer. If researchers desire to implement other unit system, appropriate conversions should be applied in the calculations. For instance, shear stress (dial reading) is calculated by dividing the shear stress (lb/100 ft^2) by 1.0678 (American Petroleum Institute, 2010).

3.2.2. Power-Law Model

Power-law model describes a fluid whose viscosity changes with the variation of shear rate. This behavior is commonly known as shear thinning or pseudoplastic. In addition, the Power-law model assumes that the fluid does not exhibit a yield stress. This model is generally used for polymer-based drilling fluids (American Petroleum Institute, 2010). Power-Law model can be defined by the following expression:

$$\sigma\left(\frac{lb}{100\ ft2}\right) = k\gamma^n \qquad 3\text{-}4$$

Whereas k (cP or Pa*S) is the consistency index and is like the Newtonian viscosity in the BP model, *n* is the flow behavior index and is an indicator of the annular velocity profile. For lower values of *n*, the velocity profile is flatter, and for higher values of *n*, the velocity profile is more pointed (Becker et al., 1991; Okrajni & Azar, 1986).

According to API methods from June 1995, the parameters from Power-Law model can be calculated for inside the drill pipe, and for the annulus. For the current study, the equations used are for the annulus, as follows:

$$n_a = 0.657 * log_{10}\left({}^{\theta_{100}}/_{\theta_3}\right) \qquad 3\text{-}5$$

$$k_a(cP) = \frac{511*\theta_3}{5.11^{n_a}} \qquad 3\text{-}6$$

θ_3 and θ_{100} refer to the shear stress (dial reading) at shear rate 3 RPM and 100 RPM respectively. If researches want to implement other unit system, appropriate conversions should be applied in the calculations. For example, shear stress (dial reading) is calculated by dividing the shear stress (lb/100 ft^2) by 1.0678 (American Petroleum Institute, 2010).

3.2.3. Herschel-Bulkley Model

This model is also called as the Yield-Power-Law model. Herschel-Bulkley (HB) model has the same parameters as the PL model, but includes a yield stress. The H-B model describes the rheological behavior of drilling fluids more accurately than other models (Baumert et al., 2005; Deng, 2018). The mathematical equation that defines the current model is as follows:

$$\sigma\left(\frac{\text{lb}}{100\ \text{ft2}}\right) = \tau_y + k\gamma^n \qquad 3\text{-}7$$

Here, τ_y is the yield stress (lb/100 ft^2) and is an analogous of *YP* in the BP model, which refers to the shear stress at zero shear rate. *K* is the consistency index (cP), and *n* is the flow index. The HB model is converted into the BP model when *n* =1 and is also reduced to PL model when τ_y is equal to zero. Therefore, the HB model is assumed to be the most complete model since it includes the other models explained in Sections 3.2.1 and 3.2.2 (American Petroleum Institute, 2010). According to the standard API RP 13D, there are two methods to calculate the parameters, the measurement, and the numerical method.

The measurement method

θ_3, θ_6, θ_{300} and θ_{600} in the equations below refer to the shear stress (dial reading) at shear rate 3, 6, 300, and 600 RPM respectively. If researches choose to implement other unit systems, appropriate conversions should be applied in the calculations. For example, shear stress (dial reading) is calculated by dividing the shear stress (lb/100 ft^2) by 1.0678 (American Petroleum Institute, 2010).

$$\tau_y\left(\frac{\text{lb}}{100\text{ ft2}}\right) = 2 * \theta_3 - \theta_6 \quad \text{3-8}$$

$$n = 3.32 * \log_{10}\frac{\theta_{600}-\tau_y}{\theta_{300}-\tau_y} \quad \text{3-9}$$

$$k\ (cP) = \frac{\theta_{300}-\tau_y}{511^n} \quad \text{3-10}$$

The numerical method

This method has been established as the most accurate to calculate the parameters of HB model (Kelessidis et al., 2006). The first step is to assume an initial value of *n*, which can be taken from the *n* value calculated in the PL model. The second step is to determine τ_y and K using equations 3-11 and 3-12. The third step is to calculate the error, as seen in equation 3-13. Steps 1, 2 and 3 should be repeated until error (Err) is at least 0.05 (recommended).

$$\tau_y = \frac{\sum\tau_i * \sum\gamma_i^{2n} - \sum\tau_i\gamma_i^n * \sum\gamma_i^n}{N * \sum\gamma_i^{2n} - (\sum\gamma_i^n)^2} \quad \text{3-11}$$

$$K = \frac{N * \sum\tau_i\gamma_i^n - \sum\gamma_i^n * \sum\tau_i}{N * \sum\gamma_i^{2n} - (\sum\gamma_i^n)^2} \quad \text{3-12}$$

$$Err = \tau_y * \sum\gamma_i^n * \ln\gamma_i + K * \sum\gamma_i^{2n} * \ln\gamma_i - \sum\tau_i * \ln\gamma_i \quad \text{3-13}$$

3.3. Hydraulic Parameters

3.3.1. Fluid Velocity Inside the Annulus

Once the proper selection of the rheological model and the determination of the parameters that characterize the respective model was done, the next step was to calculate the average fluid velocity inside the annulus and was calculated as follows (American Petroleum Institute, 2010):

$$V_a\left(\frac{ft}{min}\right) = \frac{24.51Q}{(d_h^2 - d_p^2)} \tag{3-14}$$

Q is the volumetric flow rate of the drilling fluid in gal/min, d_h is the hole diameter in inches, and d_p is the outer diameter of the drill pipe in inches.

3.3.2. Shear Rate and Shear Stress at the Wall

Since a cuttings bed on the bottom of the wellbore is expected in directional drilling, the shear stress and shear rate at the wall play an important role in evaluating the hole cleaning performance (Zamora et al., 1993). To estimate the shear rate and the shear stress at the wall, the following equations were used respectively.

First, a correction due to well geometry shall be implemented and the factor G was calculated as follows:

$$G = \left(1 + \frac{\alpha}{2}\right) * \left(\frac{(3-\alpha)*(n+1)}{(4-\alpha)*n}\right) \tag{3-15}$$

α=0 for the geometry factor in the pipe, and α=1 for the geometry factor in the annulus. The rheological parameter value *n* is also included in Equation 3-14.

Finally, the shear rate at the wall was calculated with the equation below:

$$\gamma_w = \frac{1.6GV_a}{d_{hyd}} \quad 3\text{-}16$$

d_{hyd} is the annular hydraulic diameter, and can be calculated with the following equation (API RP 13D 2017):

$$d_{hyd} = d_h - d_p \quad 3\text{-}17$$

To calculate the shear stress at the borehole wall, expressed in U.S. Customary Units, the following equation should be used

$$\tau_w\left(\frac{lb}{100ft^2}\right) = 1.066 * \left(\frac{(4-\alpha)}{(3-\alpha)}^n \tau_y + K\gamma_w^n\right) \quad 3\text{-}18$$

Where parameters τ_y, *K*, and *n* are the same as Herschel-Buckley model.

3.3.3. Generalized Reynolds Number and Frictional Factor

Laminar and turbulent are the two flow regimes in fluid mechanics. Laminar refers to situations when the particles present in the fluid follow a well-defined path, without macroscopic mixing between adjacent layers, and turbulent regime is present when the properties of the fluid, including pressure and velocity, change drastically over space and time. The generalized Reynolds number (N_{ReG}) is a parameter that determines the flow regime. On one hand, the fluid is in laminar regime when the generalized Reynolds number is less than the critical Reynold number. On the other hand, the flow is in turbulent regime when the generalized Reynolds number is higher than the critical Reynolds number. The critical Reynolds number defines the zone of transitions between the two regimes (Kundu et al., 2016).

The generalized Reynolds number (N_{ReG}) and the critical Reynolds number (N_{cRe}) for all flow conditions, can be calculated as follows respectively (American Petroleum Institute, 2010):

$$N_{ReG} = \frac{\rho V^2}{19.36\tau_w} \qquad 3\text{-}19$$

and

$$N_{cRe} = 3470 - 1370n \qquad 3\text{-}20$$

Here, ρ is the fluid density in lb/gal.

As the flow in this study is assumed to be in laminar regime, the laminar flow friction factor can be calculated using the following equation (American Petroleum Institute, 2010).

$$f_{lam} = \frac{16}{N_{ReG}} \quad 3\text{-}21$$

3.3.4. Annular Frictional Pressure Loss

Annular pressure loss is one of the most important factors to evaluate the stabilization of the wellbore and the performance of the drilling (Pilehvari et al., 1999). On the one hand, high value of pressure loss can lead to hydro fracture. On the other hand, a very low value of pressure loss may not be enough to mobilize the cuttings. Thus, an ideal pressure loss value should be maintained during the HDD procedure, so the project can be completed successfully. The frictional pressure loss in HDD borehole annulus can be estimated using the following equation (API RP 13D 2017).

$$P_a\left(\frac{\frac{lb}{100ft^2}}{inches}\right) = \frac{1.076\rho V_a^2 f_{lam} L}{10^5 d_{hyd}} \quad 3\text{-}22$$

3.3.5. Annular plug width

The annular plug width, h_p, is a measure of the flatness of the velocity profile in the annular space (Kelessidis et al., 2006). This value represents the height of the plug region where the local shear rate is low or near zero. The higher the plug region, the higher the suspension capacity of the drilling fluid (Leising & Walton, 2002; Zamora et al., 1993).

The annular plug width can be calculated as follows:

$$h_p = \frac{2\tau_y}{Pa} \quad 3\text{-}23$$

To evaluate the plug width for various operational conditions is necessary to define a dimensionless annular plug width, h_{pD} as shown in Equation 3-24.

$$h_{pN} = \frac{h_p}{H} \qquad 3\text{-}24$$

H is the total annular gap width.

3.4. Materials

Partially Hydrolyzed Polyacrylamide (HPAM), also called Flopaam in the industry, and Bentonite were used as additives for the different solutions. HPAM is a synthetic chain polymer of acrylamide monomers. This additive was supplied by SNF Floerger and two different grades were used as follows. Flopaam (3330 S) with a molecular weight (Mw) of 8×10^6 g/mol and Flopaam (3630 S) with a molecular weight (Mw) of 20×10^6 g/mol. Bentonite is a natural clay consisting predominantly of montmorillonite and the powder used for the experiments was manufactured by Baroid Halliburton Industry. The commercial name is Aquagel Gold Seal and is a Wyoming sodium bentonite that contains no polymers additives, with an approximate Mw of 422.2 g/mol.

3.5. Experimental Procedure

The first step was to define the concentrations for each additive and each sample. For the two additives, the following mixtures with their respective characteristics were prepared and tested.

Table 1. Composition and concentrations of samples

Additive	Mixture	Concentration (W%)	Molecular weight (g/mol)
HPAM	H1	0.1	$8x10^6$
	H2	0.1	$20x10^6$
	H3	0.05	$8x10^6$
	H4	0.05	$20x10^6$
Bentonite	B1	3	422.2
	B2	5	422.2

The second step was to prepare the mixtures. Each solution only contained the respective additive in the concentration specified in **Table 1**, and ionized water. Then, the solution was mixed using a magnetic stirrer, shown in **Figure 7**, at a speed high enough to make a strong vortex. The powder was introduced slowly into the side of the vortex to avoid formation of fisheyes. The solution was then stirred slowly for some minutes to ensure complete dissolution. The stirring time for each additive was different, 90 minutes for HPAM and 60 minutes for bentonite. Due to the influence of preparation and mixing techniques on the rheological properties of drilling fluids, all samples were strictly prepared under the same conditions.

Figure 7 Magnetic Stirrer

The third step was to characterize the rheological properties on a Dynamic Shear Stress Rheometer (DSR) SmartPave 102e from Anton Paar. The device is represented in **Figure 8**. The rheometer was used with a flat plate style system, and the tests carried out were flow curve, and frequency sweep test. In principle, the flow curve represents the relationship between flow behavior and flow resistance. The outputs of this test are the curve of shear stress and shear rate, as well as the curve of viscosity vs shear rate. The frequency sweep is an oscillatory test executed at variable angular frequency and a constant amplitude value. This test is also called "dynamic oscillation" and is used to study the time-dependent shear behavior of drilling fluids. Before conducting a frequency sweep test, an amplitude sweep test must be carried out to determinate the linear viscoelastic region (*LVE*) so the frequency sweep test is performed in a range with the lowest strain values, without destroying the structure of the sample (*Amplitude Sweeps :: Anton Paar Wiki*, n.d.; Mezger, 2020).

