Impact of Suspended Cuttings on Drilling Fluid Rheology and Hole Cleaning Capacity in Horizontal Directional Drilling

by

Yi Su

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Department of Civil and Environmental Engineering
University of Alberta

Abstract

Trenchless technologies are a family of techniques to install or rehabilitate conduits under the ground without conventional open excavation processes. Among them, horizontal directional drilling (HDD) is one of the most popular methods for installation of pipelines under surface obstacles, due to its exceptional performance in reducing the social, environmental and economical costs. However, the transportation of drilled cuttings out of the borehole annular space has always been a challenge for the HDD operations, and proper hole cleaning performance is vital for a successful HDD project. Some of the potential consequences of poor hole cleaning jobs include stuck pipes, excessive torque, elevated annular pressure and hydrofracture, or undesirable fluid return to the surface. These risks induce significant uncertainties in HDD design and project control, and hydrofracture is also one of the major concerns for the permitting and regulatory agencies.

The current research and understanding of cutting transportation in HDD annular spaces is still limited, especially for the horizontal and build sections. Furthermore, the practical limit of the maximum allowable pressure of the geological formations also places additional constraints on the options for improving hole cleaning performances. For example, the drilling fluids' annular flow rate should be carefully controlled to prevent excessive frictional pressure loss, because this could drastically increase the risks of hydrofracture incidents.

A comprehensive review was conducted to improve the understanding of cutting transport processes in HDD operations, as well as the established hole cleaning performance indicators for evaluating the drilling fluids. The rheological properties of drilling fluids was found to be the most important and readily controllable variable for enhanced hole cleaning performances, considering the fact that the fluid flow rate was limited by the formation's maximum allowable pressure.

In addition, it was found that the drilling fluids' hole cleaning performance can be evaluated from 2 aspects: the cutting carrying capacity and the sweeping capacity. The annular plug width, which is a parameter indicating the annular fluid velocity profile, was found to be a desirable indicator of the drilling fluids' cutting carrying capacity, while the annular friction pressure loss and the ratio of yield point and plastic viscosity was found to be suitable indicators for the drilling fluids' sweeping capacity.

Effects of suspended drilled cuttings, in this case sand particles, have been investigated by carefully measuring the fluid samples' shear stress-shear rate responses, and it was found that the solid volumetric fractions have significant impacts on the drilling fluids' rheological properties, and this effect is more profound once the solid volumetric fractions exceed 30-35%. Both the Herschel-Bulkley and the Bingham Plastic rheology models were applied to analyze the rheological parameters of the drilling fluid samples, and other parameters, including the annular plug width, friction pressure loss and the ratio of yield point and plastic viscosity were calculated. It was found that increasing solid volumetric fractions negatively impact these hole cleaning performance indicators. Considering the degree of impact and the maximum allowable pressure of the geological formations, it is recommended to keep the solid volumetric fractions as low as possible in the drilling fluid, and it should not exceed 30-35% overall. This value is consistent with

the commonly accepted fluid-to-soil ratio of 2:1 to 3:1 for HDD operation within fine sands.

Preface

This thesis is original, unpublished, independent work by the author, Y. Su.

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

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Chapter 1: INTRODUCTION

1.1. Background

Trenchless technologies are a collection of technologies that enables contractors to install or rehabilitate underground utilities and pipelines without extensive open excavation (Milligan, 2001). By reducing the associated labor costs, social costs and surface reclamation costs, trenchless technologies can achieve significant cost reductions while minimizing interference of the surrounding environment and communities (Thomson, 1987).

Among the available trenchless technologies, horizontal directional drilling (HDD) is one of the most popular choice for new installations, and is developing rapidly during the last few decades (Deng, 2018; Wang, 2017). However, its application is still limited by significant risks, while the hydrofracture, which is an unintended fluid return to the surface, remains to be one of the most concerning challenges for contractors and permitting bodies (Kennedy, 2006). Hydrofracture is often caused by high annular fluid pressure excessive of the maximum allowable pressure of the local geological formations, which is usually the result of poor hole cleaning performances and fluid circulation plan (Osbak, 2012).

Hole cleaning performances of drilling fluids have been extensively studied in the oil and gas industry, and the drilling fluids' annular flow rate and rheological properties were found to have both the highest influence and field controllability (Adari, 2000). However, in the HDD industry, drilling fluids' annular flow rate cannot be elevated to as high as that in the petroleum industry due to the risk of hydrofracture, so the drilling fluids' rheological properties became especially important (Deng, 2018). Furthermore, most of the available research focused on the rheological properties of pure drilling fluids and the impact of suspended drilled cuttings on the drilling fluids' rheology remains unclear. In order to improve the understanding of the impact of drilled cuttings on the drilling fluids' rheological properties and hole cleaning performances, investigation in two aspects need to be considered. First, the impact of drilled cuttings on the drilling fluids' rheological properties should be experimentally tested and analyzed. Second, the resulting findings should be used as inputs to evaluate the drilling fluids' hole cleaning performance parameters. With these understandings in place, it is then possible to conduct experimental investigations using flow loop devices to validate the results.

1.2. Research Objectives

The main objectives of this thesis are listed as following.

Objective 1: Provide repeatable experimental testings on the impact of suspended solid particles on the drilling fluids' rheological properties and describe the impact using available models.

Objective 2: The third objective is to better understand the influence of various operational parameters on the rheological properties of drilling fluids, including using various types of drilling fluids and solid particle sizes.

Objective 3: Based on the understanding of the impact of solid particles on drilling fluids' rheological properties, analyze the changes in the hole cleaning performance parameters and suggest a reasonable limit of solid volumetric fractions for HDD operations within similar geological conditions.

1.3. Methodology

A comprehensive literature review of previous studies related to the impact of suspended solid particles on the fluids' rheological properties, as well as the available indicators of drilling fluids' hole cleaning performance was conducted, in order to improve the understanding in these areas. The standardized sample preparation and testing procedures proposed by Chateau (2008) was employed in this thesis to analyze the impact of suspended solids on drilling fluids' rheological properties. Local industrial sands were used to represent drilled cuttings in fine sand formations, and samples of drilling fluids were prepared using pure bentonite powders and commercial HDD drilling fluid mixtures. The sand volumetric fractions were varied from 0-50% with a step size of 5%.

The impact of solid volumetric fractions on the drilling fluids' rheological properties was analyzed, and used as inputs to calculate various hole cleaning performance parameters. Based on the findings, a maximum threshold of 30-35% of solid volumetric fractions was proposed for HDD operations within fine sand formations.

1.4. Outline of Thesis

This thesis has the following structure:

Chapter 1: Introduction

A background review of the research topic, objectives and methodology was presented, as well as an outline of the thesis structure.

Chapter 2: Literature review

This chapter briefly introduced the available studies related to the impact of solid particles on the suspending fluids' rheological properties, as well as the available parameters to evaluate the drilling fluids' hole cleaning performances.

Chapter 3: Rheological impact of drilled cuttings on HDD drilling fluids

This chapter presents the experimental results of rheological testing on the mixtures of sand particles suspended in both pure bentonite dispersions and commercial HDD drilling fluids with various solid volumetric fractions. The test results were compared with previous studies. Local industrial sands were selected to represent the drilling cuttings from fine sand formations. The effect of solid particle sizes was also discussed.

Chapter 4: Impact of suspended solid cuttings on hole cleaning performance parameters

The impact of solid volumetric fractions on the hole cleaning performance parameters was calculated and discussed. The drilling fluids' hole cleaning performances were evaluated based on 2 categories: the cutting carrying capacity and the sweeping capacity. Based on the results, a suggested threshold for solid volumetric fractions of 30-35% was proposed for HDD drilling operations, and this value was compared with commonly accepted practices in the HDD industry.

Chapter 5: Summary and conclusions

This chapter presents the conclusions of this thesis, and suggested future research was also discussed.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

2.1.1. Trenchless Technology Overview

Trenchless technology can be defined as a large family of technologies and techniques to install or renovate underground conduits without extensive surface excavation (Kramer, 2012). It experienced rapid development during the last decades with the rising demand for quality development of underground utility systems with minimum neighbourhood disturbance. Urbanization has created complex underground utilities systems, and the underground space is getting more and more congested, therefore the cost of maintenance and expansions becomes significantly higher, and conventional open excavation constructions methods are often impractical, especially within urbanized city centers (Kramer, 2012). In these situations, trenchless technology offers a valuable alternative.

Trenchless technology includes many different options to address various challenges. Some of the most well-known techniques include micro-trenching, microtunneling, cured-in-place pipe (CIPP), pipe bursting, horizontal directional drilling (HDD), and many other available technologies (Malligan, 2001).

2.1.2. Different Categories of HDD

2.1.2.1. Mini-HDD operations

This type of HDD operations is often referred to as “guided boring”, and is suitable to place conduits at relatively shallow depths for a short distance, for example the local distribution lines (Slavin, 2009). The product pipe diameter is often restricted within 2-12 inches, and sometimes the project can be constructed without drilling fluid circulation (Gierczak, 2014). In general, mini-HDD projects are less complex in nature, and can be completed within weeks and without extensive engineering design (Gierczak, 2014).

2.1.2.2. Midi-HDD operations

This type of HDD operations are often classified as the product pipe diameters between 12 to 24 inches (Gierczak, 2014). This type of HDD operation is generally suitable for installing pipeline systems for power, telecommunication and gas distribution applications (Slavin, 2009). With the current demand for fiber technologies and smart cities, it can be expected that Midi-HDD to gain popularity and momentum in the coming years.

2.1.2.3. Maxi-HDD operations

This type of HDD project is considered to be the most challenging and complex among these 2 categories. Maxi-HDD is suitable for installing product pipes larger than 24 in, at greater depth and significantly longer length, and are often selected for unfavorable surface conditions, such as large river crossings (Gierczak, 2014). Maxi-HDD projects rely heavily on drilling fluid circulations in order to transport drilled soil out of the borehole in order to maintain a clean conduit to facilitate drilling and pipe placing operations. Poor hole cleaning performances in HDD projects can result in significant cost overrun and schedule delays, in addition to potential environmental impacts, including hydrofracture situations when an undesirable surface return of drilling fluids is observed (Kennedy, 2006). As a result, the drilling fluid and its circulation plan has to be carefully planned, in order to achieve optimal hole cleaning results without causing excessively high borehole fluid pressures.

2.2. Stages of HDD operations

HDD operations can generally be divided into 4 different stages, which include the site investigation and design stage, pilot hole drilling stage, back-reaming stage and the product pile pulling stage (Jariwala, 2013). Among these stages, the pilot hole drilling stage is often considered to be the most risky, as this process is carried out within a small borehole with uncertain geological conditions (Kennedy, 2006). In order to prevent hydrofracture situations from occurring, the annular fluid pressure has to be controlled below the formation's maximum allowable pressure (Rostami, 2015). This requires the drilling fluid to transport sufficient amounts of cuttings out of the borehole at a limited flow rate in order to prevent the formation of the cutting bed, which will further limit the available annular cross section area for fluid flow. In order to plan for a quality hole cleaning process, the rheological properties and drilling fluids and parameters related to hole cleaning performances must be well understood. Extensive research has been conducted in the oil and gas industry and they could provide valuable insights for research in the HDD industry.

2.3. Hole-cleaning Performance Parameters

It was found that drilling fluids' rheological properties have the highest impact on hole cleaning performances, and can also be relatively easily controlled in the field operations (Deng, 2018). Other factors include drill pipe eccentricity, hole size and hole angle, mud weight, rate of penetration, drill pipe rotation, hole cleaning pills, cutting size and cutting density (Deng, 2018). As a result, how the drilling fluids will behave under operational situations becomes especially important.

The rheological properties of drilling fluids are not only useful to predict the borehole pressure profile during desktop studies, but also an important indicator of the current condition of the drilling fluid throughout the HDD operations (Rostami, 2015). The operators will take samples of the drilling fluids and run a series of measurements, including the mud weight and the Marsh funnel viscosities, periodically during the drilling and reaming process, and adjust the amount of additives added to maintain desirable rheological properties of the drilling fluid (Gowida, 2019). However, the presence of impurities, possible intrusion of ground water and variations in rheological measurement techniques from operator to operator may lead to significant uncertainties and differences in rheological measurement results (Gowida, 2019; Maxey, 2006). Therefore, a comprehensive method to evaluate the impact of cuttings on the drilling fluid, and thus to predict the theological properties of cutting-loaded drilling fluids based on the properties of freshly prepared drilling fluids, will be of great importance in order to plan for an efficient fluid circulation strategy, and to achieve a more realistic prediction of the borehole pressure, instead of simply relying on assuming a constant rheology of freshly prepared drilling fluids through the HDD project, which is the commonly adopted method in the industry (Gowida, 2019).

Currently, research on the impact of suspended solid particles on the drilling fluids' rheological properties is still limited, and should be carefully investigated in order to improve project design and planning.

2.4. Rheological Models for Drilling Fluids

The most commonly used rheological models to describe the shear stress-shear rate relationship of drilling fluids include the Herschel-Bulkley model, the Bingham plastic model and the power law model (Pang, 2018). However, among these three models, the Herschel-Bulkley model was found to be the most suitable model for drilling fluids, because it incorporates both a term for yield stress and another for shear-thinning behavior, due to the fact that water-based drilling fluids, especially those prepared with bentonite or polymers as the main viscosifiers, exhibit a non-Newtonian, shear thinning behavior (Moyers-Gonzales, 2009).

Newtonian fluids are a type of fluids that can be described with a constant viscosity, which is independent of the shear rate applied to the fluid, when other conditions (e.g. temperature) remain constant (Chhabra, 2010). Pure water is a common example of Newtonian fluids.

The Newtonian fluids' shear stress-shear rate response can be simply described using the Equation 1:

$$\tau = \eta\gamma \qquad [1]$$

where τ is the shear stress, η is the viscosity and γ is the shear rate.

On the other hand, non-Newtonian fluids are those fluids whose viscosities are not independent of the shear rate, and thus requires a more complex model to characterize their rheological properties. As previously discussed, water-based drilling fluids used in HDD usually exhibit shear-thinning and yield stress behavior, which means that their fluid viscosities will decrease as the shear rate increases. In this case, the Herschel-Bulkley model can be selected to accurately describe the drilling fluids' rheological properties, as shown in Equation 2:

$$\tau = \tau_0 + K\gamma^n \qquad [2]$$

where τ_0 is the yield stress, K is the consistency index, n is the flow behavior index, τ is the shear stress and γ is the shear rate.

As can be seen from the Equation 2, the Herschel-Bulkley equation is more complex to use, because it involves 3 parameters, instead of the single viscosity parameter for Newtonian fluids.

The Bingham plastic model is another popular choice to describe drilling fluids' rheological properties, especially in the construction field (Rostami, 2015). It is often the preferred method for field application because it only involves two parameters, and can be readily measured using a standard viscometer with only two readings at different shear rates (Rostami, 2015). However, the Bingham plastic model is not as accurate as the Herschel-Bulkley model for common HDD drilling fluids and thus is not accurate enough for the purpose of precise project design (Rostami, 2015).

The Bingham plastic model can be described using the Equation 3:

$$\tau = YP + PV\,\gamma \qquad [3]$$

where YP is the Bingham Plastic yield point and PV is the plastic viscosity.

The third model, which is the power law model, was not considered in this thesis, because it lacks a parameter to indicate the common HDD drilling fluids' yield stress, which is a critical parameter for drilling fluids' rheological characterization and hole cleaning performance evaluation (Deng, 2018; Pang, 2018).

The model can be described using the Equation 4:

$$\tau = K\gamma^{n} \qquad [4]$$

where K is the consistency index, n is the flow behavior index, τ is the shear stress and γ is the shear rate.

By comparing Equation 4 with Equation 2, it can be seen that the yield stress term is not considered. Due to the fact that drilling fluids used in HDD operations typically exhibits a relatively large yields stress, the power law model is often not suitable for describing the drilling fluids' rheological properties (Pang, 2018).

In summary, the Herschel-Bulkley model is the most accurate method to describe drilling fluids' rheological properties, but it involves three different parameters, namely the yield stress, the consistency index and the flow behavior index, and thus is relatively complicated for field applications. The Bingham plastic model describes drilling fluids' rheological properties with only two parameters by assuming a linear relationship between the shear stress and shear rates, and thus is easier to use in field applications but at the cost of reduced accuracy, for common drilling fluids used in HDD. The power law model will not be considered in this paper because it does not consider the yield stress, which is a critical parameter when evaluating drilling fluids' hole cleaning performances.

2.5. The Impact of Solids on Newtonian Fluids' Rheological Properties

The phenomenon of solid-loaded liquid flow is abundant in both natural and industrial settings, including mud flows, landslides, concrete placement and pharmaceutical processing. Previous studies concluded that under typical HDD operational conditions of low shear rates, the cutting particles experience forces including friction, collision and hydrodynamic forces (Ancey, 2001). The relative importance of these forces depend on the suspension's solid volumetric fractions. At low solid volumetric fractions, collision between solid particles are unlikely to occur and thus the fluid flow can be classified as collision-free flow. When the solid volumetric fraction is increased, the solid particles will collide with each other, resulting in a collision-dominated flow. At even higher solid volumetric fractions, the solid particles will also experience frictional interactions with each other and the container's wall, and because this frictional interactions are much stronger than collisional forces, the flow becomes friction-dominated flow and experience very high stresses when the fluid is under shear (Iguchi, 2014; Vidyapati, 2012).

Einstein developed one of the first analytical solution for hydrodynamic forces surrounding a spherical particle, and derived a simple equation for predicting the rheological properties of dilute suspensions, as shown in Equation 5:

$$\eta_r = 1 + B\phi \quad [5]$$

where η_r is the relative viscosity of the suspension, ϕ is the solid volumetric fraction, and B is the intrinsic viscosity, with a value of 2.5 for spherical particles (Einstein, 1906). This simple yet powerful equation is applicable to solid volumetric fractions of less than 10% (Aguilera, 1999).

The relative viscosity of the suspension is determined by Equation 6:

$$\eta_r = \eta/\eta_s \quad [6]$$

where η is the viscosity of the mixture of the solid particles and the suspending fluid, and η_s is the viscosity of the suspending fluid (without solid particles).

Vand further expanded the work by considering particle-particle interactions, which was not included in Einstein's studies, and derived the analytical equation (Vand, 1948) in the form of Equation 7:

$$\eta_r = 1 + B\phi + B_1\phi^2 + \cdots \quad [7]$$

However, experimental results concluded that Equation 7 is only applicable for suspensions with solid volumetric fractions under 25% (Mueller, 2009).

Maron and Pierce further expanded the research by considering the rhombohedral close packing of spheres, which is determined by finding the maximum possible solid volumetric fraction within suspensions, and proposed the Equation 8:

$$\eta_r = [\,1 - (\phi \,/\, \phi_m)\,]^{-2} \quad [8]$$

where ϕ_m is the maximum volume fraction, determined from the close packing of spheres, as the relative viscosity of the suspension approaches infinity (Mueller, 2009; Zhou, 1995).

Finally, the well-known empirical Krieger-Dougherty equation was developed, which shared a very similar form, as shown in Equation 9:

$$\eta_r = [\, 1 - (\phi \,/\, \phi_m)\,]^{-B\phi_m} \qquad [9]$$

As can be seen by comparing Equation 8 with Equation 9, it can be found that the term $B\phi_m$ is equal to 2. Overall, the Krieger-Dougherty equation indicates that increasing solid volumetric fractions will increase the relative viscosity of the suspension, and the value will approach infinity when the solid volumetric fraction approaches infinity, which agreed well with experimental findings (Ancey, 2001).

2.6. The Impact of Solids on non-Newtonian Fluids' Rheological Properties

Current research related to the impact of solids on non-Newtonian fluids' rheological properties is still limited. As previously discussed, the rheological properties of drilling fluids can be most accurately described by the Herschel-Bulkley rheology model using three different parameters, which makes the analysis even more complex (Chateau, 2008; Mahaut, 2008).

Some researchers followed an approach to apply existing models for Newtonian fluids, e.g. the Krieger-Dougherty equation, to describe the behavior of Herschel-Bulkley fluids containing suspended solid cuttings. Erdogan, for example, concluded that the relationship between the dimensionless yield stress, which is the ratio between the mixture's yield stress and the pure suspending fluid's yield stress, and the solid volumetric fractions can be fitted well with the Krieger-Dougherty equation, based on experimental analyses on aggregated in concrete suspensions (Erdogan, 2005).

Furthermore, Chateau concluded that the mixture of solid particles within Herschel-Bulkley fluids can have their rheological properties accurately described by the Herschel-Bulkley equation with a flow behavior index equal to the suspending fluid (Chateau, 2008). Chateau also confirmed that the dimensionless consistency index, which is the ratio between the consistency index of the suspension mixture and the pure fluid, fitted well with the Krieger-Dougherty equation (Chateau, 2008). However, researchers still cannot find a comprehensive model to accurately describe the impact of solid volumetric fractions on all three parameters of the Herschel-Bulkley equation (Ovarlez, 2015). Further research is still required in order to understand the exact interactions involved in solid-loaded fluid flow, and the influence of additional factors, such as solid particle size distributions, solid particle shapes and complex suspending fluid systems (e.g. bentonite dispersions with biopolymers), still requires further research and investigations (Ovarlez, 2015; Mahaut, 2008; Chateau, 2008).

In this thesis, the impact of drilled cuttings on the rheological properties of various drilling fluids used in the HDD industry will be investigated, and the influence on the hole cleaning parameters will be calculated and discussed. Further details on the current research findings related to these topics will be presented in subsequent chapters.

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Chapter 3: IMPACTS OF CUTTINGS ON RHEOLOGICAL PROPERTY OF HORIZONTAL DIRECTIONAL DRILLING FLUIDS

3.1. Introduction

3.1.1. Background

Trenchless technology is a term used to refer to a group of methods to install new or rehabilitate existing underground infrastructure without open excavation between the product endpoints (Milligan, 2001). Significant cost reduction can be achieved by utilizing trenchless technology, through the reduction of surface reclamation costs, labor costs, and urban traffic congestion, as well as improving stakeholder relations and providing easier access to new utility customers (Thomson, 1987).

Horizontal directional drilling (HDD) is a rapidly expanding trenchless method used to install underground petroleum and utility pipelines when facing surface or operational obstacles (Wang, 2017). The operational stages of a HDD project include site investigation and detailed design, drilling a pilot hole using a steerable drill bit, hole enlargement through back-reaming, and, finally, installation of the final product pipe, known as pullback (Jariwala, 2013). During the drilling and back-reaming processes, drilling fluid is continually pumped through the drill bit back through the borehole, carrying drilled cuttings with it. At the surface, the drilling fluid is treated, which includes solid removal, fluid property reconditioning and fluid replacement (Baumert, 2005).

While HDD has many of the advantages associated with trenchless methods, including less surface disruption and labor costs, it is also vital to manage risk, as for any project. A study on over 200 HDD projects in western Canada identified that a significant portion of these risks are associated with drilling fluid and/or solids control (Osbak, 2012). For example, if there is an underestimation of the drilling fluid circulation pressure, or the hole cleaning result is poor, the required fluid circulation pressure may exceed the strength limit of the surrounding formation, and it could result in a hydrofracture, which is an inadvertent fluid return to the surface. This can cause severe harm to adjacent infrastructure, reducing drilling efficiency and causing environmental damages (Kennedy, 2006).

Drilling fluid is a vital factor in determining the success or failure of an HDD project. Some major functions of drilling fluids in HDD include cutting suspension and transportation, as well as lubrication and supporting borehole stability (Shu, 2015). As a result, the properties of drilling fluids used in HDD should be carefully designed and modelled to prevent detrimental situations from occurring. These adverse situations include high annular pressure, stuck pipes or hydrofractures, all of which have negative impacts on project cost and schedule.

The rheology of the drilling fluid is a key parameter used to predict borehole pressure profiles during the design phase. It is also used in the field as an indicator of the condition of the drilling fluid (Rostami, 2015). When the properties of the drilling fluid are being planned for a project, or the properties of freshly prepared drilling fluid are being measured, its rheological characteristics are often clearly established. However, in practice, the rheological properties of the drilling fluid are usually measured only twice a day, in contrast to mud weight and Marsh funnel viscosity, which are measured periodically, i.e. every 15 to 20 minutes during drilling (Gowida, 2019). Furthermore, significant differences in rheology measurement techniques exist from operator to operator and can lead to uncertainty in field measurements of drilling fluid rheology (Maxey, 2006). Therefore, a large gap of understanding exists between the rheology of fresh drilling fluid and cutting-loaded, or deteriorated drilling fluid. Thus, it is vital to establish the connection between these two situations and investigate the impact of cuttings on the rheology of the suspending drilling fluid. This will result in better management of the fluid circulation plan, as well as contributing to a more realistic prediction of borehole pressure, resulting in a substantial improvement over the simplified approach of assuming a constant rheology based on measurements of freshly prepared drilling fluids, which is commonly adopted by the industry (Gowida, 2019).

3.1.2. The Impact of Suspended Solids on Fluid Rheology

There is an abundance of examples of solid-loaded liquid suspensions in both the natural (e.g. mudflows and landslides) and industrial (e.g. pharmaceutical, concrete and drilling) settings. However, despite the importance of understanding the behaviour of such systems, an accurate model to predict the rheological properties of a fluid with suspended solids present does not exist. This is especially the case for drilling fluids, which are usually a complex system of components with various physical and chemical properties and particle sizes, including bentonite, water, polymer and other additives (Baumert, 2005).

The most widely used substrate for HDD drilling fluid is a mixture of bentonite and water. In the case of bentonite suspended in water, the bentonite behaves as a system of colloidal particles, with particle sizes ranging from nanometers to micrometers. The colloidal particles will not spontaneously settle under the influence of gravity, and is difficult to be removed by filtration (Lafuma, 1996; Lee, 2019). On the other hand, the cuttings, which include material such as sand particles, are not colloidal and will eventually settle, both due to their larger particle size and higher specific gravity.

Under typical operational HDD conditions (i.e. relatively low shear rates), the behavior of the finest particles is usually dominated by Brownian motion effects or colloidal forces, but larger cutting particles will be mainly influenced by gravitational, frictional, collision or hydrodynamic forces (Ancey, 2001). The relative importance of these forces depends on the volumetric fractions of the solids within the suspension. These can be divided into three different categories from the perspective of particle-particle interactions. The three categories, listed in order of increasing volumetric fraction of solids, are collision-free flow, collision-dominated flow, and contact- or friction-dominated flow (Iguchi, 2014). When solid particles are added to fluids and become suspended, the solid particles will experience collisional and frictional interactions with each other and the borehole wall, and, as a result, create additional stresses when the suspension is under shear (Vidyapati, 2012). When the solid volumetric fraction is low, solid particles occupy only a limited portion of the suspension: thus, the probability of particle collision and friction is relatively low and the impact of the solids on the suspension rheology is also low. As the solid volumetric fraction increases, the probability of particle collision becomes higher, and the impact on suspension rheology is more observable. When the solid volumetric fraction is further increased, solid particles occupy a significant portion of the suspension, and the bulk behavior of the mixture is influenced by both the collisional and frictional interactions, thus the impact on suspension rheology increases drastically (Iguchi, 2014; Vidyapati, 2012; Ancey, 2001).

Therefore, the bulk properties of solid suspensions are a very complex function of a variety of factors, including (1) properties of the solids (i.e. volumetric fraction, particle shape and size, as well as particle size distribution), (2) rheological properties of the suspending fluid, and (3) overall system properties (i.e. preparation method and temperature) (Ancey, 2001). However, a predictive constitutive model to describe both the collisional and frictional interactions between the solid particles within a suspension is still lacking, and much research has focused on treating the mixture of solid particles and suspending fluids as a whole and measuring the overall rheology of the mixture under shear stresses (Mueller, 2009).

In this paper, the scope of investigation will be limited to the influence of sand particles, which are chemically inert, for simplification. Further research will be conducted on the impact of reactive components, e.g. clay particles.

3.1.3. The Impact of Solids on the Rheology of Newtonian Fluids

Newtonian fluids are a group of fluids that can be characterized by a viscosity (the ratio of shear stress and shear rate) independent of the shear rate (Chhabra, 2010). A simple Newtonian fluid model can be described by Equation 1:

$$\tau = \eta\gamma \tag{1}$$

where τ is the shear stress, η is the viscosity and γ is the shear rate.

Most previous research has focused on modelling solid particles suspended in Newtonian fluids, e.g. water. Einstein developed a model for estimating the rheology of dilute suspensions of rigid spheres with the same particle size (i.e. monodisperse spherical particles) by deriving an analytical solution for the hydrodynamic forces surrounding a sphere, the result is shown in Equation 2:

$$\eta_r = 1 + B\phi \tag{2}$$

where η_r is the relative viscosity of the suspension, ϕ is the solid volumetric fraction, and B is the intrinsic viscosity, with a value of 2.5 for spherical particles (Einstein, 1906). The relative viscosity of the suspension is determined by Equation 3:

$$\eta_r = \eta/\eta_s \tag{3}$$

where η is the viscosity of the mixture of the solid particles and the suspending fluid, and η_s is the viscosity of the suspending fluid (without solid particles). This is a rather simple equation; however, the assumption holds only for dilute suspensions: typically, the solid volumetric fraction should be lower than 10% (Aguilera, 1999).