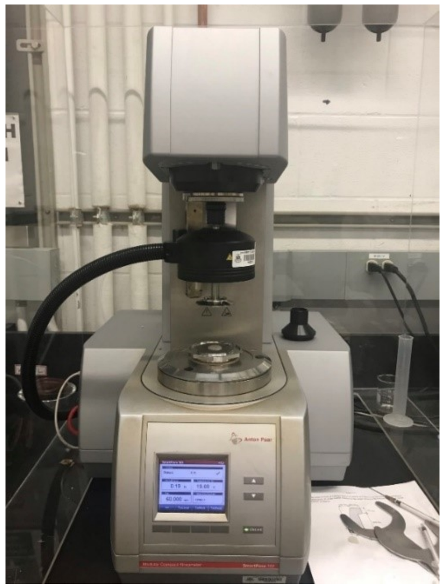

Figure 8 Dynamic Shear Stress Rheometer (DSR)

All tests were performed under the same temperature (25 ° C), which was guarantee by the DSR rheometer. Additionally, all samples were characterized twice in order to get reliable data.

3.6. Results and Discussions

The first part of the experimental program consisted of getting the rheograms and the viscosity curves for the different samples, as well as to perform the frequency sweep tests. In addition, a discussion of the viscoelastic behavior of each sample according to its concentration and molecular weight was realized. The second part consisted of calculating the parameters of the three different models. The models chosen are

Bingham-Plastic model, Power-Law model, and Herschel-Bulkey model. After careful analysis, the model that best describe the tendency of the measured data was chosen. Finally, a connection between the viscosity and the elasticity components of drilling fluid, and hole cleaning indices were considered.

Two different concentrations and two different molecular weights (Mw) for HPAM were used for the experimental program. The four different samples were labelled H1, H2, H3, and H4, respectively. For clarification about the characteristics of each HPAM solution, please refer to **Table 1**. In addition, two different concentrations of sodium bentonite were prepared. The concentrations used were 3%, which were labelled B1, and 5%, which were labelled B2.

3.6.1. Viscosity Properties of Drilling Fluids Samples

Partially Hydrolyzed Polyacrylamide (HPAM)

The shear stress vs shear rate and the viscosity vs shear rate diagrams of HPAM are presented in Figure 9 and in Figure 10, respectively. The rate of change in a shear stress vs shear rate curve indicates the viscosity of the fluid and having two curves with similar slope shows that their viscosity properties are alike. The results indicate that all drilling fluids have a shear thinning behavior and a small yield stress. On the one hand, H3 and H4 curves, that are represented in Figure 9, whose additive concentrations are the same (0.05%), but which possess different Mw, have almost identical shear stress curves. On the other hand, H1 and H2 curves, that are represented in Figure 9, whose additive concentrations are the same (0.1%), but which possess different Mw, have different shear stress curves, especially the slope of the curves. The same tendency is seen in the viscosity vs shear rate curves shown in Figure 10.

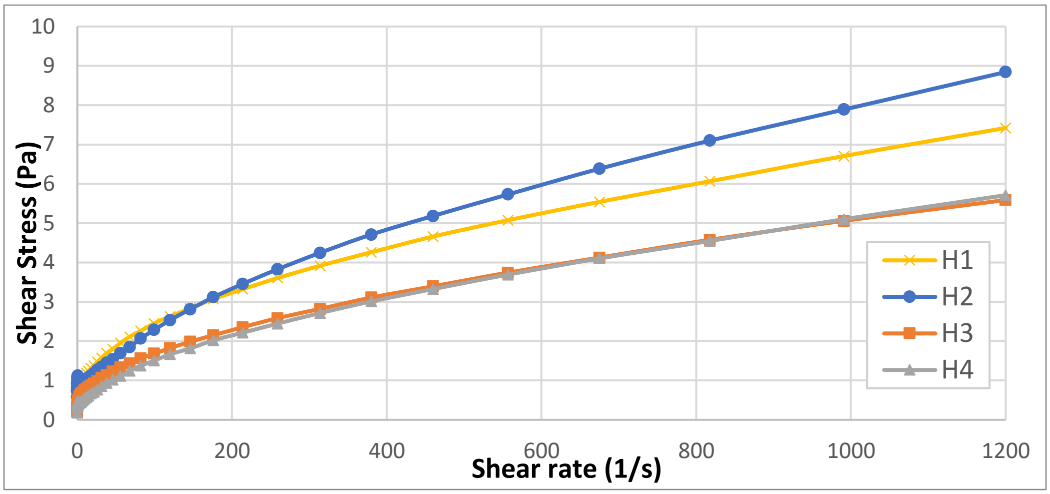

Figure 9 Shear Stress vs Shear Rate curves of HPAM additive

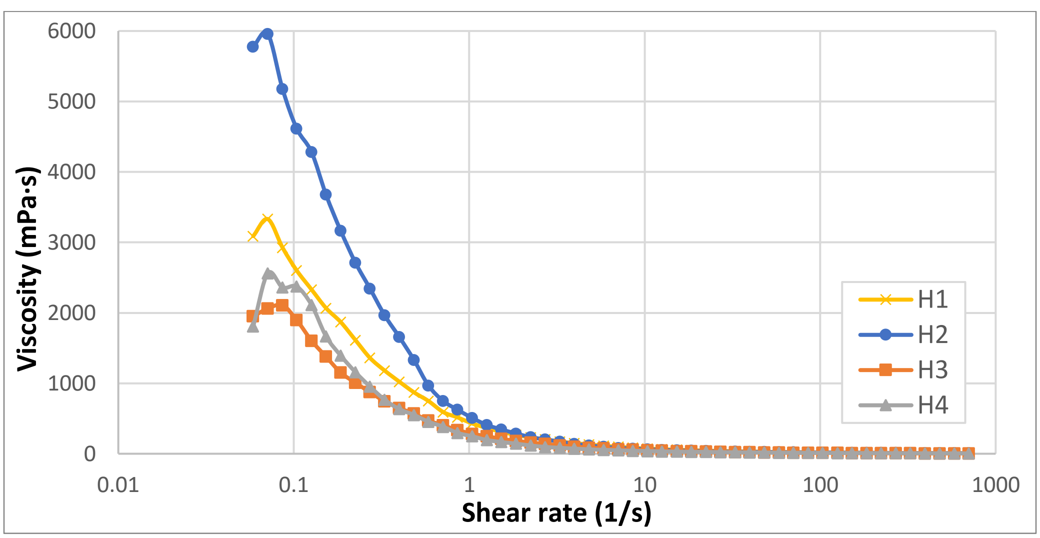

Figure 10 Viscosity vs Shear Rate curves of HPAM additive

The results suggest that up to a certain concentration, the viscosity component of a drilling fluid changes according to its Mw. For this case, the viscosity property increases when the Mw is higher. Previous studies have shown that the features of polymer molecules influence the rheological properties of the mixture (Bird et al., 1977). In addition, Plank (1992) stated that high molecular weight polymers in water-based drilling fluids could improve rheological properties compared to low molecular weight polymers. The results are in accordance with the literature review, but only up to a certain concentration of the polymer. For a 0.05% concentration, the viscosity component is almost identical for solutions with molecular weight (Mw) of 8 million Dalton and 20 million Dalton, respectively. Another conclusion drawn from Figure 9 and Figure 10 is related to the behavior of solutions when the concentration is increased. The viscosity of the solutions of both Mw rises, as the polymer concentration is increased. This change is more pronounced in solutions with higher molecular weight.

Bentonite

The shear stress vs shear rate curves, and the viscosity vs shear rate diagrams of bentonite are presented in **Figure 11** and in **Figure 12**, respectively. The results indicate that all drilling fluids have a shear thinning behavior and a small yield stress. As shown in **Figure 11**, a gradual increase of shear stress occurs when the percentage of bentonite concentration rises from 3% (B1) to 5% (B2). The same tendency is seen in the viscosity vs shear rate curves shown in **Figure 12**. Similarly, Deng (2020) reported that increasing bentonite concentrations causes the yield stress and the apparent viscosity to rise.

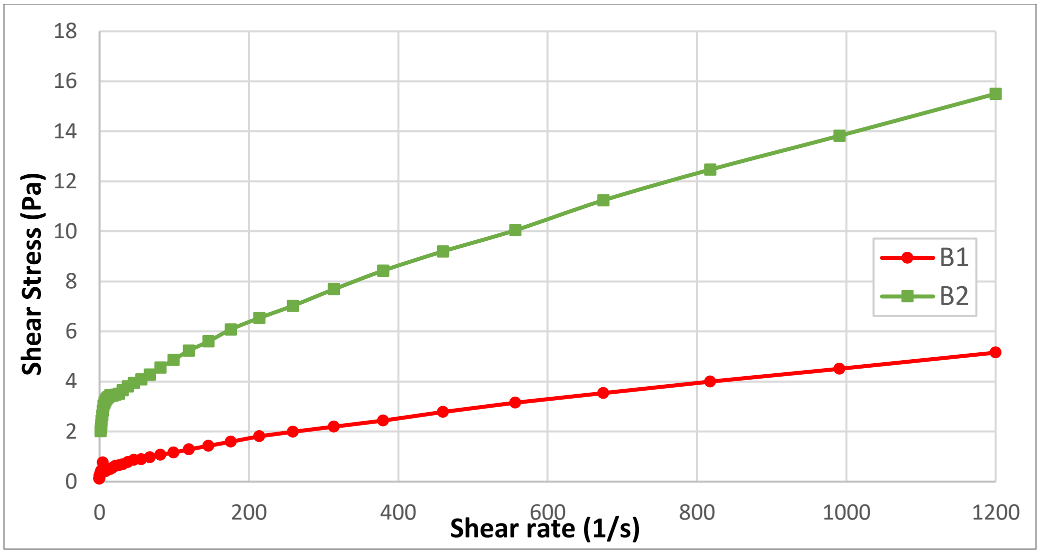

Figure 11 Shear Stress vs Shear Rate diagrams of bentonite

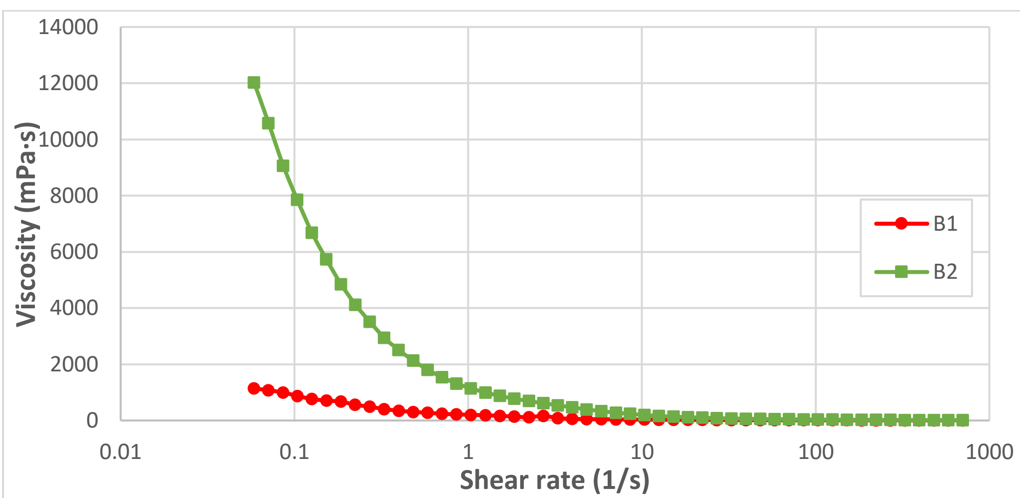

Figure 12 Viscosity vs Shear Rate diagrams of bentonite

3.6.2. Elastic Properties of Drilling Fluids Samples

Figure 13 and **Figure 15** show the frequency sweep tests of all HPAM solutions, as well as all bentonite solutions, respectively. In each graph there are two curves, which represents the storage or elastic modulus and the loss or the viscous modulus. Before conducting the frequency sweep tests, an amplitude sweep test for each sample was conducted to identify its linear viscoelastic region (*LVE*). This data is important so the frequency sweep test is performed in a range with the lowest strain values and without destroying the structure of the sample (*Amplitude Sweeps :: Anton Paar Wiki*, n.d.; Mezger, 2020).