Further development includes the work of Vand, who also considered particle-particle interactions (which were neglected by Einstein) and derived the following analytical solution in the form of (Vand, 1948) Equation 4.

$$\eta_r = 1 + B\phi + B_1\phi^2 + \cdots \tag{4}$$

However, by comparison with experimental results, it was found that this equation is only suitable for semi-dilute suspensions, where the solid volume fraction is lower than approximately 25% (Muller, 2009).

Maron and Pierce incorporated another factor, the rhombohedral close packing of spheres, in their empirical suspension viscosity model based on experimental findings (Maron, 1956), as in Equation 5. From this model,

$$\eta_r = [\, 1 - (\phi \,/\, \phi_m)\,]^{-2} \qquad [5]$$

where ϕ_m is the maximum volume fraction, determined from the close packing of spheres, as the relative viscosity of the suspension approaches infinity (Zhou, 1995).

The well-known empirical Krieger-Dougherty equation (Equation 6) also shares a very similar form. However, it includes both the intrinsic viscosity and the rhombohedral close packing terms as curve fitting parameters, and was considered to be one of the most successful models to fit experimental data (Krieger, 1959; Mueller, 2009).

$$\eta_r = [\, 1 - (\phi \,/\, \phi_m)\,]^{-B\phi_m} \qquad [6]$$

By comparing Equations 5 and 6, it is evident that the term $B\phi_m$ is equal to 2. The value for the maximum close packing of polydisperse particles (i.e. particles with different particle sizes) is higher than that for monodisperse particles (Laskowski, 2013). This is because smaller particles tend to fit in the voids between larger particles, thus increasing the highest possible total solid volumetric fraction. For random close packing of monodisperse rigid spheres, numerical simulation results indicate that the maximum packing density is 0.64 (Rintoul, 1998). However, in experimental settings, the maximum packing density is reported to be dependent on shear forces (Wildemuth, 1984). This is because under conditions of high shear, particle orientation is optimized. In this case, particle migration results in smaller particles fitting in the voids more efficiently in polydisperse suspensions, effectively increasing the maximum limit of particle packing density (Wildemuth, 1984).

3.1.4. The Impact of Solids on the Rheology of Non-Newtonian Fluids

The viscosities of non-Newtonian fluids are not independent of shear rate, and thus require a more complex model to describe their rheology. Most drilling fluids used in HDD, including bentonite-based drilling fluids, exhibit yield stress, as well as shear-thinning behavior when an increasing yield stress is applied (Moyers-Gonzalez, 2009). In this case, the Herschel-Bulkley (H-B) model (Equation 7) can be used to accurately describe fluid rheology (Pang, 2018):

$$\tau = \tau_0 + K\gamma^n \qquad [7]$$

where τ_0 is the yield stress, K is the consistency index, n is the flow behavior index, τ is the shear stress and γ is the shear rate.

Unlike Newtonian fluids where the impact of suspended solid particles can be described as a function of the relative viscosity of the mixture, all three parameters of the Herschel-Bulkley model should be considered when analyzing the impact of solid particles on the rheology of drilling fluids used in HDD. Due to its complexity, the study of the impact of suspended solid particles on the mixture's bulk rheology is very limited (Mahaut, 2008). For example, Ancey focused on suspensions of sand and glass particles within a clay dispersion, and experimentally showed that adding solid particles generally results in an increasingly marked enhancement of the yield stress of a suspension (Ancey, 2001). Another important experimental observation is that when the solid volumetric fraction exceeds approximately 50% of the maximum solid concentration (i.e. over 30%-35%

volumetric fraction), the solid particles had a pronounced and increasing impact on the yield stress of the mixture, and ultimately the yield stress approached infinity for solid concentrations near the maximum packing density (Ancey, 2001).

Some researchers have attempted to apply existing models applicable to Newtonian fluids – e.g., the Krieger-Dougherty equation – to describe the bulk behavior of a mixture of solid particles suspended in a non-Newtonian fluid. For example, on the basis of experiments conducted by using a mixture of glass beads in a solution containing bentonite, Mahaut concluded that the relationship between the elastic modulus of the mixture and the volumetric fraction of solids could be described accurately using the Krieger-Dougherty equation (Mahaut, 2008).

Erdogan analyzed the bulk rheology of aggregates in concrete suspensions, and concluded that the relationship between the dimensionless consistency index (the ratio between the consistency index of the suspension mixture and the pure suspending fluid) and the solid volumetric fraction of aggregates in concrete suspensions fits well with the Krieger-Dougherty equation (Erdogan, 2005).

Chateau analyzed experimental data from the literature and proposed a new model to predict the impact of suspended solid particles on the yield stress and consistency index of Herschel-Bulkley fluids (Chateau, 2008). Chateau concluded that the dimensionless yield stress (the ratio between the yield stress of the mixture and the pure suspending fluid) and the dimensionless consistency index fit with the K-D equation with reasonable accuracy (Chateau, 2008). The dimensionless yield stress and dimensionless consistency index are given in Equations 8 and 9,

$$\tau_N = \tau_M / \tau_F \quad [8]$$

$$K_N = K_M / K_F \quad [9]$$

where τ_N is the dimensionless yield stress, τ_M is the yield stress of the mixture of solid particles and the suspending fluid, and τ_F is the yield stress of the pure suspending fluid; K_N is the dimensionless consistency index, K_M is the consistency index of the mixture of solid particles and the suspending fluid, and K_F is the consistency index of the pure suspending fluid.

Chateau (2008) also concluded that for suspending fluids that fit the Herschel-Bulkley model, the rheology of suspensions of solid particles could be satisfactorily modeled as for a Herschel-Bulkley fluid with a flow behavior index equal to the suspending fluid. This important observation was incorporated into the current work, and the data analysis in this work was done based on the assumption of a constant flow behavior index. However, it should be noted that the yield stress data that Chateau adopted was measured by imposing a very small rotational velocity on a vane rheometer after the suspension sample was in its at-rest state (zero stress) for 100 seconds (Mahaut, 2008; Chateau, 2008). As a result, the static yield stress was being measured, instead of the dynamic yield stress. By definition, the static yield stress is measured when flow is initiated, typically using the method discussed above, whereas the dynamic yield stress is often measured based on a shear stress-shear rate curve (i.e. a rheogram) extrapolated to zero shear rate (Cheng, 1986). For thixotropic fluids, including bentonite dispersions, where the yield stress increases with the sample resting period, the static yield stress could be considerably high compared to the dynamic yield stress. In addition, the static yield stress is usually very unstable, and extremely sensitive to slight disturbance and preparation methods (Mahaut, 2008; Cheng, 1986).

A recent paper by Ovarlez reviewed the model proposed by Chateau and concluded that it predicts the static yield stress of suspensions of solid particles in Herschel-Bulkley fluids with reasonable accuracy, but fails to predict the dynamic yield stress by curve fitting the rheograms with the Herschel-Bulkley model (Ovarlez, 2015). The author of the review also suggested that they were unable to compare the dynamic yield stress values to any other properties of the Herschel-Bulkley fluids tested in his experiments, including bentonite dispersions, and thus were unable to predict the value of the dynamic yield stress of the suspensions (Ovarlez, 2015).

Similarly, the rheology of drilling fluids used in HDD can also be described using the Bingham plastic model, and is in fact very commonly used to predict annular pressure in HDD operations due to its simplicity of measurement (Rostami, 2015). However, the Bingham plastic model is not as accurate as the Herschel-Bulkley model, and provides a very conservative estimate when measured at 2 shear rates at high shear rate ranges of 300-600 rpm, and thus may not lead to an accurate value for hydraulic design calculations (Rostami, 2015).

The Bingham plastic (BP) model can be described by the following equation:

$$\tau = YP + PV\,\gamma \qquad [10]$$

where YP is the Bingham Plastic yield point and PV is the plastic viscosity.

There are practical limitations related to static yield stress measurements: for instance, a very sensitive rheometer is required, along with the need for repeatable measurements with complex sample preparation methods. This is the case for both measurements in the laboratory or at HDD project sites. To overcome this, in the current work the rheograms of suspensions of solid particles for a pure bentonite dispersion and a commercial HDD drilling fluid are obtained, with volumetric fractions of solids ranging from 0% to 50%, to analyze the impact of solid particles (i.e. cuttings) on the drilling fluids used in HDD. In this way, a more realistic prediction of borehole fluid pressure can be obtained, instead of assuming a constant rheology, as measured on freshly prepared drilling fluid, throughout the entire drilling process. By doing so, an optimized fluid-to-solid ratio can be planned for during HDD operations.

3.2. Methodology

3.2.1. Material

Experiments were conducted on suspensions of industrial sands with different particle sizes in bentonite dispersions and commercial HDD drilling fluids as analogues of cutting-loaded drilling fluids. Local sands were sourced from Sil Industrial Minerals, Edmonton, AB (Canada) and the measured grain density was 2675 kg/m^3. The sand particles were washed thoroughly with deionized water five times to remove residual impurities, then dried and passed through a series of sieves to obtain sand with different particle sizes. The washing step was critical in obtaining reproducible results.

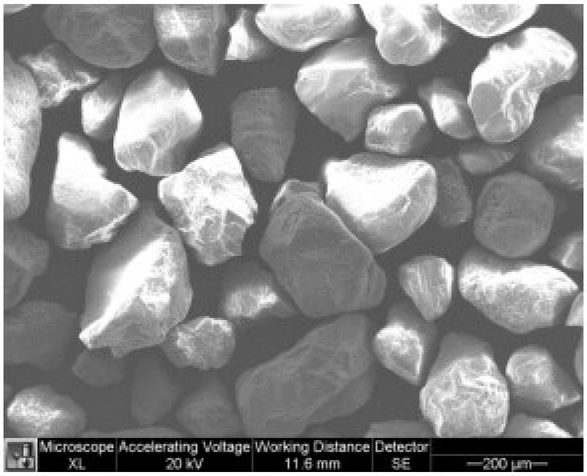

Figure 1. SEM image of Sil-1 sand particles (Sarker, 2016).

The pure bentonite powder used in this experiment was manufactured by Baroid Industrial Drilling Products, according to the requirements of American Petroleum Institute (API) Specification 13A, Section 9. The bentonite used is a gray, dry-powdered clay without any polymer additives. Extra High Yield Commercial HDD Drilling Fluid (Wyo-Ben), referred to as "commercial HDD drilling fluid" throughout this paper, was also used to represent the actual HDD drilling muds used at HDD project sites. This is a light tan, odorless dry powder, and is composed of Wyoming bentonite with polymer additives for enhanced yield stress.

Pure bentonite powder was dried in an oven at 90°C for 24 hours, then covered and cooled to room temperature. After this, dry bentonite powder (5% by weight) was dispersed into de-ionized water using a 3-spindle Hamilton Beach Commercial Mixer (Figure 2) to create a suspending drilling fluid. After mixing, air bubbles were removed from the samples by manual stirring and vacuum degassing. Samples were then allowed to cool to room temperature (22°C) for 1.5 hours, and used immediately after preparation.

The same steps were used to prepare sample using the commercial HDD drilling fluid; however, the concentration used was 3% by weight, in accordance with the suggested application concentration.

Figure 2. The 3-spindle Hamilton Beach Commercial Mixer.

After the suspended fluid samples were prepared, sand particles were weighed and added to the fluid samples according to the desired volumetric percentage, ranging from 0% to 50%. The limit of 50% was determined because reproducible samples were not obtained at higher solid volumetric fractions, possibly due to the inevitable presence of air in the samples, similar to issues reported in previous literature (Mahaut, 2008). Each mixture of suspending fluid and sand particles was mixed using a 3-spindle commercial mixer at low shear, alternating with manual stirring to prevent any temperature rise and shear-induced particle migration at high shear rates (Leighton, 1987). A syringe was then used to carefully remove air bubbles and transfer 16.8 mL of the mixture into a Brookfield RST-SST Rheometer (Figure 3) for analysis.

Figure 3. The Brookfield RST-SST Rheometer.

The Brookfield RST-SST Rheometer utilizes a CCT-25 spindle with an MBT-25 chamber to form coaxial cylinder geometry for obtaining the rheograms. Samples were allowed to rest for a period of 30 seconds to control the degree of thixotropy. A sample volume of 16.8 mL was required to perform the rheology tests. The shear rates were set to span 5 sec^{-1} to 1000 sec^{-1}, with 10 evenly spaced data points recorded within this range. The time steps between measurements were controlled to ensure stable readings, and the recorded shear stress readings were stored in the rheometer and then exported to Excel and OriginLab for further analysis. During the measurements, the temperature was controlled at 22°C, which was confirmed by readings using a built-in platinum thermometer.

For each sample combination, trials were conducted for four different time steps (30, 50, 100 and 200 s) and repeated 5 times to ensure data reproductivity. The time between measurements is critical and should be long enough for the shear induced flow to stabilize but short enough to prevent any solid settlement due to gravity. If the time between measurements is too small, a typical rheogram would show a straight line without any shear-thinning observations, and if the time between measurements is too large, the rheogram would indicate extremely high shear stresses after a few data points. This is possibly due to the fact that the solid particles have settled and the shear stress was generated from the particle-particle friction within a densely packed particle bed.

The following Table 1 summarizes the testing parameters for the materials used in the experiments.

Table 1. Basic properties and parameters of drilling fluid samples

	Pure Bentonite Dispersion	**Commercial HDD Drilling Fluid**
Base Fluid Concentration (wt.%)	5	3
Base Fluid Density (g/mL)	1.038	1.025
Sand Volumetric Fraction (%)	0%-50%	0%-50%
Sand Particle Size Range (μm)	80-160, 160-315	160-315
Temperature (°C)	22	22
Sample Volume (mL)	16.8	16.8
Sample Resting Time (s)	30	30

3.3. Results

3.3.1. Properties of the suspending base fluid

3.3.1.1. Bentonite Dispersion, 5%

A rheogram for a dispersion of 5% bentonite was also fitted using the Herschel-Bulkley model with excellent accuracy, as shown in Figure 4. This solution exhibits a relatively small dynamic yield stress of 5.967 Pa at a concentration of 5%, and a moderate shear thinning behavior with a flow behavior index of 0.701. Table 2 summarizes the Herschel-Bulkley model parameters for this suspending base fluid:

Table 2. Herschel-Bulkley parameters for 5% bentonite dispersion

Herschel-Bulkley Parameters	Curve Fitting Results
Yield Stress, τ_0 (Pa)	5.967
Consistency Index, K (Pa·s^n)	0.085
Flow Behaviour Index, n	0.701
R^2	0.997

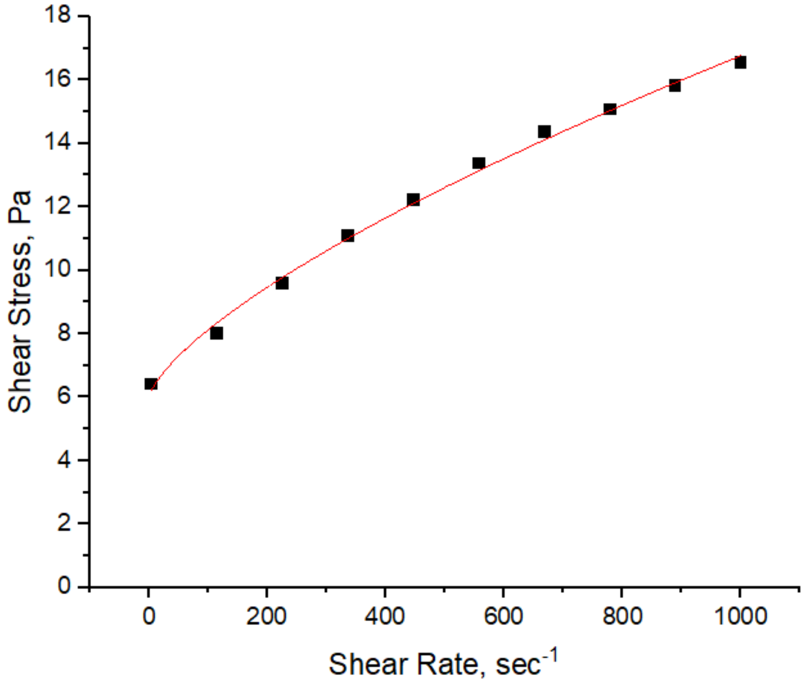

Figure 4. Rheogram of 5% bentonite dispersion fitted with Herschel-Bulkley model.

Similarly, the rheology of a 5% dispersion of pure bentonite can also be described using the Bingham plastic model with reasonable accuracy, with a yield point of 7.168 Pa and a plastic viscosity of 0.010 Pa·s, as shown in Figure 5. Table 3 summarizes the Bingham plastic model parameters for the 5% bentonite dispersion.

Table 3. Bingham plastic model parameters for 5% bentonite dispersion

Bingham Plastic Model Parameters	**Curve Fitting Results**
YP (Pa)	7.168
PV (Pa·s)	0.010
R^2	0.977

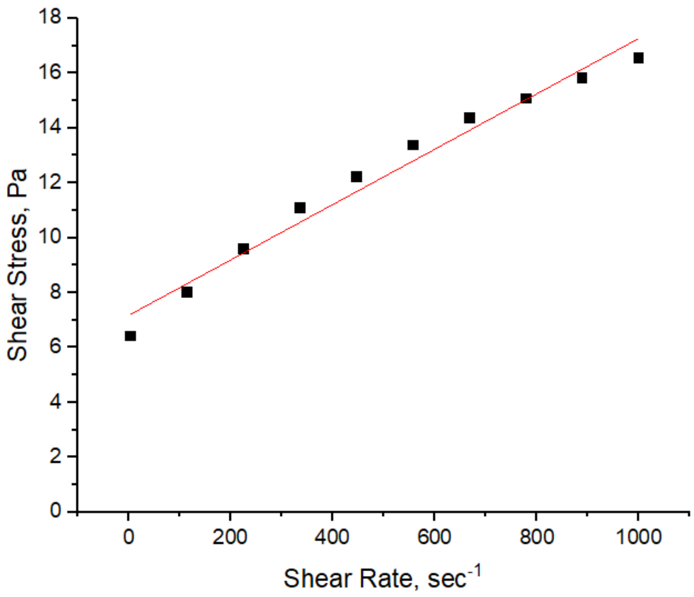

Figure 5. Rheogram of 5% bentonite dispersion fitted with the Bingham plastic rheology model.

3.3.1.2. Commercial HDD drilling fluid, 3%

The rheogram of the commercial HDD drilling fluid, as shown in Figure 6, can be accurately described using the Herschel-Bulkley rheology model. This fluid exhibits a large dynamic yield stress of 12.453 Pa at a concentration of only 3%, and a strong shear thinning behavior, with a flow behavior index of 0.630. Table 4 summarizes the Herschel-Bulkley model parameters for this suspending base fluid:

Table 4.Herschel-Bulkley model parameters for the 3% commercial HDD drilling fluid

Herschel-Bulkley Parameters	Curve Fitting Results
Yield Stress, τ_0 (Pa)	12.453
Consistency Index, K (Pa·s^n)	0.194
Flow Behaviour Index, n	0.630
R^2	0.997

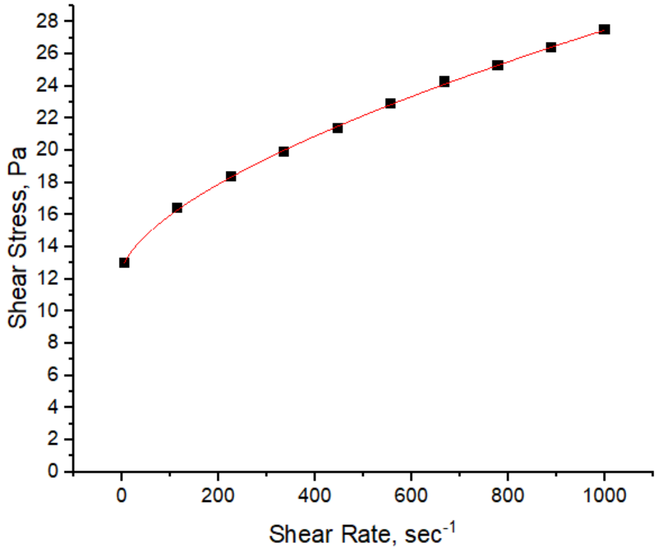

Figure 6. Rheogram for 3% commercial HDD drilling fluid fitted using the Herschel-Bulkley model

The rheology of the pure commercial HDD drilling fluid can also be described with the Bingham plastic model, as in Figure 7. In this paper, the entire shear rate range was included for model fitting for improved accuracy, instead of selecting only two data points, similar to the approach utilized by Rostami (Rostami, 2016). The commercial HDD drilling fluid exbibits a Bingham plastic yield point of 14.660 Pa and a plastic viscosity of 0.014 Pa·s. The Bingham plastic model parameters for this suspending base fluid are summarized in Table 5.

Table 5. Bingham plastic model parameters for 3% commercial HDD drilling fluid

Bingham Plastic Model Parameters	Curve Fitting Results
YP (Pa)	14.660
PV (Pa·s)	0.014
R^2	0.970

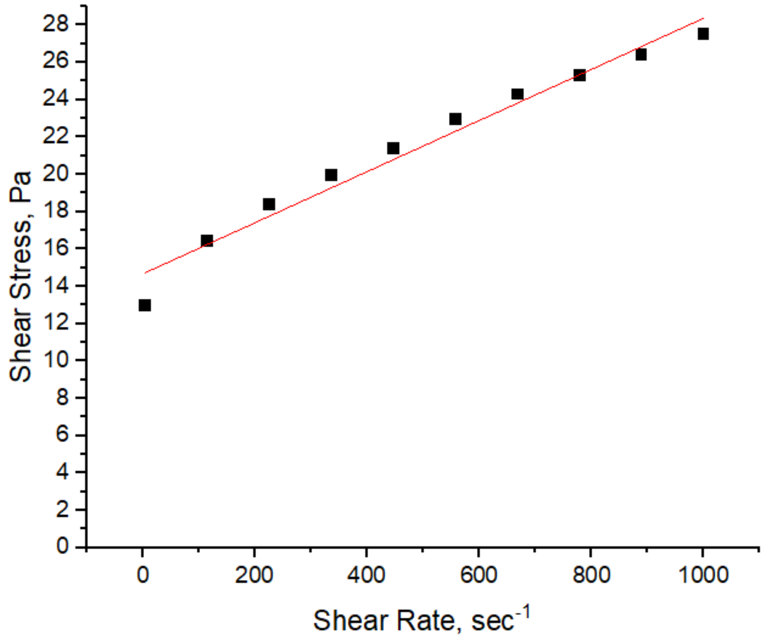

Figure 7. Rheogram of 3% commercial HDD drilling fluid fitted using Bingham plastic model.

3.3.2. Effect of sand volumetric fraction on the rheology of 5% pure bentonite dispersion

Upon adding sand particles to the 5% bentonite , a slight change in the suspension rheology was observed for low solid fractions. However, this effect was more pronounced when the solid volumetric fraction exceeded 25%. As the volumetric fraction of solid approached 50%, the mixture became very thick and resembled a soft-solid paste instead of a free-flowing fluid. Extensive manual mixing was required because the commercial mixer failed to thoroughly mix the suspension. Instead, it was observed to only mix a limited portion of the suspension, right around the mixing blades. At even higher solid volumetric fractions, reproducible results were not obtained, and the rheometer could not provide sufficient torque. As a result, the upper range of the volumetric fraction of solids studied was limited to 50% in this paper, as shown in Figure 8 below.

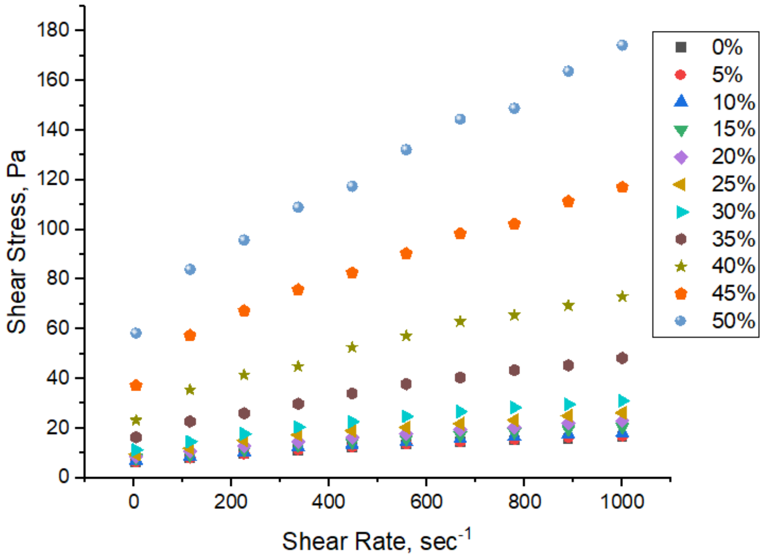

Figure 8. Rheogram for 5% bentonite dispersion with addition of sand particles to achieve solid volumetric fraction from 0 to 50%.

Based on the findings of Chateau that the Herschel-Bulkley model with a constant flow behavior index is best suited for describing the impact of suspended solid particles on the fluid rheology, the rheology data will be fitted accordingly, which in this case is the flow behavior index, n of 0.701.

Table 6 summarizes the detailed Herschel-Bulkley model fitting parameters for the bentonite dispersion containing sand particles (particle size range of 160-315 µm and solid volumetric fraction range of 0-50%).

Table 6.Herschel-Bulkley model parameters for the mixture of sand and 5% pure bentonite dispersion

Solid Volumetric Fraction	$\boldsymbol{\tau_0}$ **(Pa)**	$\boldsymbol{K}$ **(Pa·s^n)**	**n**	$\boldsymbol{\tau_N}$	$\boldsymbol{K_N}$
0%	5.967	0.085	0.701	1.000	1.000
5%	6.054	0.089	0.701	1.014	1.045
10%	6.519	0.095	0.701	1.093	1.110
15%	6.943	0.107	0.701	1.163	1.252
20%	7.721	0.121	0.701	1.294	1.417
25%	8.824	0.138	0.701	1.479	1.617
30%	10.550	0.166	0.701	1.768	1.941
35%	15.156	0.262	0.701	2.540	3.074
40%	23.060	0.402	0.701	3.864	4.709
45%	37.980	0.636	0.701	6.365	7.335
50%	55.330	0.918	0.701	9.273	10.752

The dimensionless consistency index can be satisfactorily fitted using the Krieger-Dougherty equation, with 0.624 for the value of ϕ_m, 2.372 for the value of B, and a R^2 value of 0.980.

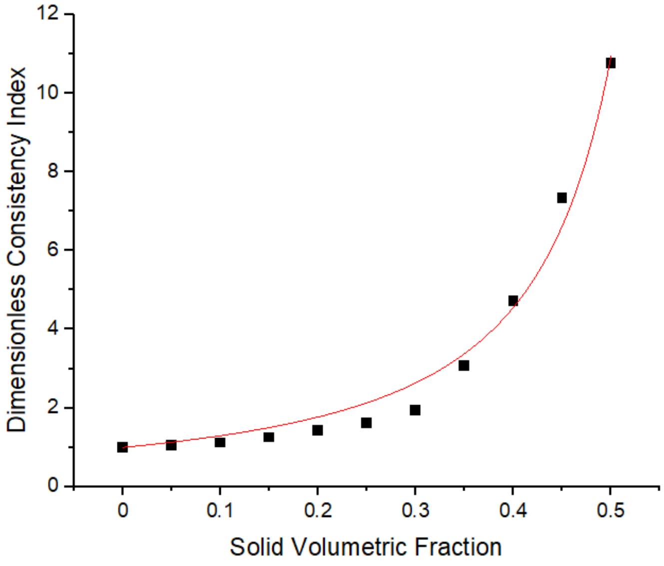

Figure 9. The impact of sand particles on the dimensionless consistency index of the mixture.

The dimensionless dynamic yield stress was also able to fit the Krieger-Dougherty equation, with 0.624 for the value of ϕ_m, 2.204 for the value of B, and a R^2 value of 0.980. The value for ϕ_m was held constant for both of the dimensionless values because it represents the maximum rhombohedral close packing of the solid particles.