Partially Hydrolyzed Polyacrylamide (HPAM)

Overall, the figures below show that the storage modulus is higher than the loss modulus in the whole frequency range. Thus, elastic behavior dominates over the viscous behavior. The only exception is H1, which curves interception occurs in 0.03 rad/sec approximately and the elastic behavior becomes dominant only after that point. In addition, we can classify the figures above according to their behavior into two groups. One group contains the frequency sweep tests from solutions H1 and H3, which are the solutions of eight million Dalton Mw but different additive concentration. From these graphs, the slopes of the curves, the storage and the loss modulus, of H1 is close to the slopes of the curves, storage and loss modulus, of H3. The other group contains the frequency sweep tests of solution H1 and H3, which are the solutions of twenty million Dalton Mw but different additive concentration. From these graphs, the slopes of H2 curves are alike to the slope of H4 curves. These results suggest that the slope of the storage and the loss curves of HPAM solutions depend only on the molecular weight of the additive. Moreover, the concentration of the additive may influence the magnitude of both modulus. As the concentration of the additive rises, the elastic and viscous components increase in magnitude.

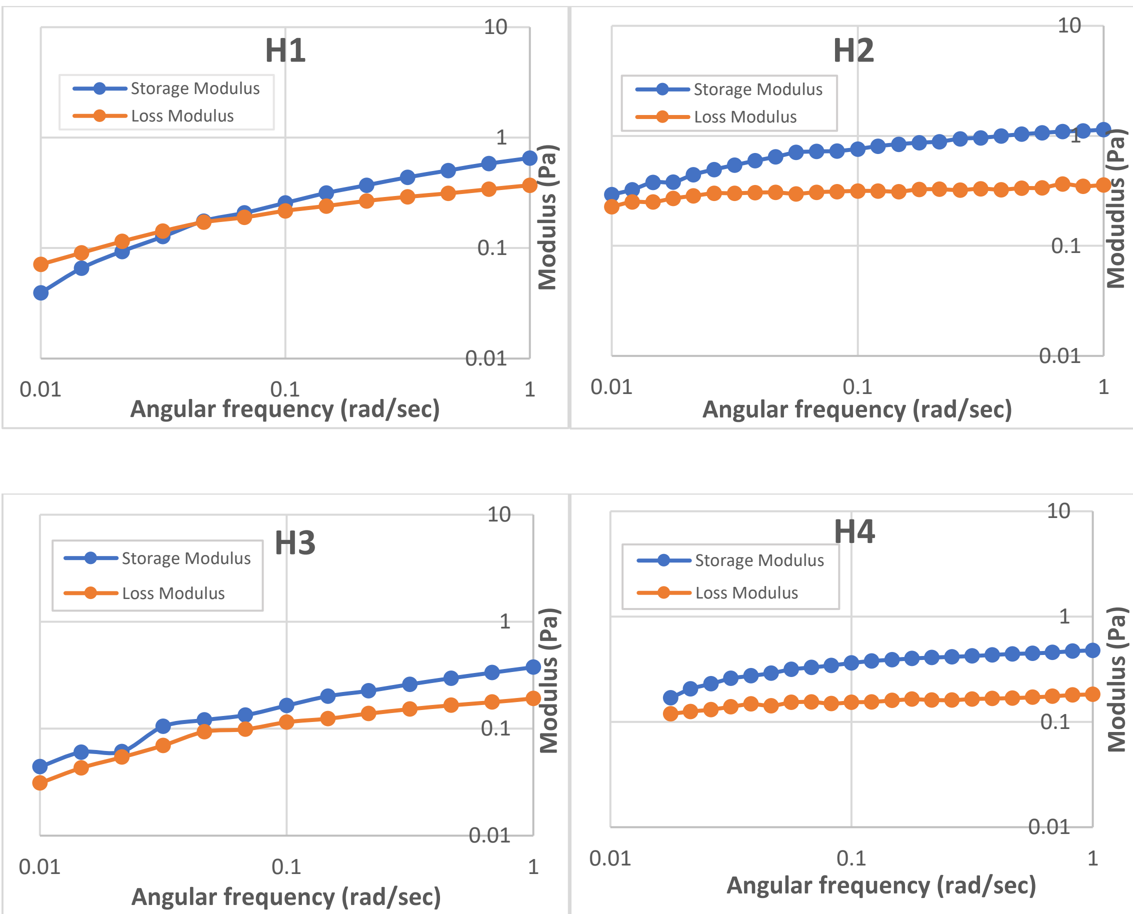

Figure 13 Frequency sweep tests of HPAM solutions

Figure 14 contains one graph that shows only the storage modulus of all HPAM solutions. In general, it can be concluded from figure below that the higher the concentration and the molecular weight of the additive, the elastic component may increase over the whole angular frequency. For instance, the solution H2, whose concentration is 0.1% and possesses twenty million Dalton Mw, exhibits the higher elastic magnitude. On the other hand, the solution H3, whose concentration is 0.05 % and possesses eight million Dalton Mw, shows the lower elastic magnitude.

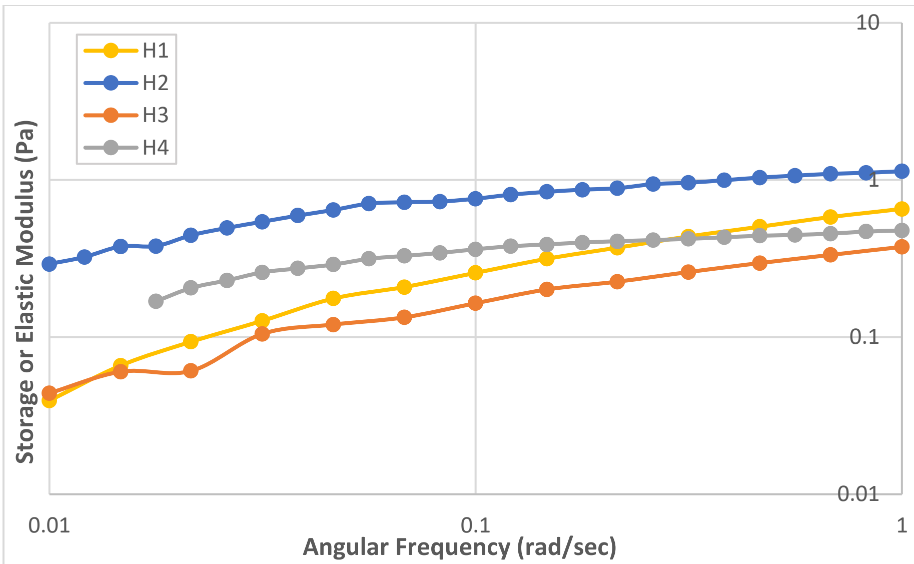

Figure 14 Elastic modulus vs Angular frequency of HPAM solutions

Bentonite

In Figure 15 are illustrated the angular frequency sweep tests for bentonite solutions B1 (3%) and B2 (5%), respectively. Also, in Figure 16 are only shown the elastic component of bentonite solutions B1 and B2, respectively. These results indicate that increasing the bentonite concentration, cause the elastic and viscous component to rise. For example, the storage modulus increases from 0.26 Pa to 2.7 Pa and the loss modulus rises from 0.07 Pa to 0.45 Pa, for an angular frequency of 1 rad/sec, when bentonite concentration increases from 3% to 5%. Furthermore, the results also show that the elastic component is dominant over the whole angular frequency range for both solutions.

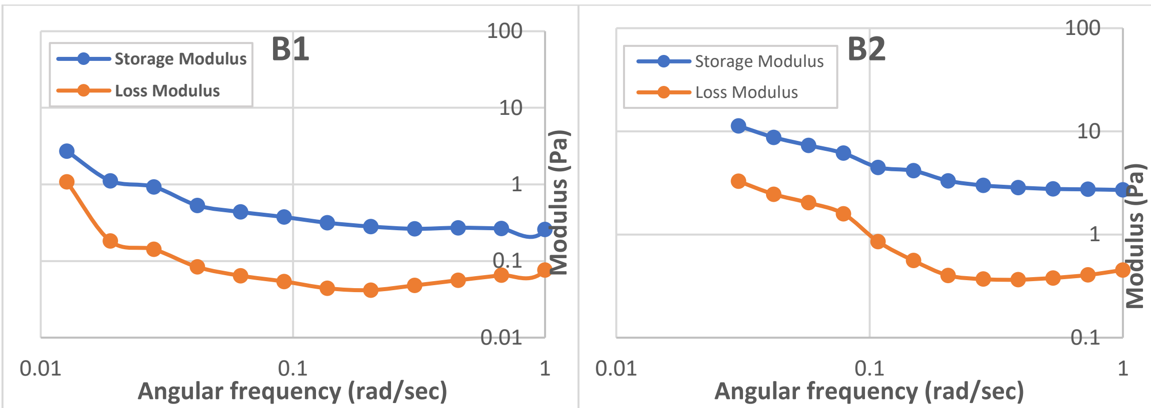

Figure 15 Frequency sweep tests of bentonite solutions

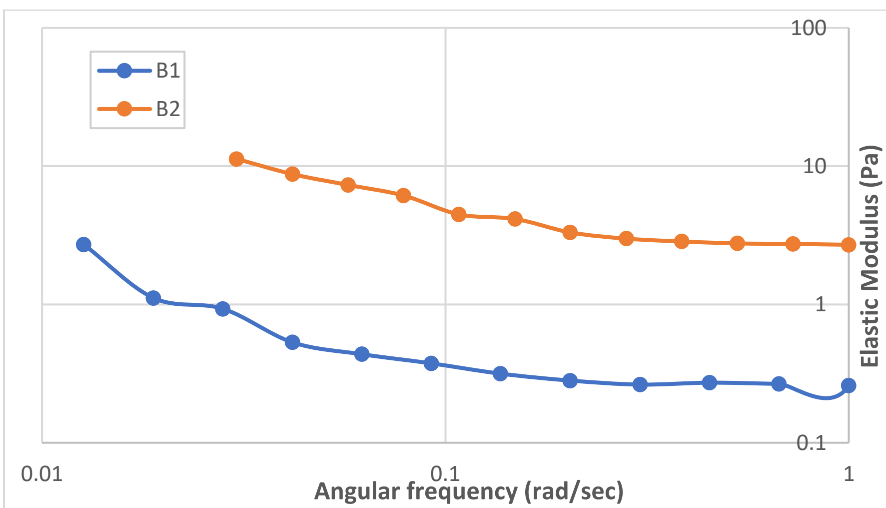

Figure 16 Elastic modulus vs Angular frequency of bentonite solutions

3.6.3. Rheological Models

The rheological models used to fit the measured data are the BP model, the PL model, and the HB model. For the HB model, the measurement method and the numerical method are used for the predictions of the rheological parameters.

Partially Hydrolyzed Polyacrylamide (HPAM)

Figure 17 to **Figure 20** represent the shear stress vs shear rate of the measured data and the predictions from the models used. After analyzing the patterns in these figures, the following conclusions can be drawn. The BP model, which is shown in grey color in all figures, is a good fit for shear rates higher than 300 (1/sec) approximately. This indicates that for lower shear rates, the BP model is not adequate since overestimates the actual shear stress. The PL model, which is represented in yellow, has the following behavior for all cases. For shear rates lower than 300 (1/sec) approximately, the data has a good adjustment, but for shear rates higher than 300 (1/sec), the data under predict the actual shear stress. Moreover, it can be clearly seen in **Figure 17-Figure 20** that the HB model has the best adjustment over the total shear rate range. Although there are two methods to calculate the parameters of the HB model, it is not clear which one has the best adjustment based on these graphical representations. The green and the orange are used in the graphs to show the numerical and the measurement methods, respectively.