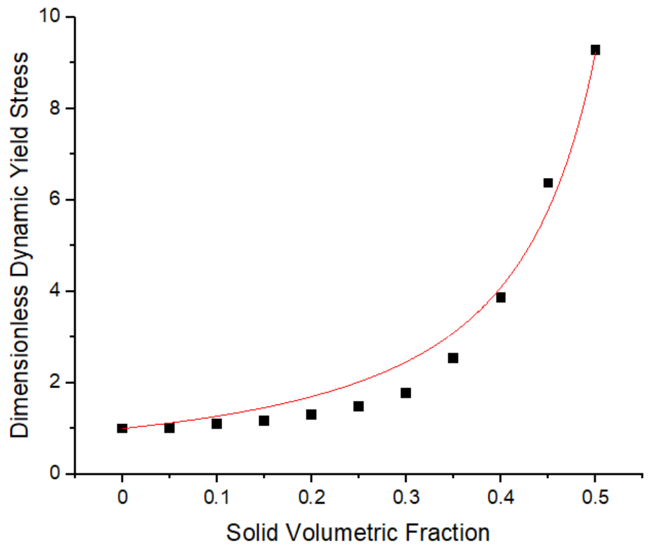

Figure 10. The impact of sand particles on the dimensionless dynamic yield stress of the mixture.

Based on the figures above, it can be seen that the value of the dimensionless consistency index and the dimensionless dynamic yield shared a very similar trend.

Despite the similarity between the expressions of both the dimensionless dynamic yield stress and the dimensionless consistency index, the author was unable to establish the relationship between these two values, similar to the observation of Ovarlez (Ovarlez, 2015).

If the Bingham plastic rheology model is selected instead of the Herschel-Bulkley model, then the following fitting parameters, shown in Table 7, can be obtained.

Table 7.Bingham plastic model parameters for the mixture of sand particles and 5% bentonite dispersion

Solid Volumetric Fraction	YP (Pa)	PV (Pa*sec)	YP_N	PV_N
0%	7.168	0.010	1.000	1.000
5%	7.309	0.011	1.020	1.045
10%	7.845	0.011	1.095	1.111
15%	8.391	0.013	1.171	1.262
20%	9.372	0.014	1.308	1.427
25%	10.756	0.016	1.501	1.619
30%	12.888	0.020	1.798	1.940
35%	18.801	0.031	2.623	3.082
40%	28.780	0.047	4.015	4.695
45%	46.924	0.074	6.547	7.306
50%	68.014	0.109	9.489	10.794

Where YP_N is the dimensionless Bingham plastic yield point and PV_N is the dimensionless plastic viscosity, defined below:

$$YP_N = YP_M \,/\, YP \tag{11}$$

$$PV_N = PV_M \,/\, PVK_F \tag{12}$$

Where YP_M is the Bingham Plastic Yield Point of the mixture of solid particles and the suspending fluid, and YP_F is the Bingham Plastic Yield Point of the pure suspending fluid; and PV_N is the plastic viscosity of the mixture of solid particles and the suspending fluid, PV_M is the plastic viscosity of the pure suspending fluid.

Similarly, the dimensionless Bingham Plastic yield point and the dimensionless plastic viscosity values were fitting using the Krieger-Dougherty equation. The value for $\phi_m$was held constant for both of the dimensionless values because it represents the maximum rhombohedral close packing of the solid particles.

The dimensionless Bingham Plastic yield point was had 0.624 for the value of ϕ_m, 2.233 for the value of B, and a R^2 value of 0.97.

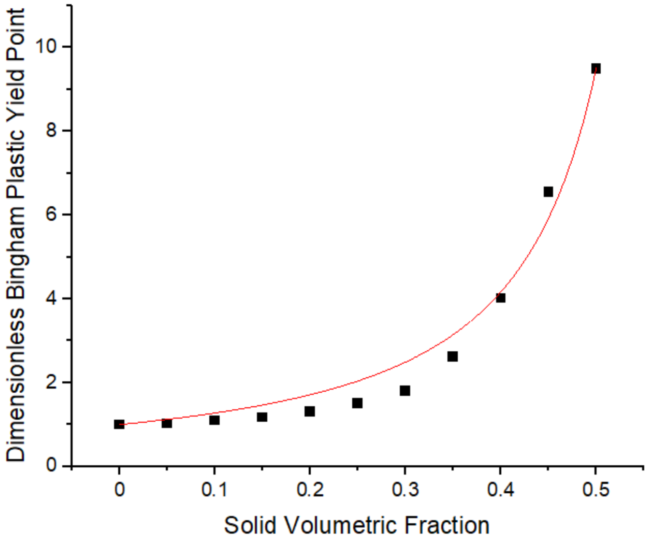

Figure 11. The impact of sand particles on the dimensionless Bingham plastic yield point of the mixture.

The dimensionless plastic viscosity had 0.624 for the value of ϕ_m, 2.374 for the value of B, and a R^2 value of 0.98.

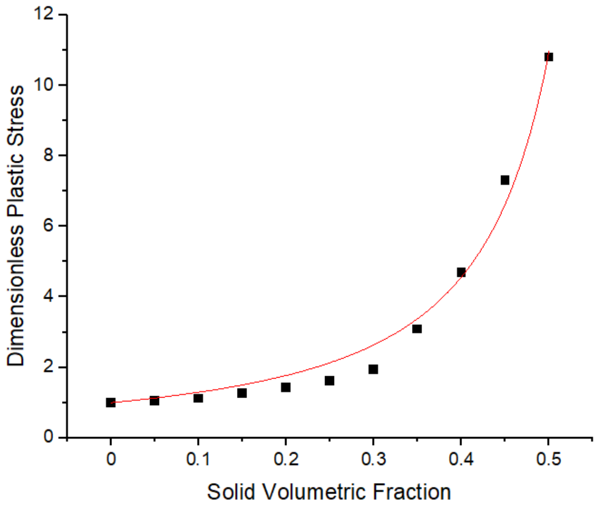

Figure 12. The impact of sand particles on the dimensionless plastic viscosity of the mixture.

3.3.3. Effect of sand volumetric fraction on the rheology of 3% pure commercial HDD drilling fluid

Testing with the 3% commercial HDD drilling fluid presents additional challenges. First of all, because this commercial product is a mixture of bentonite and polymers, the resulting dispersion could be considered as a mixture of bentonite dispersion and polymer dispersion, and each constituting component will have different properties, e.g. yield stress and consistency index. In the work of both Mahaut and Chateau, the suspending fluid's Herschel-Bulkley properties (i.e. yield stress, shear thinning behavior) was generated by one single component, e.g. Carbopol or bentonite (Mahaut 2008, Chateau, 2008). They did not consider the situation when the Herschel-Bulkley fluids are prepared using a mixture of chemicals, and thus their observations may not be perfectly valid for the case of the commercial HDD drilling fluid. In addition, it was observed that the 3%

commercial HDD drilling fluids tends to capture higher amount of air bubbles during mixing, thus extreme care should be taken to generate reproducible results.

Exactly the same procedures are applied to the 3% commercial HDD drilling fluid samples, and the results will be summarized below, with very similar observations.

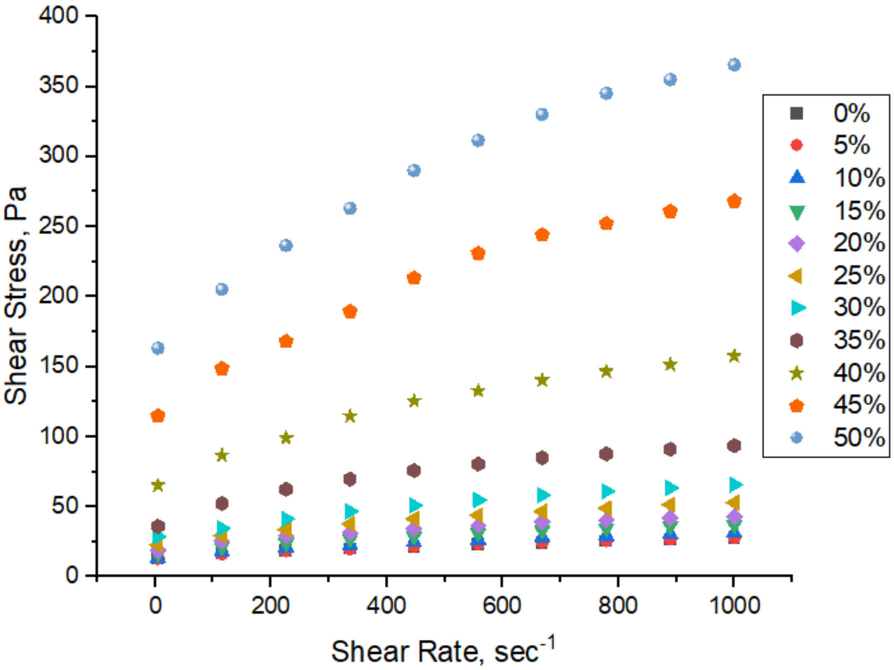

Figure 13. The rheogram of the mixture of sand particles and 3% commercial HDD drilling fluid.

Based on the findings of Chateau, the rheology data will be fitting using the Herschel-Bulkley model based on the assumption of a constant flow behavior index, which is 0.630 in this case.

The following Table 8 summarizes the detailed Herschel-Bulkley model fitting parameters for the mixture of sand particles (Particle Size Range: 160-315 μm; Solid Volumetric Fraction Range: 0-50%) and 3% commercial HDD drilling fluid.

Table 8.Herschel-Bulkley model parameters for the mixture of sand particles and 5% bentonite dispersion

Solid Volumetric Fraction	τ_0 (Pa)	K (Pa*s^n)	n	τ_N	K_N
0%	12.453	0.194	0.630	1.000	1.000
5%	12.495	0.204	0.630	1.003	1.050
10%	13.491	0.237	0.630	1.083	1.222
15%	15.752	0.281	0.630	1.265	1.447
20%	18.651	0.327	0.630	1.498	1.686
25%	21.417	0.414	0.630	1.720	2.136
30%	26.174	0.520	0.630	2.102	2.685
35%	37.486	0.767	0.630	3.01	3.957
40%	62.998	1.258	0.630	5.059	6.492
45%	107.939	2.159	0.630	8.668	11.139
50%	153.808	2.833	0.630	12.351	14.617

The dimensionless consistency index can be satisfactorily fitted using the Krieger-Dougherty equation, with 0.633 for the value of ϕ_m, 2.789 for the value of B, and a R^2 value of 0.97.

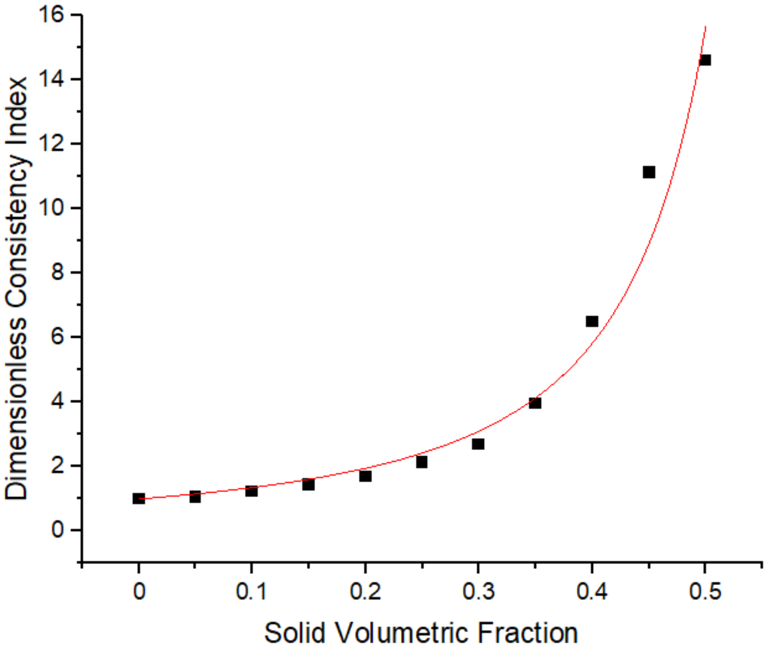

Figure 14. The impact of sand particles on the dimensionless consistency index of the mixture.

The dimensionless dynamic yield stress was also able to fit the Krieger-Dougherty equation, with 0.633 for the value of ϕ_m, 2.571 for the value of B, and a R^2 value of 0.98. The value for ϕ_m was held constant for both of the dimensionless values because it represents the maximum rhombohedral close packing of the solid particles.

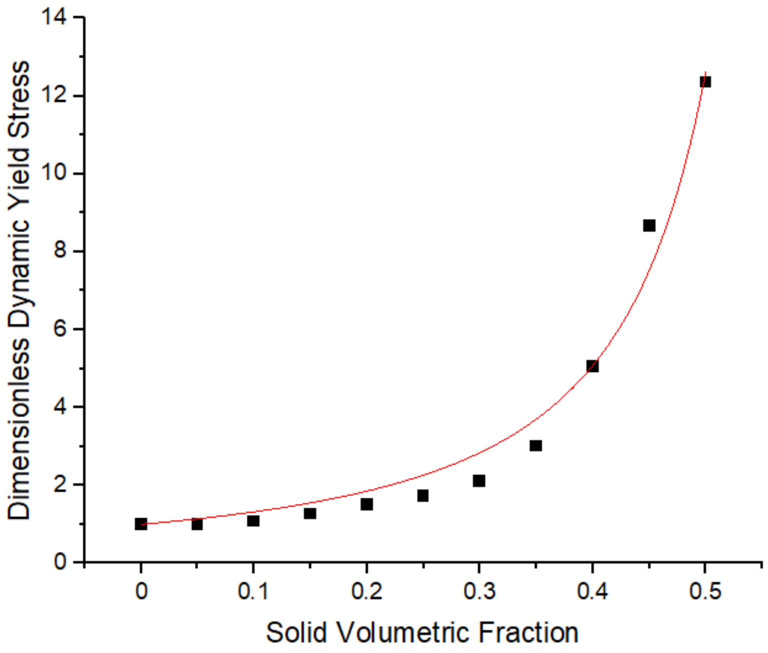

Figure 15. The impact of sand particles on the dimensionless dynamic yield stress of the mixture.

Compared with the mixture of sand with 5% pure bentonite dispersion, it can be seen that both the dimensionless dynamic yield stress and dimensionless consistency index are more significantly impacted by the suspended solid particles in the 3% commercial HDD drilling fluid.

If the Bingham plastic rheology model is selected instead of the Herschel-Bulkley model, then the following fitting parameters can be obtained, as shown in Table 9.