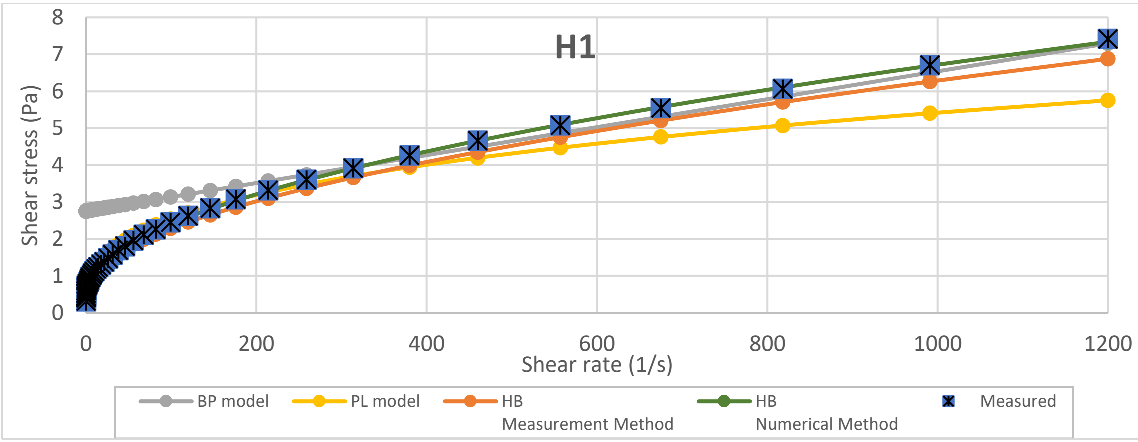

Figure 17 Comparison of measured data and the predictions from models of solution H1

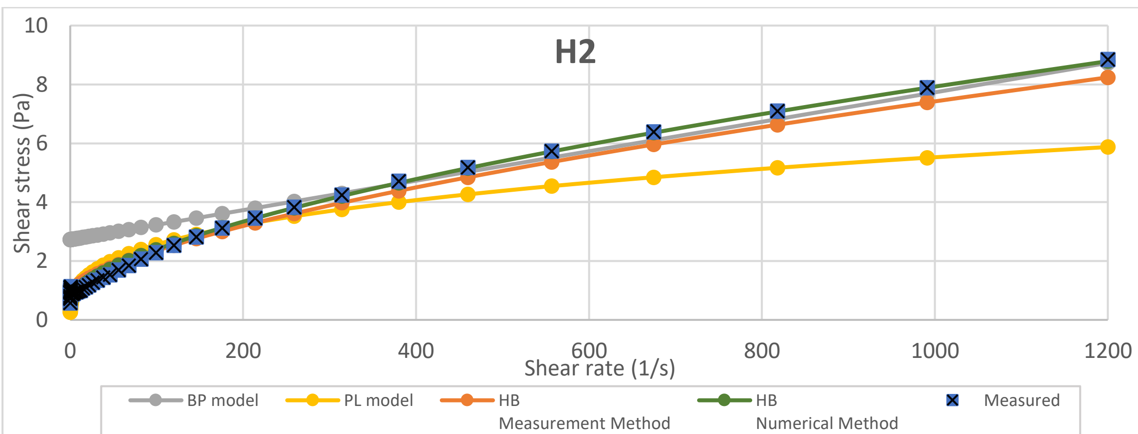

Figure 18 Comparison of measured data and the predictions from models of solution H2

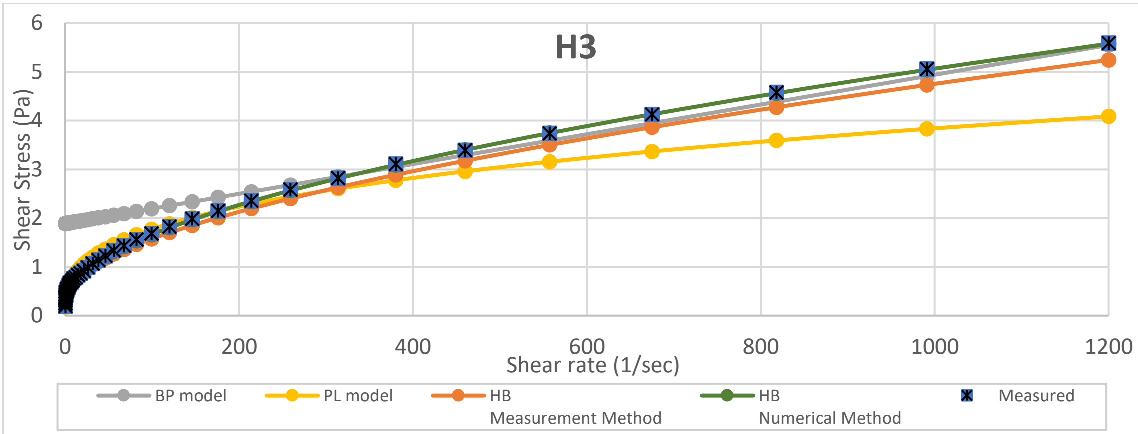

Figure 19 Comparison of measured data and the predictions from models of solution H3

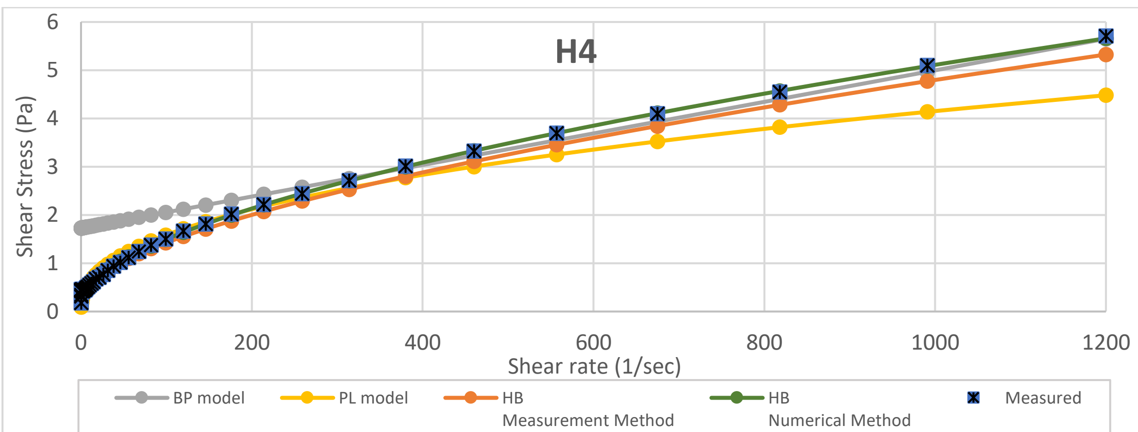

Figure 20 Comparison of measured data and the predictions from models of solution H4

The coefficient of determination (R^2) and the Best Index Value (*BIV*) are used to select the best method to calculate the parameters of the HB model. The coefficient of determination R^2 is normally used for linear functions, and *BIV* is defined by the following formula:

$$BIV = \sum_i(\hat{y}_i - \bar{y})^2 \Big/ \sum_i(y_i - \bar{y})^2 \qquad 3\text{-}25$$

The closer the value of R^2 or BIV to one, the better is the capacity of the rheological model to approximate the measured data. **Table 2** shows the R^2 values for the three models used, and for the different HPAM solutions. The results, as shown in **Table 2**, indicate that the rheological model that best fits the measured data is the HB model. Nevertheless, it is not clear which method, measure or numerical, is the most adequate since almost all R^2 values are equal to 1.

Table 2. Coefficient of determination (R^2) for HPAM solutions

	H1	H2	H3	H4
BP model	0.91	0.96	0.93	0.95
PL model	0.98	0.91	0.97	0.97
HB model measurement method	1.00	1.00	1.00	1.00
HB model Numerical method	1.00	0.99	1.00	1.00

The table below illustrates the *BIV* values for the three models used, and for the different HPAM solutions. The results with *BIV* also confirm that the *HB* model is the best rheological model that approximates the behavior of HPAM solutions. Interestingly, the *BIV* values for the measure method and the numerical method are different, opposite to the R^2 indicator. The *BIV* indicator shows that the numerical method is the most adequate to calculate the parameter of the HB model. This finding is consistent with Kelessidis et al. (2006) and Deng (2000), who also recommended the use of *BIV* indicator for determining the quality of the model prediction, as well as the numerical method for calculating the parameters of the HB model.

Table 3. Best Index Value (*BIV*) for HPAM solutions

	H1	H2	H3	H4
BP model	0.21	0.31	0.25	0.29
PL model	0.47	0.43	0.44	0.54
HB model measurement method	0.50	0.59	0.54	0.60
HB model Numerical method	0.62	0.74	0.65	0.72

Bentonite

The same analyses done in the previous section with HPAM solutions are realized with bentonite solutions, resulting in the same conclusions. **Figure 21** and **Figure 22** show the measured data and the predictions from rheological models for bentonite 3% and 5%, respectively. For both cases, the green curve, which represents the HB numerical method, is the one that fits better with the measured data, which is represented as blue spots. The same conclusions made about the BP model and the PL model in the previous section for HPAM solutions also apply for bentonite solutions.

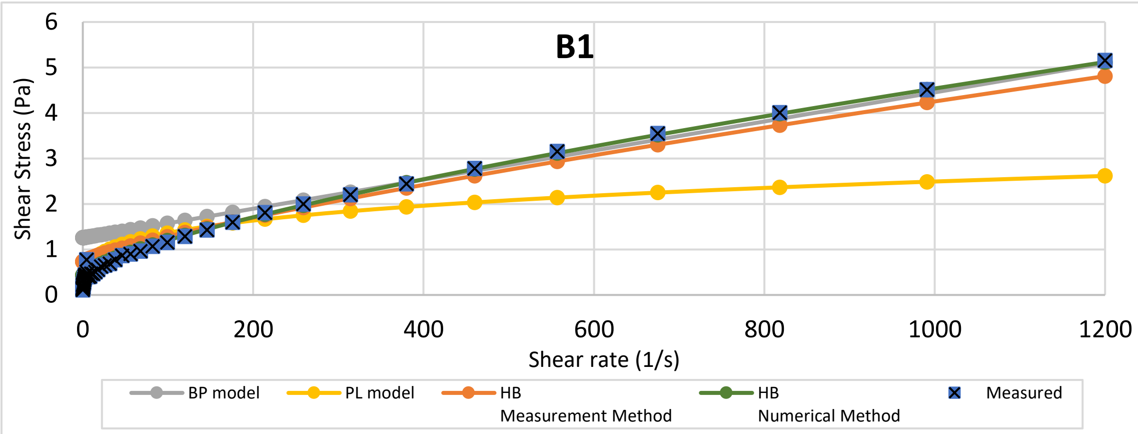

Figure 21 Comparison of measured data and the predictions from models of solution B1

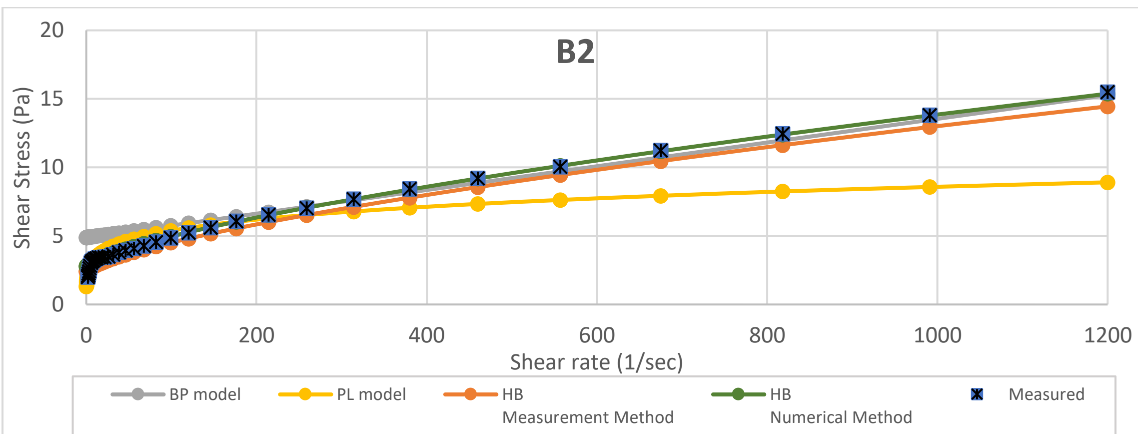

Figure 22 Comparison of measured data and the predictions from models of solution B2

Table 4 shows the R^2 indicators for the different rheological models evaluated, and it can be concluded that the HB model is the most appropriate. However, the R^2 values are the same for measurement and numerical method for each of the bentonite concentrations.

Table 4. Coefficient of determination (R^2) for bentonite solutions

	B1	B2
BP model	0.96	0.93
PL model	0.89	0.90
HB model measurement method	0.99	0.98
HB model Numerical method	0.99	0.98

In addition to the R^2 indicator, the *BIV* indicator is also evaluated, as shown in **Table 5**. In agreement with the R^2 indicator, the HB rheological model best suits the measured data. However, *BIV* indicator points out that the numerical method is more adequate since its value is closer to 1. This result also shows that the *BIV* indicator is more accurate than the R^2 indicator.

Table 5. Best Index Value (*BIV*) for bentonite solutions

	B1	B2
BP model	0.39	0.36
PL model	0.25	0.32
HB model measurement method	0.50	0.59
HB model Numerical method	0.71	0.66

3.6.4. Parameters of the Rheological Models

Partially Hydrolyzed Polyacrylamide (HPAM)

Table 6 presents the parameters of the BP model, the PL model, and the HB model. Analyzing the information given below, the following conclusions can be drawn. According to the parameters of the BP model, the highest yield point (*YP*) values are for H1 and H2, which represent the solutions with highest additive concentration, and the lowest YP values are for H3 and H4, which represent the solutions with lowest additive concentration. The average of H1 and H2, as well as H3 and H4, are 2.74 and 1.81, respectively. The deviation standard of H1 and H2, as well as H3 and H4, are 0.02 and 0.11, respectively. Consequently, it is probable that the yield point only depends on the additive concentration, and the Mw does not have a big influence on the *YP* value. The *PV* values for all HPAM solutions are similar, except for H2, which represents a 0.1% of concentration and 20 million Daltons (Mw). The results for the PL model parameter show that all solutions have a shear thinning behavior because all *n* values are lower than 1. In addition, the H4 solution, which has an additive concentration of 0.05% and 20 million Dalton, has the pointiest velocity profile over the other solutions. A pointer velocity profile is not desired from the hole cleaning perspective since a flat velocity profile benefits the cuttings transport by the suspension mechanism. The fluid consistency index (*K*), which is an indicator of the viscosity, is higher for the solution with maximum concentration and lower for those of minimum concentration. Solutions

H1 and H2 have a 0.1% of concentration, and H3 as well as H4, have a 0.05% of concentration.

The table below also shows the parameters of the HB model, and the following conclusions are drawn. For solutions H3 and H4, whose concentrations are 0.05% but which have different Mw, the parameters *n* and *K* are almost identical. In general, solutions showing identical viscosity properties have close values for *n* and *K* parameters. Moreover, solutions H1 and H2, whose concentrations are 0.1% but have different Mw, the parameters *n* and *K* differ in value. These findings agree with the conclusion in section 3.6.1, in which the shear stress vs shear rate graph, as well as the viscosity vs shear rate graph, for the same set of HPAM solutions are analyzed. This result confirms that the molecular structure of HPAM influences the rheological behavior of solutions, in particular the viscosity, but only up to a certain concentration. Another parameter from the HB model is the yield stress τ_y. In general, higher concentration of the additive induces higher yield stress. Conversely, a lower concentration of the additive leads to a decrease in yield stress. An interesting finding is that the $\tau_y$value for H3 and H4 solutions are different while their viscosity properties, represented by *n* and *K* parameters, are almost identical. τ_y is an indicator of the suspension capacity of a drilling fluid, so if a set of solutions have different τ_y values, their hole cleaning indicators may also be different. This finding shows that viscosity is not the only rheological parameter that matter, since there are other factors that influence the hole cleaning assessment.

Table 6. Parameters of the rheological models evaluated of HPAM solutions.

		H1	H2	H3	H4
BP model	*YP (Pa)*	2.76	2.73	1.89	1.73
	PV (Pa.s)	3.78E-03	5.00E-03	3.05E-03	3.27E-03
PL model	*n*	0.33	0.33	0.34	0.42
	K $(Pa.S^n)$	0.56	0.55	0.38	0.23
HB model	τ_y *(Pa)*	0.58	0.60	0.43	0.23
	n	0.53	0.61	0.57	0.58
	K $(Pa.S^n)$	0.16	0.11	0.09	0.09

Bentonite

Table 7 shows the parameters of the three rheological models for the two bentonite solutions that were labelled as B1 and B2. Overall, these results indicate that raising the bentonite concentration from 3% (B1) to 5% (B2), causes the rheological parameters to increase, and flattens the velocity profile. The factors that illustrate the drilling fluid capacity to suspend cuttings are *YP* from the BP model and τ_y from the HB model. While the bentonite concentration rises from 3% to 5%, *YP* increases from 1.26 Pa to 4.89 Pa and τ_y increases from 0.42 Pa to 2.77 Pa. The parameters *K*, from the PL and the HB models, are used to evaluate the viscosity component of a solution. *K* increases from 0.41 to 2.11 (from the PL model) and *K* increments from 0.03 to 0.09 (from the HB model) when bentonite concentration increases. An indicator of the flatness of a velocity profile is the *n* parameter from the PL and the HB model. The flatter the velocity profile, the lower the value of *n*. For the PL and the HB model, the *n* value decreases as bentonite concentration increases, as seen in the table below.

Table 7. Parameters from the rheological models evaluated for bentonite solutions.

		B1	B2
BP model	*YP (Pa)*	1.26	4.89
	PV (Pa.s)	3.20E-03	8.65E-03
PL model	*n*	0.26	0.20
	K (Pa.S^n)	0.41	2.11
HB model	τ_y *(Pa)*	0.42	2.77
	n	0.72	0.70
	K (Pa.S^n)	0.03	0.09

3.6.5. Hydraulic Parameters

A theoretical case study was created so other parameters such as frictional pressure loss was considered into the hole cleaning assessment. The characteristics of the case study, such as the diameter of the wellbore, the diameter of the drill pipe, and pump capacity can be seen in **Table 8**.

Table 8. Case study parameters

Borehole Diameter (m)	0.31
OD (m)	0.14
Q (L/min)	1,461

Partially Hydrolyzed Polyacrylamide (HPAM)

Table 9 shows the shear rate and shear stress on the wall, as well as the frictional pressure loss for the four HPAM solutions. The results from the frictional pressure loss indicate that the additive concentration has a big influence in the frictional pressure loss and the molecular weight has a small impact on the frictional pressure loss. While solutions H1 and H2 (additive concentration of 0.1%) have a frictional pressure of 44.55 Pa/m and 42.22 Pa/m, respectively, solutions H3 and H4 (additive concentration of 0.05%) have a frictional pressure loss of 30.31 Pa/m and 24.23 Pa/m, respectively.

Table 9. Hydraulic parameters for HPAM solutions

	H1	**H2**	**H3**	**H4**
γw (1/sec)	36.48	34.02	35.03	34.72
τw (Pa)	1.91	1.81	1.30	1.04
ΔP (Pa/m)	44.55	42.22	30.31	24.23

Bentonite

The shear rate and shear stress in the wall, as well as the frictional pressure loss, for the two bentonite solutions are presented in **Table 10**. These results indicate that an increment of bentonite from 3% to 5%, raise the shear stress at the wall 5.13 times and increases the frictional pressure loss 5.14 times.

Table 10. Hydraulic parameters for bentonite solutions.

	B1	B2
γw (1/s)	31.65	32.01
τw (Pa)	0.97	4.98
ΔP (Pa/m)	22.58	116.19

3.6.6. Hole Cleaning Assessment

Partially Hydrolyzed Polyacrylamide (HPAM)

As mentioned in Section 2.5.4, the ratio of yield point (*YP*) and plastic viscosity (*PV*) has been used extensively in the drilling research as an indicator of the hole cleaning performance. The higher the indicator, the higher the hole cleaning performance. In this section, the *YP/PV* indicator is calculated for all HPAM solutions, as seen in **Figure 23**.

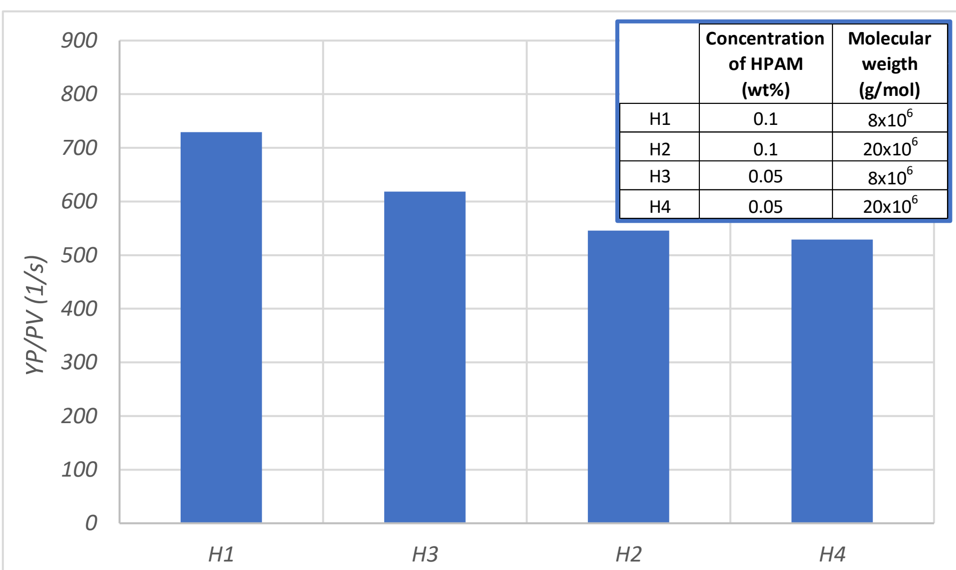

Figure 23 *YP/PV* Hole cleaning indicator for HPAM solutions.

The results in **Figure 23** point out that the solutions with better hole cleaning performance are those with Mw of 8 million g/mol or Dalton, which are H1 and H3, whereas the solutions with lower hole cleaning performance are H2 and H4, whose Mw are 20 million Dalton. Additionally, the *YP/PV* indicators for H2 and H4 are almost the same with an average of 537.1 and a deviation standard of 16.7. Overall, these results indicate that the hole cleaning performance, evaluated by *YP/PV* indicator, depends mainly on the molecular weight of the additive and the concentration of the additive only has a minor influence.

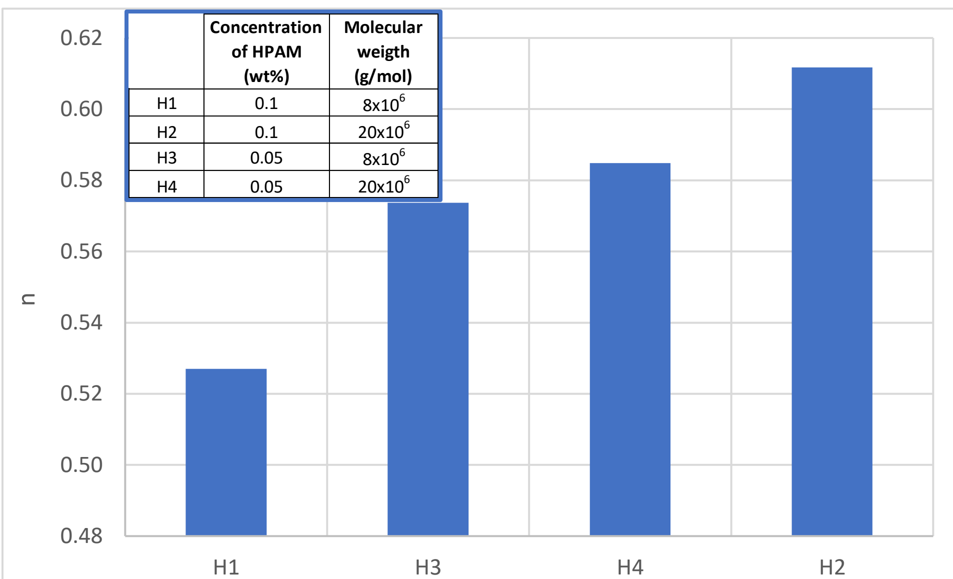

Figure 24 *n* parameter from HB model for HPAM solutions.