Table 9.Bingham plastic model parameters for the mixture of sand and 3% commercial HDD drilling fluid

Solid Volumetric Fraction	YP (Pa)	PV (Pa*sec)	YP_N	PV_N
0%	14.660	0.014	1.000	1.000
5%	14.818	0.014	1.011	1.050
10%	16.260	0.017	1.109	1.212
15%	18.973	0.020	1.294	1.443
20%	22.494	0.023	1.534	1.668
25%	26.168	0.029	1.785	2.130
30%	32.073	0.037	2.188	2.689
35%	46.803	0.053	3.193	3.872
40%	77.717	0.088	5.301	6.436
45%	132.864	0.152	9.063	11.090
50%	186.431	0.199	12.717	14.564

Similarly, the dimensionless Bingham plastic yield point and the dimensionless plastic viscosity values were fitting using the Krieger-Dougherty equation. The value for $\phi_m$was held constant for both of the dimensionless values because it represents the maximum rhombohedral close packing of the solid particles.

The dimensionless Bingham Plastic yield point was had 0.633 for the value of ϕ_m, 2.610 for the value of B, and a R^2 value of 0.98, as shown in Figure 16.

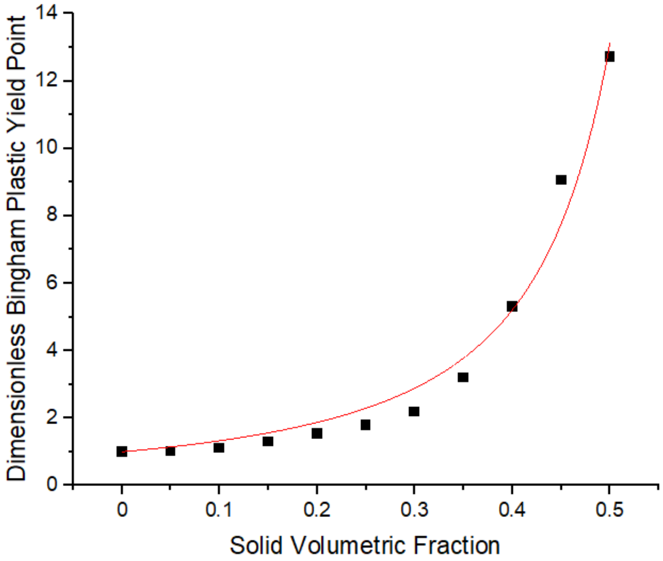

Figure 16. The impact of sand particles on the dimensionless Bingham Plastic yield point of the mixture.

The dimensionless plastic viscosity had 0.633 for the value of ϕ_m, 2.784 for the value of B, and a R^2 value of 0.97.

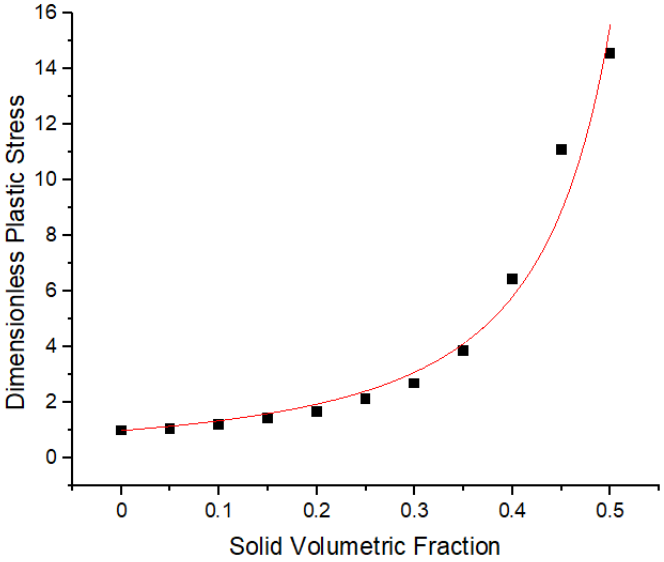

Figure 17. The impact of sand particles on the dimensionless plastic viscosity of the mixture.

3.3.4. Effect of particle sizes on the rheology of 5% pure bentonite dispersion

The testing and analyzing processes were repeated for sand particles with different size distribution ranges, and very similar results were obtained, indicating that within the ranges of particle sizes tested, the size of solid particles did not have a significant impact on its influence of the suspension's rheology, which is consistent with the observations of Mahaut and Chateau (Mahaut, 2008; Chateau, 2008). The results are summarized in the Figure 17 and Figure 18 below.

The dimensionless consistency index for both sand particle size ranges can be fitted well with the Krieger-Dougherty equation, with 0.624 for the value of ϕ_m, 2.372 for the value of B, and a R^2 value of 0.98.

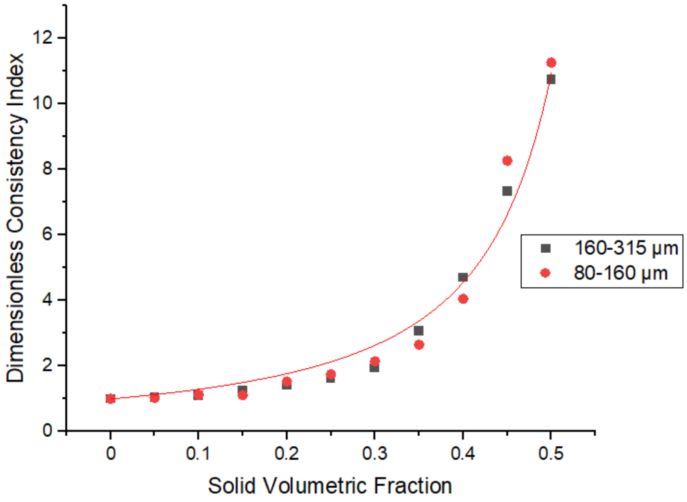

Figure 18. The impact of sand particles on the dimensionless consistency index of the mixture.

The dimensionless consistency index for both sand particle size ranges can be fitted well with the Krieger-Dougherty equation, with 0.624 for the value of ϕ_m, 2.213 for the value of B, and a R^2 value of 0.98.

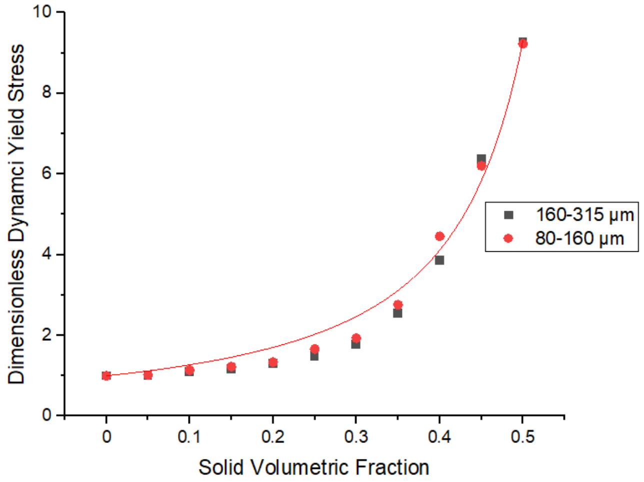

Figure 19. The impact of sand particles on the dimensionless dynamic yield stress of the mixture.

3.4. Discussion

3.4.1. Selection of rheology models

It can be seen that both the Herschel-Bulkley model and Bingham plastic model can be used to describe the rheology of pure or solid-loaded suspending fluids commonly used in HDD. Herschel-Bulkley model has superior accuracy, especially in the low shear rate regions, typically encountered in HDD operations, and thus was deemed more suitable for rheology analysis, despite the limitations of relative complexity (Rostami, 2015).

If the Herschel-Bulkley rheology model is selected, it was shown that the flow behavior index can be assumed to be constant for pure suspending drilling fluids and mixture of solids particles, within the range of solid volumetric fraction being testes (i.e. 0-50%), this finding is consistent with Chateau (Chateau, 2008).

3.4.2. The impact of solid volumetric fractions on suspension rheology

In this paper, the solid particles tested are local industrial sands, with a sphericity of 56.6. The particle size ranges were controlled to be either 80-160 μm or 160-315 μm. As a result, these particles are neither perfectly spherical nor monodisperse, in contrast to the glass beads which are commonly selected in other papers (Mahaut, 2008; Tsai, 1989; Chan, 1984). However, given the fact that the particle size range is still relatively small, observations are still consistent with the findings of Chateau and Ovarlez (Chateau, 2008; Ovarlez, 2015). Research involving wider particle size ranges are still limited, and can be a potential topic for future research.

In addition, the impact of solid volumetric fractions on the suspension's dynamic yield stress, instead of static yield stress, was investigated. It can be seen that both the dimensionless dynamic yield stress and the dimensionless consistency index of the mixture of solid particles and suspending fluid could be described using the Krieger-Dougherty equation, with reasonable accuracy. In addition, the value of ϕ_m can be assumed constant for both dimensionless values, allowing a certain degree of convenience in applying the models.

The theoretical value for ϕ_m was reported to be 0.64 based on numerical simulation of monodisperse particles of perfect spheres, and the theoretical value for B is 2.5 (Rintoul, 1998; Einstein, 1906). The experimental findings of this paper agreed well with these theoretical values, despite the fact that the solid particles used are neither perfectly spherical nor monodisperse.

By comparing the impact of solid volumetric fractions on both the dimensionless dynamic yield stress and the dimensionless consistency index, even though both values could be accurately modelled by the Krieger-Dougherty equation, the exact relationship between these 2 parameters remains unclear.

3.4.3. Recommended fluid-to-soil ration for HDD in fine sand formations

Based on the experimental findings, it was found that the increasing solid volumetric fractions will have an increasingly marked enhancement of the mixture's dynamic yield stress and the consistency index. Similar observation applies to the Bingham Plastic rheology model as well. Based on experimental results, this effects becomes more profound when the solid volumetric fraction exceeds approximately 30-35%, which is consistent with the findings of Ancey (Ancey, 2001). This solid volumetric fraction threshold agrees with the HDD industry's experience-based practice of maintaining a fluid-to-soil ration of 2:1 to 3:1 within fine sand formations (Vroom, 2018).

3.5. Conclusions

This paper introduces a new approach to describe the mixture of solid particles and suspending fluids commonly used in HDD. It was found that both the dimensionless dynamic yield stress and the dimensionless consistency index can be fitted well using the Krieger-Dougherty equation, while maintaining a constant flow behavior index, for solid volumetric ranges below 50%. It was found that the solid volumetric fraction has an increasing effect on the mixture's rheology, especially when the solid volumetric fraction exceeds 30-35%. A similar approach can also be applied to the commonly used Bingham Plastic model, and the values for ϕ_m and B are close to the theoretical values of 0.64 and 2.5 in all cases, despite the fact that the solid particles are neither perfectly spherical nor monodisperse. However, the exact relationship between the dynamic yield stress and the consistency index remains unclear at this point. The impact of particle sizes was not significant at the particle size ranges tested in this paper.

It was concluded that the solid particles suspended in drilling fluids used in HDD could have a extremely strong impact on the mixture's rheology, and having excessively high solid volumetric fraction in the drilling fluid could result in significant increases in borehole fluid pressure. Based on the experimental data, the suggested fluid-to-soil ratio for HDD operations within fine sand formations was suggested to be from 2:1 to 3:1.

3.6. Reference

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Chapter 4: IMPACT OF VOLUMETRIC FRACTION OF CUTTINGS ON HOLE CLEANING PERFORMANCE OF DRILLING FLUIDS DURING HORIZONTAL DIRECTIONAL DRILLING

4.1. Introduction

4.1.1. Background

Trenchless technology is a term that describes various methods to install or rehabilitate underground utilities or pipelines without the surface disruption commonly associated with conventional excavation processes (Ali, 2007). Trenchless methods are valuable tools to maintain or renew underground utility and pipeline systems, especially for urban zones or areas with surface obstacles, such as river crossings.

A study by the Federation of Canadian Municipalities indicated that 55% of Canadian sewer infrastructure does not meet current standards, despite the fact that Canadian municipalities spend \$12-\$15 billion on these systems every year (Allouche, 2003; NRC, 2002). The need for an effective and cost-efficient method to address these challenges is urgent, and HDD is one available tool that has been demonstrated to have the potential to minimize risks and reduce overall costs of construction within an urban environment (Woodroffe, 2008). HDD is especially effective for sites with existing infrastructure, congested underground utilities and other social costs such as high demand for traffic or business needs, due to the ability to install pipelines without creating open cut trenches on the surface (Leuke, 2005; Woodroffe, 2008).

HDD operations consist of the following stages: constructing entry and exit pits, drilling the pilot bore, back reaming, and product pipe pulling (Woodroffe, 2008). Among these stages, drilling the pilot bore was found to have the highest risk, due to the fact that pilot bore is drilled with a smaller diameter within a formation where the exact soil properties involve a high degree of uncertainty, and if the drilling fluid pressure surpasses the maximum allowable pressure, hydrofracture could occur (Rostami, 2015).

Hydrofracture is a situation involving unwanted or inadvertent fluid return to the surface, which can result in significant project delays and cost overruns, and is a major concern for regulatory and permitting agencies. It has thus limited the application of HDD within environmentally sensitive areas (Bennett, 2008). As a result, both the maximum allowable pressure of the underground formation and the minimum required drilling fluid pressure should be carefully estimated in order to minimize the risks associated with hydrofracture events from arising. There are well established methods to evaluate the maximum allowable pressure for different geological conditions, including the cavity expansion model for HDD in soil and the tensile strength model for HDD in rock (Bennett, 2008). However, current research on the minimum required fluid pressure is still limited, especially for fluid behavior under the influence of suspended solid cuttings and the resulting impact on the fluid pressure within HDD boreholes (Benett, 2008). Recent work has found that when solid particles are suspended within drilling fluid, the overall rheology of the mixture strongly depends on the volumetric fraction of solids; however, the impact of changes in fluid rheology on annular frictional pressure loss and the hole cleaning performance of the drilling fluid remains to be investigated (Su, 2020).

4.1.2. Hole Cleaning Performance of Drilling Fluids

Hole cleaning performance is a vital factor that determines the success or failure of an HDD project, and poor hole cleaning results in significant risks. For example, research by Osbak (2012) found that tripping to clean the borehole had the highest frequency of occurrence of HDD risk events identified in the analysis of over 200 projects. Moreover, stuck product lines had the greatest impact on the project schedule, and both of these situations are directly related to poor hole cleaning (Osbak, 2012). Other costly operational problems associated with poor cleaning include hydrofracture, as discussed above, as well as high drag forces acting on drill pipes and blockage of annular spaces (Pilehvari, 1999). It is therefore critical to predict and evaluate the hole cleaning performance of drilling fluid prior to commencement of an HDD project.

Hole cleaning performance has been extensively studied in the petroleum industry, and could provide valuable insights for HDD design considerations. This is despite the fact that hole cleaning in HDD is more challenging because of the maximum allowable pressure of the formation, lower fluid velocity and more shallow borehole (Deng, 2018). Adari (2000) has summarized a list of variables that could influence hole cleaning performance. There were two factors identified, namely flow rate and drilling fluid rheology, that have both high influence on hole cleaning performance and high controllability in the field, and thus are deemed to be the most important variables (Adari, 2000). It should be noted that the drilling fluid pressure in HDD operations is limited by the maximum allowable pressure of the soil formation. Furthermore, the drilling fluid pressure has two components: frictional pressure loss and hydrostatic pressure, of which the latter one depends on the bore path design and depth of the bore (ASTM 1962). As a result, this paper will focus on the use of frictional pressure loss to evaluate the hole cleaning performance of drilling fluid on the basis of a constant flow rate. The goal is to evaluate the hole cleaning performance of drilling fluid by analyzing a series of hydraulic and rheological parameters under the constraint of a limited range of frictional pressure loss, so that the total fluid pressure can be controlled and the risk of hydrofracture is minimized.

4.1.3. Hydraulic and Rheological Parameters Important for Hole Cleaning Performance Analysis

First of all, the rheological properties of drilling fluids must be clearly described to better understand their behavior under different operational conditions. There are three models, namely the Bingham plastic model, the power law model and the Herschel-Bulkley model, which are commonly used in the industry to describe the rheology of drilling fluid (Deng, 2018). Of these three, the power law model was not included in this analysis due to the lack of consideration of yield stress, since yield stress is an important factor related to the cutting suspension abilities of the drilling fluid (Deng, 2018; Zakerian, 2018).

The Herschel-Bulkley model was more suitable to describe the rheology of the drilling fluid, because it captures the yield stress of the drilling fluid and its shear thinning properties at the same time (Davison, 1999). Using the Herschel-Bulkley model, the shear stress, , can be expressed using Equation 1,

$$\tau = \tau_0 + K\gamma^n \quad [1]$$

where τ_0 is the yield stress, K is the consistency index, n is the flow behavior index, and γ is the shear rate.

Shear thinning properties are observed in the majority of water-based drilling fluids, which contributes positively to efficient cutting transport, because this allows for higher drilling fluid flow rate at a given frictional pressure loss. This is in contrast to Newtonian fluids, because in this case the viscosity decreases when subjected to higher shear rates (Abdo, 2013).

The Bingham plastic model, on the other hand, captures the yield point of the drilling fluid, but does not consider the shear thinning behavior (Deng, 2018). In this case, the shear stress can be expressed by Equation 2,

$$\tau = YP + PV\gamma \qquad [2]$$

where YP is the Bingham plastic yield point and PV is the plastic viscosity.

In Chapter 3, based on experimental investigation, it was found that the suspended solid volumetric fraction has a more pronounced effect on the rheological properties of the drilling fluid as the solid volumetric fraction increases, especially when the solid volumetric fraction exceeded 30-35%. A constant flow behavior index, n, can be used to describe the rheological behaviour of both the pure drilling fluid and the mixture (Chateau, 2008).

The impact of the solid volumetric fraction on the rheological properties of the drilling fluid can be modelled using the Krieger-Dougherty equation, with values for the maximum rhombohedral close packing of the solid particles, ϕ_m, and the intrinsic viscosity, B, very close to the theoretical values of 0.64 and 2.5, respectively, as shown in Chapter 3.

The Krieger-Dougherty equation was first developed to describe the impact of solid volumetric fraction on the rheological behavior of Newtonian fluids, and was later found to also be applicable for Herschel-Bulkley fluids. The equation has the original form as given in Equation 3 (Krieger, 1959; Chateau, 2008):

$$\eta_r = [\, 1 - (\phi \,/\, \phi_m) \,]^{-B\phi_m} \qquad [3]$$

where η_r is the relative viscosity of the suspension, ϕ is the solid volumetric fraction, ϕ_m is the maximum close packing of spheres (representing the highest possible volume fraction of particles as the relative viscosity of the suspension approaches infinity), and B is the intrinsic viscosity of the suspending fluid.

In addition to these rheological parameters, Deng has suggested that the hole cleaning performance of the drilling fluid can be evaluated based on two components. These are the cutting carrying capacity, which can be best described by the annular plug width, and sweeping capacity, which can be described by the frictional pressure loss and the ratio of YP to PV (Deng, 2018).

The yield stress of a drilling fluid is an important measure of its cutting transportation abilities, especially when the circulation of fluid stops, and it also determines the plug width of the fluid flow (Khalil, 2011), which will be discussed below. On the other hand, excessive yield stress is undesirable, because it represents the minimum shear stress required to initiate fluid flow, and thus drilling fluid with a very high yield stress will require a large pump output in order to initiate and maintain fluid circulation (Khalil, 2011).

The plug width (h_p) is defined as the height of the unsheared plug region for fluid flow in the annular space (Zamora, 1993; Kelessidis, 2006). For the laminar flow of yield stress fluids in a conduit, there could be a rigid, unsheared region of the fluid's velocity profile where the local shear stress is smaller than the yield stress of the fluid (Zamora, 1993; Kelessidis, 2006; Deng, 2018). This plug width can be used as an indicator of the flatness of the velocity profile, and a larger plug width is beneficial for effective hole cleaning (Leising, 2002; Powell, 1991; Zamora, 1993). Some of the main mechanisms of the increased efficiency of hole cleaning include: the local shear rate in the plug region is close to zero, leading to a high local fluid viscosity which will help to suspend cuttings and prevent settlement; and suspended cuttings near the borehole wall will tend to migrate to the central unsheared region, where the velocity gradient is low (Leising, 2002; Powell, 1991; Zamora, 1993).

As previously discussed, the frictional pressure loss is a constraint imposed on the drilling fluid, in order to control annular pressure and minimize the risk of hydrofracture. At a given flow rate, a drilling fluid with a lower frictional pressure loss is deemed superior, because this means that the drilling fluid can be circulated at higher flow rates under the constraint of the maximum allowable pressure, and because the flow rate has the most significant impact on the hole cleaning performance, thus a higher efficiency in terms of cutting removal can be expected.

4.2. Methodology

This chapter builds on the experimental findings of Chapter 3, which focused on the impact of suspended solid cuttings on the rheology of drilling fluids used for HDD. In that chapter, the authors used local sands with different particle size ranges and added them to both a dispersion of 5% pure bentonite and a 3% extra high yield commercial HDD drilling fluid samples to analyze the impact of suspended sands on the rheological parameters of drilling fluids used in HDD. Table 1 summarized the basic properties of the materials selected for this paper.

Table 10. Properties and basic parameters of bentonite dispersion and commercial HDD drilling fluid samples

	Pure Bentonite Dispersion	Extra High Yield Commercial HDD Drilling Fluid
Base fluid concentration (wt %)	5	3
Base fluid density (g/mL)	1.038	1.025
Volumetric fraction of sand (%)	0%-50%	0%-50%
Particle size range of sand (μm)	160-315	160-315
Temperature (°C)	22	22
Sample Volume (mL)	16.8	16.8
Sample Resting Time (sec)	30	30

The rheological parameters obtained from experimental measurements were analyzed according to the methods and procedures outlined in API Recommended Practice 13D – Rheology and Hydraulics of Oil-well Drilling Fluids 2017 (API RP 13D 2017).

In this paper, a simplified model of the horizontal section of an HDD borehole was constructed. The basic operational parameters have been summarized in Table 2 and are similar to those used in a previous study on the effects of drilling fluid additives on hole cleaning performance for drilling fluids used in HDD (Deng, 2018).

Table 11. Operational parameters for simplified HDD borehole section

Borehole diameter (in)	12.25
Outside diameter of drill pipe (in)	5.5
Volumetric flow rate of drilling fluid (gal/min)	386

Following the equations and procedures suggested by API Recommended Practice 13D (API RP 13D 2017), the rheology and hydraulics properties of solid-loaded drilling fluids can be estimated and analyzed. The following section describes the results of a series of important parameters useful to understand the impact of suspended solid cuttings on the rheology of the drilling fluid and annular pressure loss.

4.3. Results

4.3.1. Average Annular Fluid Velocity

The average fluid velocity in the HDD borehole annulus is usually the first parameter to be determined when evaluating the rheology of drilling fluid and hole cleaning performance (Chen, 1972). The annular fluid velocity was found to have a significant impact on the hole cleaning performance during drilling operations, and it was also found that increasing flow velocity will always result in better hole cleaning performance (Luo 1988, Hussain, 1983). However, in HDD projects, increasing the annular fluid velocity is not always practical, because if the annular fluid pressure is excessively high, it could lead to hydrofracture, which poses significant risks to the surrounding environment and for the HDD project as a whole (Pilehvari, 1999).

The average fluid velocity in the annulus, V_a, can be calculated as in Equation 4 (API RP 13D 2017):

$$V_a = \frac{24.51Q}{(d_h^2 - d_p^2)} \quad [4]$$

where Q is the volumetric flow rate of the drilling fluid (386 gal/min), d_h is the hole diameter (12.25 in), and d_p is the outer diameter of the drill pipe (5.5 in). The resulting average fluid velocity in the borehole annulus for the given flow rate is therefore 78.964 ft/min. This value will be used as a basis to compare the frictional pressure loss of the drilling fluid in the HDD annulus, which will help to evaluate the sweeping capacity of the drilling fluid, as previously discussed.

4.3.2. Annular Hydraulic Diameter

The hydraulic diameter is an important factor used to predict annular pressure loss, and is thus critical to controlling borehole pressure during HDD (Scheid, 2011). The value of the annular hydraulic diameter is used to compute the Reynolds number, which indicates the nature of the fluid flow regime – i.e. laminar flow, transient flow or turbulent flow) (Gavrilakis, 1992).

The annular hydraulic diameter can be calculated as below (API RP 13D 2017):

$$d_{hyd} = d_h - d_p \quad [5]$$

where d_{hyd} is the hydraulic diameter, in this case 6.75 in.

4.3.3. Drilling Fluid Rheology

The drilling fluid's rheological property is a parameter that has both high influence on hole cleaning performance and high controllability in the field (Adari, 2000). The fluid rheological properties describes the resulting shear stress (τ) when a fluid is subject to a shear rate (γ), and is commonly modelled in the drilling industry using the Herschel-Bulkley equation and the Bingham plastic equation (Stickel, 2005), as discussed previously.

The main difference between these 2 models is that the Herschel-Bulkley equation incorporates a third parameter, n, to account for the fluid's shear thinning behavior, and is thus more accurate for modelling drilling fluids, e.g. bentonite dispersions (Kelessidis, 2006). The Bingham Plastic model, on the other hand, is simpler and more commonly used in the field to produce quick rheological analysis with limited experimental apparatus (Wang, 1999).

Tables 3 and 4 summarize the rheological parameters obtained for measurements of mixtures of sand particles of various volumetric fractions with two different drilling fluids, as discussed in Chapter 3.

4.3.3.1. Mixtures of Sand Particles and 5% Pure Bentonite

Table 12. Herschel-Bulkley model parameters for mixture of sand particles and 5% pure bentonite dispersion

Solid Volumetric Fraction	τ_M (Pa)	K (Pa·s^n)	n	τ_M (lb$_f$/100 ft^2)	K (lb$_f$·s^n/100 ft^2)
0%	5.967	0.085	0.701	12.462	0.1783
5%	6.054	0.089	0.701	12.644	0.186
10%	6.519	0.095	0.701	13.615	0.198
15%	6.943	0.107	0.701	14.501	0.223
20%	7.721	0.121	0.701	16.126	0.253
25%	8.824	0.138	0.701	18.430	0.288
30%	10.550	0.166	0.701	22.034	0.346
35%	15.156	0.262	0.701	31.655	0.548
40%	23.060	0.402	0.701	48.162	0.840
45%	37.980	0.626	0.701	79.322	1.308
50%	55.330	0.918	0.701	115.559	1.917

Table 13. Bingham plastic model parameters for the mixture of sand and 5% pure bentonite dispersion

Solid Volumetric Fraction	YP (Pa)	PV (Pa·sec)	YP (lb$_f$/100 ft^2)	PV (cP)
0%	7.168	0.010	14.970	10.106
5%	7.309	0.011	15.264	10.552
10%	7.845	0.012	16.385	11.223
15%	8.391	0.013	17.525	12.757
20%	9.372	0.014	19.575	14.414
25%	10.756	0.016	22.465	16.354
30%	12.888	0.020	26.917	19.592
35%	18.801	0.031	39.266	31.135
40%	28.780	0.047	60.108	47.423
45%	46.924	0.074	98.004	73.795
50%	68.014	0.109	142.051	109.020

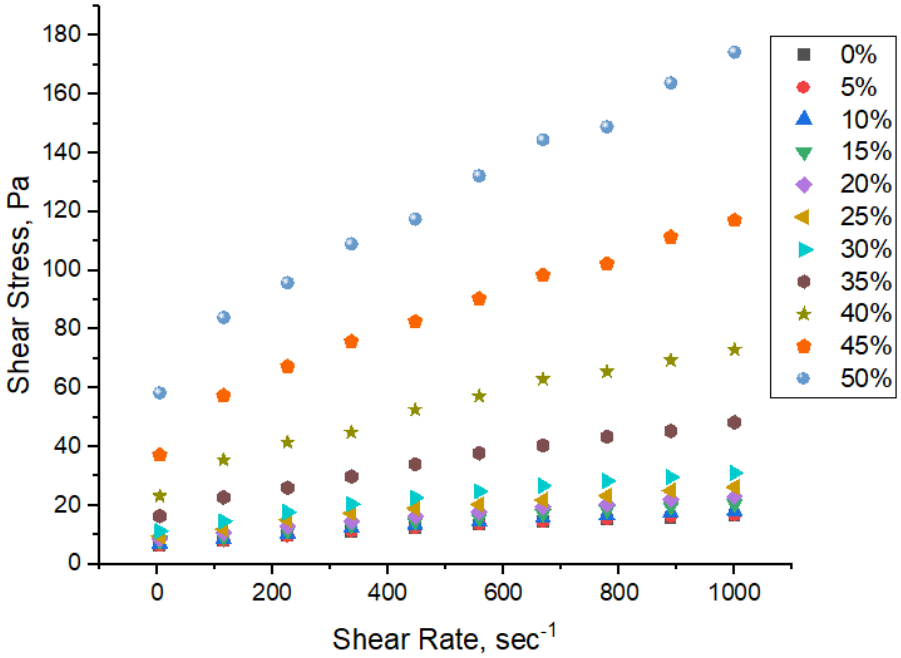

Figure 1. Rheogram for mixture of sand and 5% pure bentonite dispersion.