Other parameter that can work as an indicator of the hole cleaning performance is the flow behavior index (*n*) from the HB model. If *n* is lower than 1, it means that the drilling fluid is showing a shear thinning behavior. Moreover, the lower the *n* value, the flatter the velocity profile. Research indicates the advantages of a flatter velocity profile, such as the increment of the suspension area for cuttings, inside the annulus. Thus, a better hole cleaning performance is obtained. **Figure 24** shows the n values for all HPAM solutions, and the results indicate that H1 represents the best hole cleaning performance, while H2 shows the worst hole cleaning performance. Another conclusion is that the n value for H2, H3, and H4 are similar with an average of 0.59 and a deviation standard of 0.01. This also indicates that their hole cleaning behavior is similar. Even though the results of YP/PV indicator and n parameter are not the same, they share some similarities as follows. Both agree that H1, which has a medium Mw with at the highest HPAM concentration, represents the best hole cleaning performance. Furthermore, H2 and H4, whose Mw are twenty million Dalton, but which possess different additive concentration, show similar hole cleaning performance.

YP (from the BP model) and τ_y (from the HB model) are other variables that can work as indicators of the hole cleaning performance. These variables represent the measurement of the minimum shear stress required to initiate the fluid movement. Moreover, they indicate the suspension capacity of the drilling fluid. If the suspension capacity of a fluid is high, the cuttings can be transported more efficiently so the hole cleaning performance is greater. **Figure 25** and **Figure 26** present the variables τ_y and YP, respectively. In general, the results correspond with the other hole cleaning performance indicators as follows. H1 solution represents the best hole cleaning performance, whereas H4 exhibits the worst hole cleaning performance. τ_y and YP show the same tendency over the same conditions. However, it is notorious that YP values are significantly higher than τ_y, which is due to the overprediction of the BP model that is mentioned in Section 3.2.1. τ_y values are more realistic since the HB model, in which τ_y is a parameter, is the one with better fitness adjustment to the measured data.

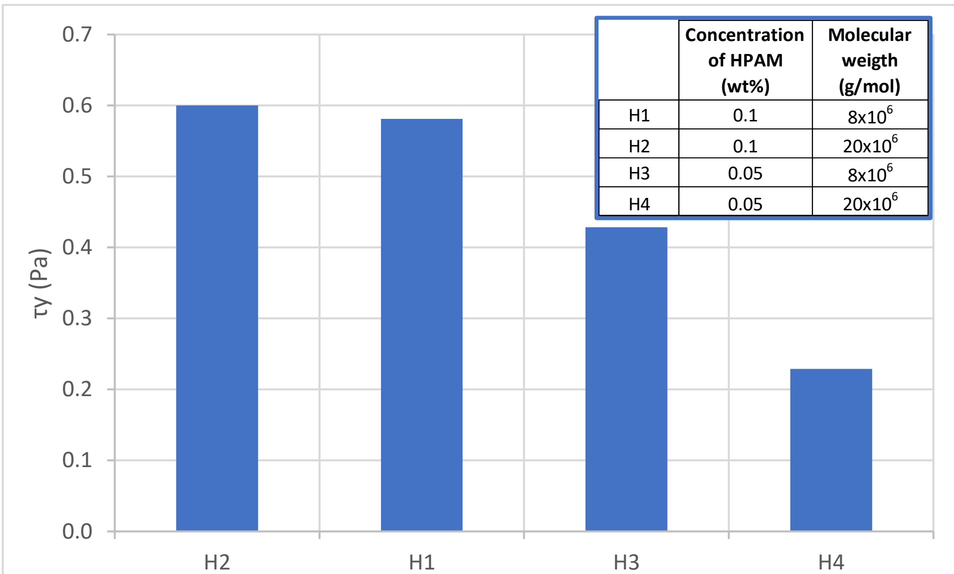

Figure 25 τ_y parameter from HB model for HPAM solutions.

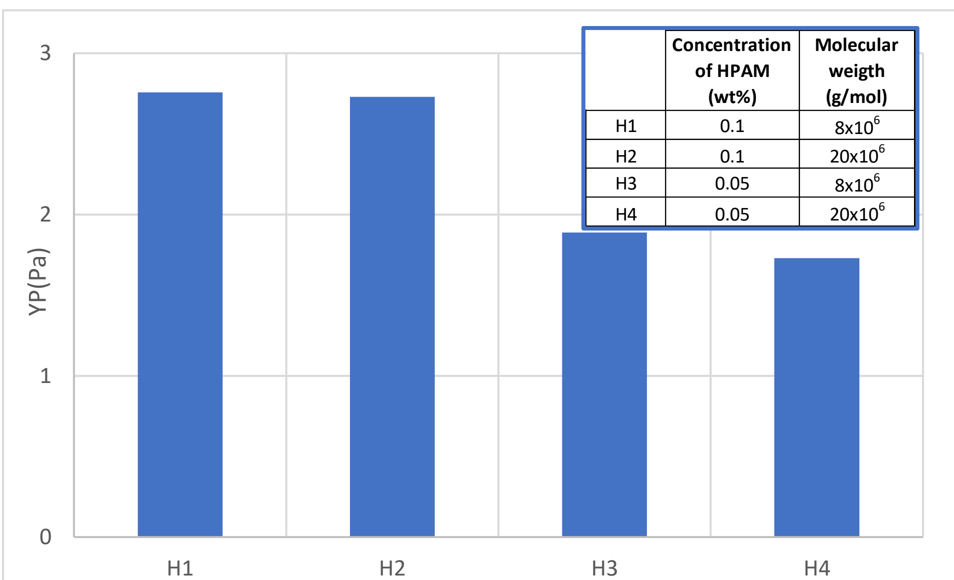

Figure 26 *YP* parameter from BP model for HPAM solutions.

The hole cleaning assessment can be a tricky task, so parameters (such as *YP/PV* and *n)* should not only be considered, but also others, including the frictional pressure loss, the viscosity, and elasticity to get a more accurate assessment. For this reason, a summary of previous analyses and findings are going to be included in this section.

Figure 27 presents the frictional pressure loss for the different HPAM solutions. As mentioned in Section 3.6.5, the additive concentration has a big influence in the frictional pressure loss and the molecular weight has a small impact on the frictional pressure loss. Correlating the results from *YP/PV* indicator and frictional pressure loss, the following conclusion is made. The solution H1 shows the highest frictional pressure loss and represents the best hole cleaning performance among the HPAM solutions, whereas solution H4 shows the lowest frictional pressure loss as well as the worst hole cleaning performance. This outcome points out that generally the relation between the *YP/PV*, as an indicator of hole cleaning performance, and frictional pressure loss is directly proportional.

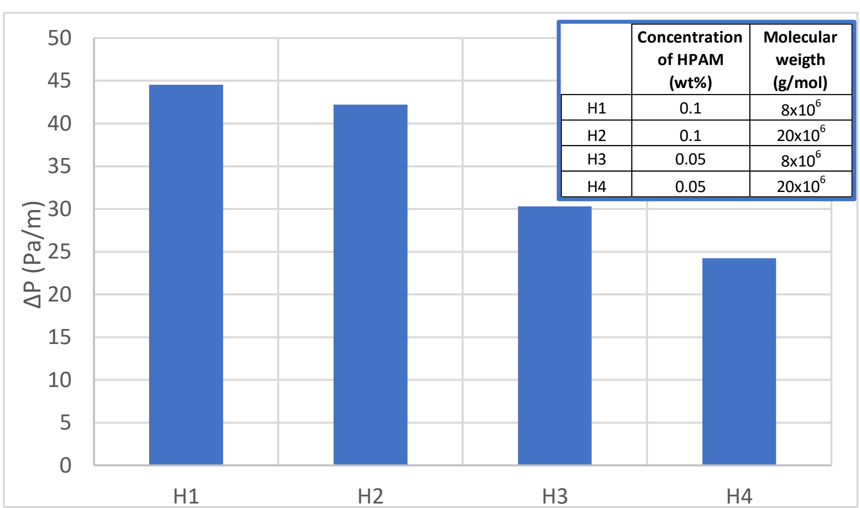

Figure 27 Frictional pressure loss for HPAM solutions

Viscosity is another rheological property that should be evaluated into the hole cleaning assessment. Previously in Section 3.6.1, some conclusions were made by the analysis of shear stress vs shear rate curves, as well as viscosity vs shear rate curves. Additionally, in Section 3.6.4, the parameters related to viscosity from rheological models were evaluated. There is an agreement in the findings of both sections, which basically states that Mw has a big influence on the viscosity but only up to a certain additive concentration, as seen in **Figure 28**. The hole cleaning indicators have some correlations with the viscosity findings. For instance, the highest viscosity correlates with the highest hole cleaning performance and the lowest viscosity correlates with the lowest hole cleaning performance. This result indicates that generally, viscosity and hole cleaning performance have a directly proportional relationship.

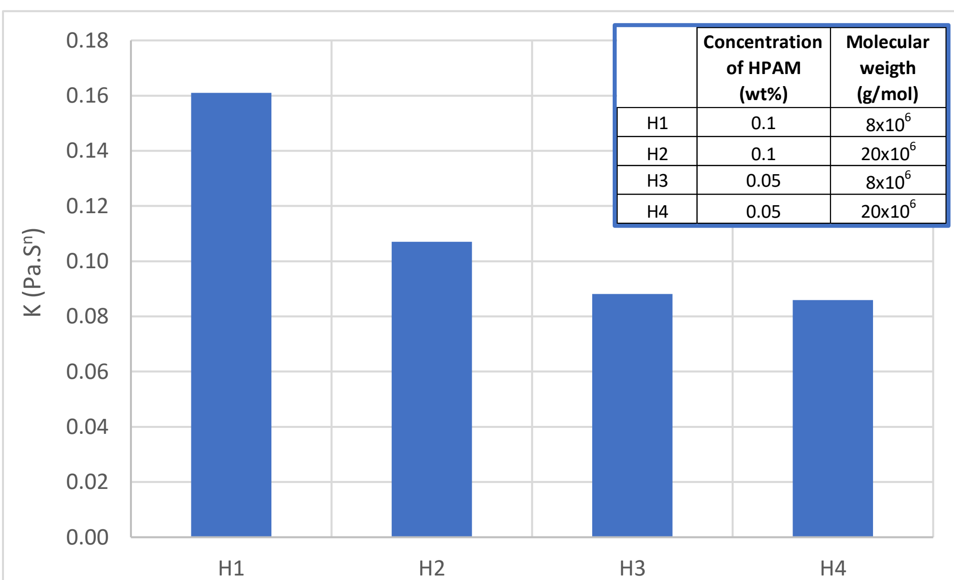

Figure 28 *K* parameter from HB model for HPAM solutions.

Another parameter in consideration is the elasticity. Section 3.6.1 discusses the frequency sweep tests, which results in several findings. First, elastic behavior is dominant over the whole angular frequency range for all HPAM solutions. Second, higher concentration of the additive and the molecular weight allow a stronger elastic behavior. Conversely, lower concentration of the additive and molecular weight guide to a weaker elastic behavior. Comparing the results from *YP/PV* indicator and elastic modulus that are represented in **Figure 23** and **Figure 16**, the following can be concluded. Whereas solutions with higher elastic modulus, such as H2 and H4, show the worst hole cleaning performance, solutions with lower elastic modulus, such as H1 and H3, show the best hole cleaning performance. Thus, weaker elastic behavior may be beneficial for hole cleaning performance in HPAM solutions.

Bentonite

The same analyses done in the previous section with HPAM solutions are realized with bentonite solutions. **Figure 29** to **Figure 32** show the hole cleaning indicator *YP/PV*, the parameter *n* from HB model, and the yield stress from the BP and HB models, respectively. Overall, an increment of bentonite from 3% to 5% causes the following: The hole cleaning performance improves 1.43 times, the velocity profile flattens 1.3 times, which means an increment of the suspension area inside the annulus, and the yield stress rises in average 3.6 times for the BP and HB models.

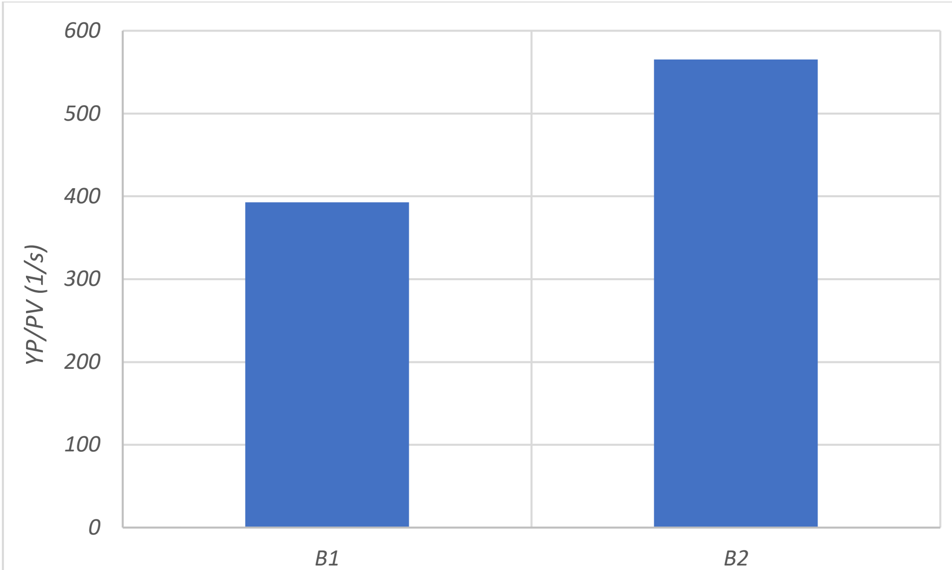

Figure 29 *YP/PV* Hole cleaning indicator for bentonite solutions.

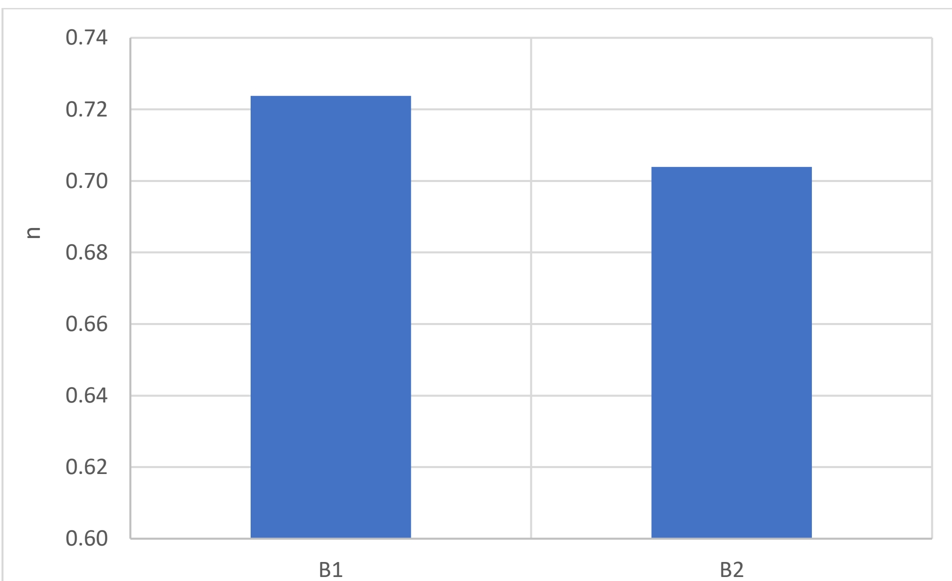

Figure 30 *n* parameter from HB model for bentonite solutions.

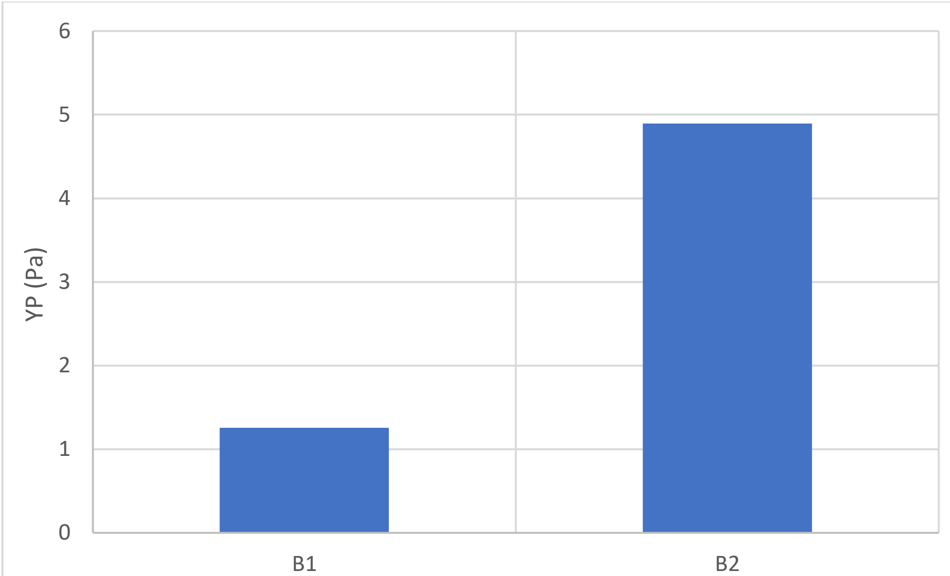

Figure 31 *YP* parameter from BP model for bentonite solutions.

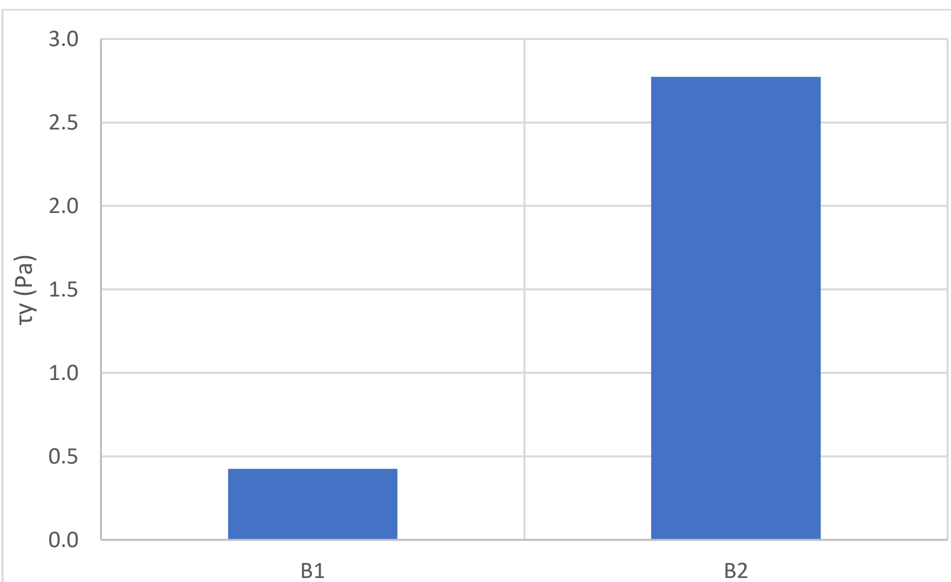

Figure 32 τ_y parameter from HB model for bentonite solutions.

Other parameter in consideration is the frictional pressure loss that is represented in **Figure 33**. When the bentonite rises from 3% to 5%, the frictional pressure loss increases 5.15 times. This indicates that there is a substantial increment of the frictional pressure loss, which may induce hydro fracture that leads to the collapse of the wellbore. Although an increment of bentonite helps in the cuttings transport, and therefore, improves hole cleaning performance, it also raises the frictional pressure loss that causes severe problems in the drilling process. Thus, a balance is desired in which cuttings are transported efficiently without compromising the stability of the wellbore.

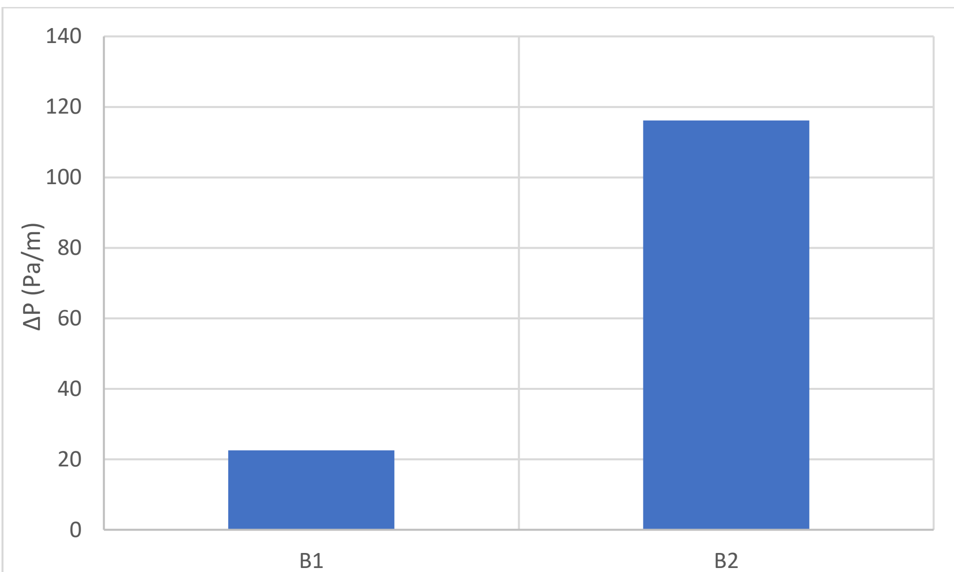

Figure 33 Frictional pressure loss for bentonite solutions

Viscosity and elasticity are other rheological properties that should be evaluated into the hole cleaning assessment. Previously in Sections 3.6.1 and 3.6.2, it was mentioned that an increment of bentonite concentration from 3% (B1) to 5% (B2) causes a gradual increase of viscosity and elasticity, respectively. Additionally, *K* variable from the HB model increases 3 times when bentonite concentration raises, as seen in **Figure 34**.

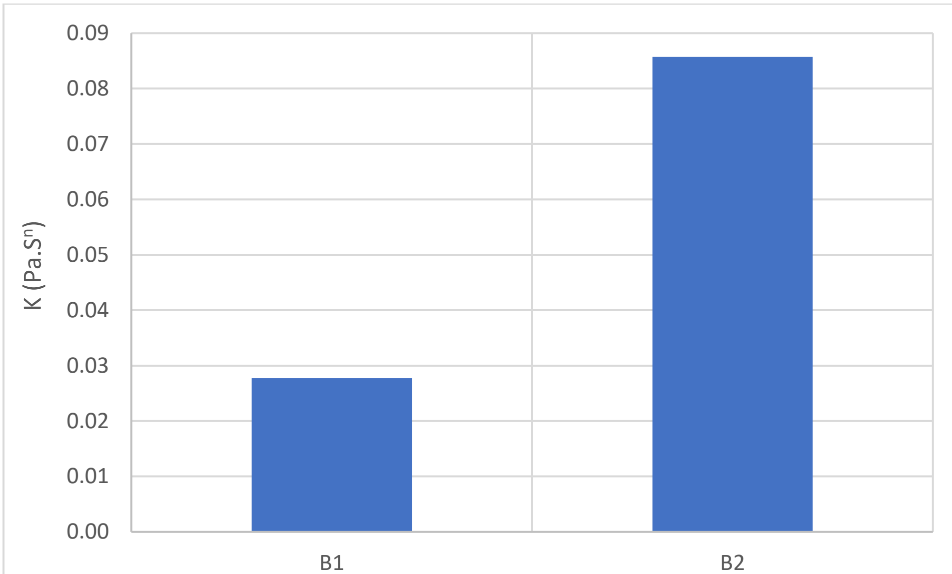

Figure 34 *K* parameter from HB model for bentonite solutions.

In summary, an increment of bentonite concentration causes the raising of all rheological parameters, the viscosity, and the elasticity. This also results in the enhancement of the hole cleaning performance. Comparison of bentonite and HPAM results demonstrate some similarities such as the relationship of the hole cleaning performance with the concentration of the additive, the yield stress, and the viscosity. Conversely, the relationship between hole cleaning performance and elasticity is different for HPAM and bentonite. The increment of elasticity affects in a negative way the hole cleaning performance in HPAM while in bentonite solutions is the opposite.

3.6.7. Highlighted Findings

Interesting findings that deserve to be pointed out are the following. First, solutions H3 and H4 show similar viscosity properties, as seen in Sections 3.6.1 and 3.6.4, but present different yield stress, elasticity, and hole cleaning performance, as shown in Sections 3.6.2 and 3.6.6. The *YP* decreases from 1.89 Pa to 1.72 Pa and the τ_y reduces from 0.43 Pa to 0.23 Pa when the hole cleaning indicator *YP/PV* changes from 618.55 to 528.73, as seen in **Figure 35**. The elasticity, which is measured by frequency sweep tests, of both solutions are represented in **Figure 14**. On the one hand, H4 shows the strongest elasticity capacity and the lowest *YP/PV* indicator. On the other hand, H3 represents the weaker elasticity capacity and the highest *YP/PV* indicator. This case indicates that viscosity and elasticity are important, and that each property influences the hole cleaning performance. Additionally, it shows that if a solution, with HPAM as an additive, exhibits a high elasticity capacity, the hole cleaning performance may get worse.

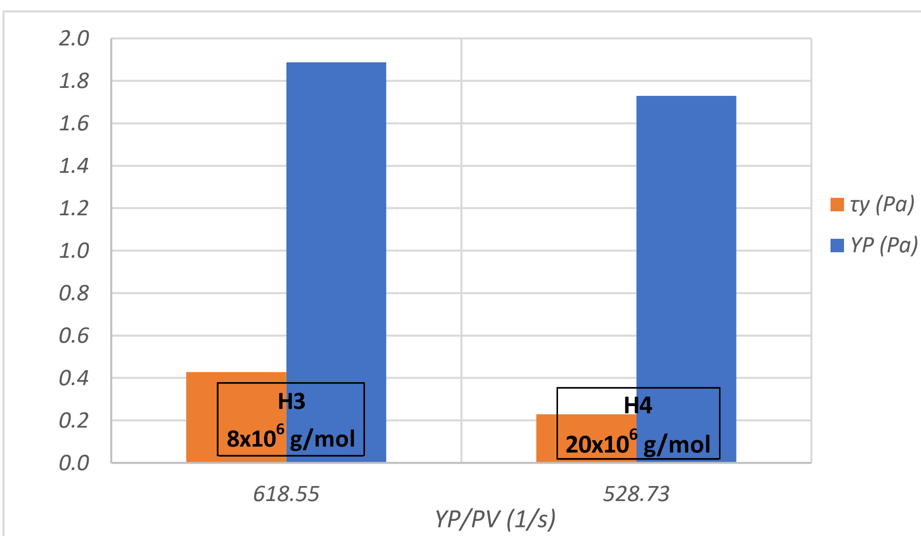

Figure 35 Correlation between *YP*/*PV* hole cleaning indicator and yield stress of solutions H3 and H4

Second, analyzing the results of *YP/PV* indicator and the frictional pressure loss for H2, H4, and B2 solutions, as seen in **Table 11**, we can conclude the following: Although the three solutions have similar hole cleaning performance as indicated by *YP/PV*, their frictional pressure loss are different. B2 solution possess the highest frictional pressure loss, which is 116.19 Pa, and the other HPAM solutions have a similar frictional pressure loss of 537.1 Pa in average. In this case, it is adequate to prefer the HPAM solutions than the bentonite one since the latter induces a higher pressure to the formation, and therefore, a higher risk of hydro fracture. Nevertheless, other factors, including the cost and the additive concentration, should be considered when selecting the drilling fluid. The prices of bentonite and HPAM differ significantly in value. For instance, 10 grams of HPAM can cost 130 CAD while 22 kilograms of bentonite can cost 20 CAD. Even though the bentonite is markedly cheaper than the HPAM, the concentration used for HPAM (between 0.05% and 0.1%) is significantly less than the bentonite (between 1% and 5%).

Table 11. Hole cleaning indicator and frictional pressure loss of some HPAM and bentonite solutions.

	H2	**H4**	**B2**
YP/PV(1/S)	545.47	528.73	565.43
ΔP (Pa/m)	42.22	24.23	116.19

Chapter 4: SUMMARY AND CONCLUSIONS

4.1. Conclusions

The aim of the present research was to conduct rheological tests on drilling fluids with different compositions and investigate the impact of their properties into the hole cleaning performance in HDD. In particular, study the elasticity property that is seldom considered into the assessment of hole cleaning performance. HPAM (two different grades and two different concentrations) was used in first part of experiments, and bentonite (two different concentrations) was used for the second part of experiments. The most important conclusions for each experimental part are as follows:

HPAM

These experiments shows that the molecular structure of the additive has an influence on the rheological properties of HPAM solutions. Consequently, attention should be given to the molecular structure of the additive when selecting a HPAM drilling mud for an HDD project. The following conclusions point out the impact of the molecular structure of HPAM on the different variables involved in the hole cleaning process.

- In the one hand, solutions H3 and H4, whose concentrations are 0.05% but which have different Mw (8 million and 20 million Dalton respectively), showed almost identical viscosity properties. In the other hand, solutions H1 and H2, whose concentrations are 0.1% but have different Mw (8 million and 20 million Dalton respectively), showed different viscosity properties. This indicates that up to a certain concentration of the additive, the Mw influences the viscosity. In this case, when the molecular weight (Mw) increases, the viscosity raises.

- The rate of change of the elastic modulus with respect to angular frequency depended only on the Mw of the additive. Higher molecular weight of the additive induced higher elastic component over the whole angular frequency.
- The frictional pressure loss slightly varies over the whole shear rate range when the Mw of the additive changed from 8 million to 20 million Dalton in HPAM solutions.
- Solutions that gave the best hole cleaning performance had a Mw of 8 million Dalton. Conversely, solutions that gave the worst hole cleaning performance had a Mw of 20 million Dalton. These results indicate that the hole cleaning performance, evaluated by *YP/PV* indicator, significantly depends on the Mw of the additive while the concentration of the additive only has a minor influence.

The relevance of the concentration of the additive on rheological properties is clearly supported by the following findings:

- The viscosity of the solution raised, as the polymer concentration was increased. This change was more pronounced in the solution with higher molecular weight.
- The parameters from the BP model (Yield point (*YP*)) and the parameters from the HB model (The fluid consistency index (*K*) and the yield stress (τ_y)) were

highly influenced by the concentration of the additive. Overall, an increase of the concentration of the additive induced higher values of the parameters mentioned.

- The frictional pressure loss had a significant variation when the additive concentration varied. When the concentration of the additive increased, the frictional pressure raised.

Other major findings about HPAM rheological tests are as follows:

- The storage modulus was higher than the loss modulus over the whole frequency range. Thus, elastic behavior dominated over the viscous behavior. The only exception was H1, which curves interception occurred in 0.03 rad/s approximately and the elastic behavior became dominant only after that point.
- The results from *YP/PV* indicator, the n parameter as well as the τ_y parameter from HB model, indicated that H1, which had a medium Mw of 8 million Dalton at the highest HPAM concentration investigated (0.1%), represented the best hole cleaning performance.

Bentonite

After analyzing the rheological tests of bentonite solutions, the following conclusions are drawn:

- A gradual increase of shear stress occurred when the percentage of bentonite concentration increased from 3% (B1) to 5% (B2). The same tendency was seen in the viscosity vs shear rate curves.
- Increasing the bentonite concentration, caused the elastic and viscous component to raise. In addition, the frequency sweep tests showed that elastic behavior dominated over the whole angular frequency range.
- Overall, the results indicate that raising the bentonite concentration causes the rheological parameters to increase and flattens the velocity profile, and therefore, enhance the hole cleaning performance.
- These results indicate that an increment of bentonite from 3% to 5%, raised the frictional pressure loss 5.14 times. This fact shows that there is a substantial increase of the frictional pressure loss, which might induce hydro fracture that leads to the collapse of the wellbore. Although an increment of bentonite helps in the cuttings transport, and therefore, improves the hole cleaning performance, it also rises the frictional pressure loss that causes severe problems in the drilling process.

Rheological Models

The BP model, the PL model, and the HB model were implemented to fit the measured data and the following conclusions are drawn:

- It was found that for lower shear rates, the BP model was not adequate since overestimated the actual shear stress.

- Based on the findings, the following can be concluded for the PL model: for shear rates lower than 300 (1/s) approximately, the data had a good adjustment, but for shear rates higher than 300 (1/s), the data under predicted the actual shear stress.
- The HB model had the best adjustment over the total shear rate range. Additionally, the *BIV* indicator showed that the numerical method is the most adequate to calculate the parameters of the HB model.
- The data showed that the *BIV* indicator was more accurate than the R^2 indicator.

General

Other significant findings to emerge from this study about HPAM and bentonite rheological tests are the following:

- For both experimental parts, the results show that viscosity and elasticity matter and each property influence the hole cleaning performance.
- Comparison of bentonite and HPAM results demonstrated some similarities such as the relationship of the hole cleaning performance with the concentration of the additive, the yield stress, and the viscosity. Conversely, the relationship between hole cleaning performance and elasticity was different for HPAM and bentonite. The increment of elasticity affects in a negative way the hole cleaning performance in HPAM while in bentonite solutions is the opposite.
- Comparison of the frictional pressure loss and the hole cleaning performance of solutions H2, H4, and B2, the following was identified: although the three solutions showed similar hole cleaning performance as indicated by YP/PV, their

frictional pressure loss were different. B2 solution possessed the highest frictional pressure loss and the other HPAM solutions had a similar frictional pressure loss. In this case, it is preferable to choose the HPAM solutions than the bentonite one since the latter induced a higher pressure to the formation, and therefore, a higher risk of hydro fracture. Nevertheless, other factors, including the cost and the additive concentration, should be considered when selecting the drilling fluid. It is well known that the bentonite is markedly cheaper than the HPAM. However, the concentration used for HPAM (between 0.05% and 0.1%) is significantly less than for bentonite (between 1% and 5%). This finding leads us to the conclusion that selecting the additives of the drilling fluid is not an easy task since it depends on multiples factors. The final decision should always be the one which delivers the project on time, on budget, and on value.

4.2. Future Research

As mentioned throughout this thesis book, the behavior of the drilling fluid changes accordingly to the external conditions that it faces. One of those external conditions is the temperature, which was kept constant (25 ° C) for all experiments carried out. Therefore, a recommendation for future research is to vary the temperature and evaluate the influence of it on the other variables of study.

One of the objectives of this study was to study the influence of the elasticity in the hole cleaning performance, which is seldom done in research. The elasticity was measured by the elastic modulus obtained by the frequency sweep tests. However, there are other variables and methods that can be implemented to measure the elasticity.

The hole cleaning performance was evaluated by the ratio of *YP/PV* and other rheological parameters, which are only indicators of the hole cleaning. A fluid loop is necessary to double check the accuracy of the indicators. Moreover, with the fluid loop, other variables can be included into the investigation, such as the pipe rotation, which seems to bring advantage to the cuttings transportation.

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