4.3.3.2. Mixtures of Sand Particles and 3% commercial HDD drilling fluid

Table 14. Herschel-Bulkley model parameters for the mixture of sand particles and 3% commercial HDD drilling fluid

Solid Volumetric Fraction	τ_M (Pa)	K (Pa·s^n)	n	τ_M (lb$_f$/100 ft^2)	K (lb$_f$·s^n/100 ft^2)
0%	12.453	0.194	0.630	26.001	0.405
5%	12.495	0.204	0.630	26.097	0.425
10%	13.491	0.237	0.630	28.176	0.495
15%	15.752	0.281	0.630	32.899	0.586
20%	18.651	0.327	0.630	38.953	0.683
25%	21.417	0.414	0.630	44.7302	0.864
30%	26.174	0.520	0.630	54.665	1.087
35%	37.486	0.767	0.630	78.292	1.602
40%	62.998	1.258	0.630	131.575	2.628
45%	107.939	2.159	0.630	225.436	4.509
50%	153.808	2.833	0.630	321.235	5.917

Table 15. Bingham plastic model parameters for the mixture of sand and 3% commercial HDD drilling fluid

Solid Volumetric Fraction	YP (Pa)	PV (Pa·s)	YP (lb$_f$/100 ft^2)	PV (cP)
0%	14.660	0.014	30.618	13.692
5%	14.818	0.0144	30.948	14.373
10%	16.260	0.017	33.959	16.593
15%	18.973	0.020	39.626	19.762
20%	22.494	0.023	46.979	22.847
25%	26.168	0.029	54.653	29.166
30%	32.073	0.037	66.987	36.818
35%	46.8033	0.053	97.750	53.014
40%	77.717	0.08811	162.315	88.117
45%	132.864	0.152	277.492	151.831
50%	186.431	0.199	389.370	199.399

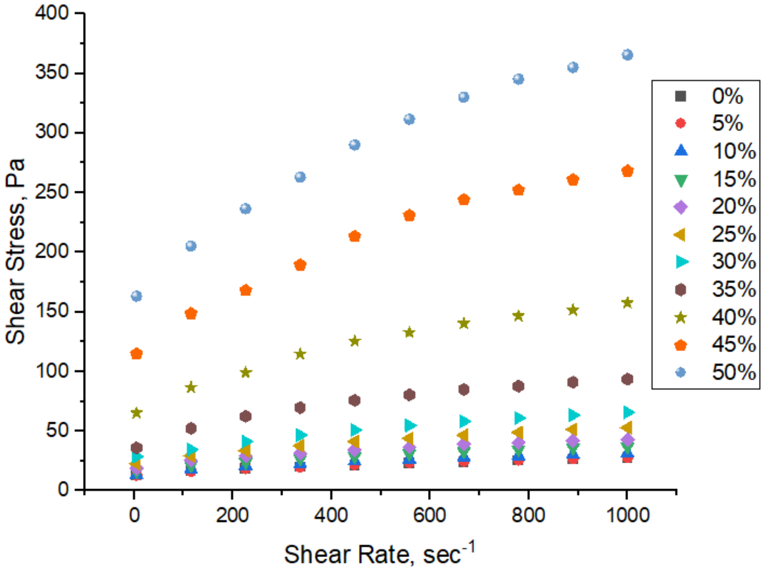

Figure 2. The rheogram of the mixture of sand particles and 3% commercial HDD drilling fluid.

4.3.4. The Ratio of Yield Stress and Yield Point

With the information available, the R ratio, which is another parameter for fluid rheology characterization, can be computed as below (API RP 13D 2017):

$$R = \frac{\tau_M}{YP}\ (for\ YP > 0) \qquad [5]$$

where τ_M is the dynamic yield stress of the mixture of sand particles with the drilling fluid as in the Herschel-Bulkley model, and YP is the Bingham plastic yield point.

Table 7 summarizes the results of the R ratio for different mixtures of drilling fluid containing sand particles.

Table 16. R ratio for different mixtures of drilling fluid containing sand particles

Sand Volumetric Fraction	pure bentonite dispersion	commercial HDD drilling fluid
0%	0.833	0.8497
5%	0.828	0.843
10%	0.831	0.829
15%	0.827	0.830
20%	0.824	0.829
25%	0.820	0.818
30%	0.819	0.816
35%	0.806	0.801
40%	0.801	0.811
45%	0.809	0.812
50%	0.814	0.825

It can be seen that all of the above values of R ratio are between 0 and 1, which is an indication that these fluids are all Herschel-Bulkley fluids (R = 0 for power law fluids, R = 1 for Bingham plastic fluids and 0 < R < 1 for Herschel-Bulkley fluids) (API RP 13D 2017).

4.3.5. Shear Rate Geometry Correction Factors

For the flow in the HDD annulus (between the borehole wall and the outside wall of the drill pipes), the shear rate should be adjusted to account for the flow conduit geometry, and the well geometry factor can be calculated as below (API RP 13D 2017):

$$B_a = \left[\frac{(3-\alpha)n+1}{(4-\alpha)n}\right]\left[1+\frac{\alpha}{2}\right] \qquad [6]$$

where α is the well geometry factor, which is equal to 1 for flow in the annulus, and B_a is the shear rate correction factor. The shear rate correction factor for well geometry only depends on the fluid's flow behavior index and the well geometry factor. Furthermore, Equation 6 is derived based on the assumption that the HDD annulus can be modelled using an equivalent slot with reasonable accuracy (Zamora, 1974).

Based on the finding that for Herschel-Bulkley fluids the flow behavior index of a mixture containing solid particles can be taken to be the same value as for the pure suspending fluid, the well geometry factor can be calculated as 1.71365 for the 5% pure bentonite dispersion and 1.79371 for the 3% extra high yield commercial HDD drilling fluid (Chateau, 2008).

4.3.6. Overall Geometry Factor

According to API RP 13D (2017), the value of the geometry factor, G_f, is assumed to be the same as for the well geometry factor. This assumption was used throughout this paper.

4.3.7. Shear Rate and Shear Stress at the Wall

One of the most important purpose of drilling fluid circulation is to suspend the cuttings and carry them out of the borehole to prevent the formation of a cutting bed (Ariaratnam, 2007; Shu, 2014). However, in order to erode and remove a cutting bed once it has already been formed, a high shear stress and high shear rate in the regions near the wall are necessary to lift the cuttings from the cutting bed surface and suspend them in the drilling fluid (Leising, 2002; Powell, 1992; Zamora, 1993). As a result, it is necessary to estimate their values in order to predict the drilling fluid’s hole cleaning performances.

However, it should be noted that this does not mean that a higher shear stress at the borehole wall is always better for HDD operations, because this value is directly related to the viscosity of the drilling fluid, as well as to the frictional pressure loss (Zhu, 2012).

Considering the fact that frictional pressure loss is the major limitation for HDD design, the value of shear stress at the borehole wall alone should not be taken as a indicator of successful hole cleaning in HDD.

The shear rate at the wall can be calculated using Equation 7:

$$\gamma_w = \frac{1.6 G_f V_a}{d_{hyd}} \qquad [7]$$

where γ_w is the shear rate at the wall, which is 32.075 s^{-1} for the 5% pure bentonite dispersion, and 33.574 s^{-1} for the 3% commercial HDD drilling fluid.

The shear stress at the borehole wall, expressed in API viscometer dial readings, can be computed using Equation 8.

$$\tau_v = \frac{(4-\alpha)}{(3-\alpha)}^n \tau_M + K\gamma_w^n \qquad [8]$$

The shear stress at the borehole wall, expressed in U.S. Customary Units, can be computed as:

$$\tau_w = 1.067\tau_v \qquad [9]$$

The following table summarizes the values of the shear stresses at the borehole wall for different mixtures of solid particles with the drilling fluid:

Table 17. Shear stress at the wall for drilling fluids with different volumetric fractions of sand particles

Sand Volumetric Fraction	τ_w for pure bentonite dispersion ($lb_f/100ft^2$)	τ_w for commercial HDD drilling fluid ($lb_f/100ft^2$)
0%	18.701	37.719
5%	19.005	37.935
10%	20.449	41.124
15%	21.852	48.057
20%	24.326	56.848
25%	27.798	65.655
30%	33.243	80.380
35%	48.053	115.333
40%	73.144	193.527
45%	120.032	331.612
50%	174.936	470.155

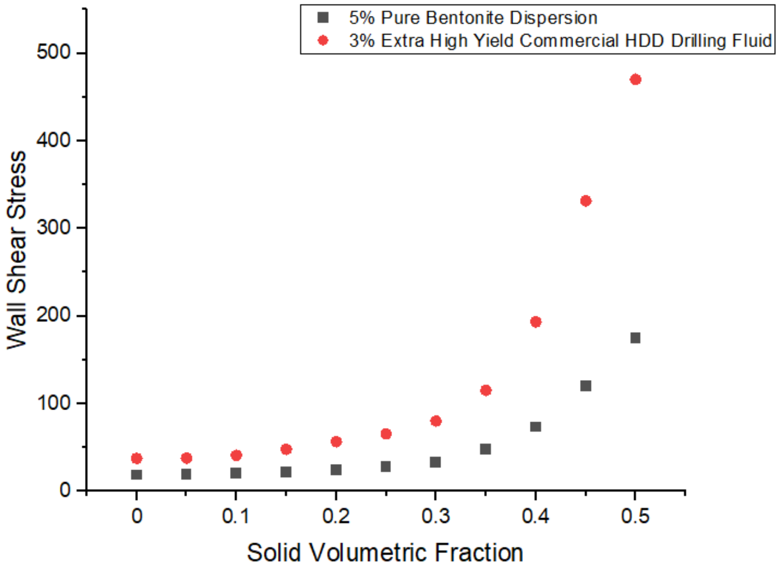

Figure 3. Shear stress at borehole wall for two drilling fluids containing various solid volumetric fractions

Figure 4 shows the shear stress at the borehole wall for each drilling fluid containing different amounts of sand particles. It can be seen that the solid volumetric fraction has an increasing impact on the wall shear stress of both drilling fluids, especially when the solid volumetric fraction exceeds 30-35%. It should also be noted that the impact of increasing solid volumetric fraction had a more profound effect for the 3% extra high yield commercial drilling fluid compared to the 5% pure bentonite dispersion. Considering that the values of the flow behavior index and shear rate at the borehole wall for both fluids are relatively similar, the most significant impact on the change in the shear stress at the wall comes from the yield stress and the consistency index of the fluid. Moreover, because the yield stress and consistency index can both be described using the Krieger-Dougherty equation, it is not surprising that the wall shear stress also exhibits a very similar trend.

A new term, the dimensionless wall shear stress, can be defined as:

$$\tau_{wN} = \tau_{wM} \,/\, \tau_{wF} \qquad [10]$$

where τ_{wN} is the dimensionless wall shear stress, τ_{wM} is the shear stress at the wall for the mixture of drilling fluid and sand particles, and τ_{wF} is the wall shear stress of the pure drilling fluid. The results for the dimensionless shear stress at the wall for both mixtures are shown in Table 9.

Table 18. Dimensionless shear stress at the wall for different mixtures of drilling fluids containing sand particles

Sand Volumetric Fraction	τ_{wN} for pure bentonite dispersion	τ_{wN} for commercial HDD drilling fluid
0%	1.000	1.000
5%	1.016	1.006
10%	1.093	1.090
15%	1.168	1.274
20%	1.301	1.507
25%	1.486	1.741
30%	1.778	2.131
35%	2.570	3.058
40%	3.911	5.131
45%	6.418	8.792
50%	9.354	12.465

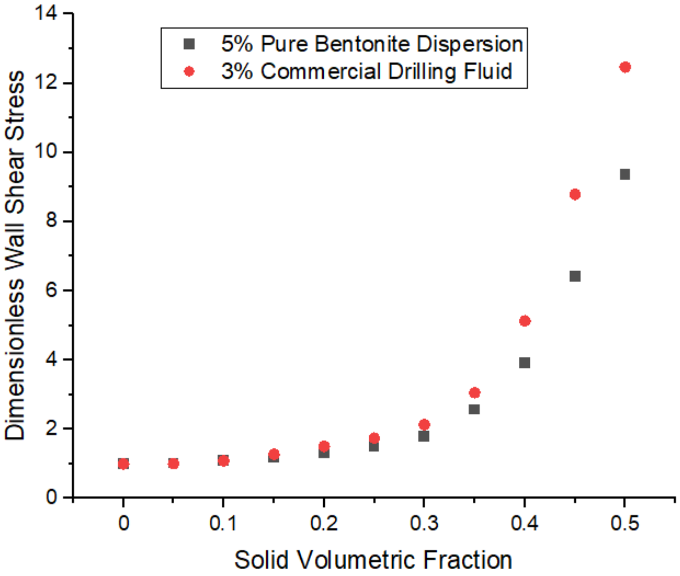

Figure 4. Relationship between shear stress at the wall and volumetric fraction of solids

Overall, the shear stress at the wall can be described using the Krieger-Dougherty equation for both the pure bentonite dispersion and the commercial drilling fluid, with

ϕ_m of 0.633 for both drilling fluid samples, and B of 2.258 for pure bentonite dispersion, 2.584 for commercial drilling fluid samples, and a R^2 of 0.98.

4.3.8. Generalized Reynolds Number and Critical Reynolds Number

The generalized Reynolds number is a parameter that helps to determine the flow regime based on the fluid and conduit properties (Zamora, 1974). At lower generalized Reynolds numbers, the flow tends to be laminar: that is, the fluid particles follow a well-defined path, without macroscopic mixing between adjacent layers (Kundu, 2016). However, when the generalized Reynolds number approaches the critical Reynolds number, the flow regime becomes transitional flow, and at even higher generalized Reynolds numbers, the flow becomes turbulent (Schut, 1965).

In order to confirm that the flow is laminar, it is necessary to calculate both the generalized Reynolds number (N_{ReG}) and the critical Reynolds number (N_{cRe}) for all flow conditions (API RP 13D 2017):

$$N_{ReG} = \frac{\rho V^2}{19.36\tau_w} \qquad [11]$$

and

$$N_{cRe} = 3470 - 1370n \qquad [12]$$

where ρ is the fluid density. At the critical Reynolds number, the flow regime changes from laminar to transitional flow.

Table 10 summarizes the basic properties of the pure drilling fluids and the sand particles.

Table 19. Properties and basic parameters of drilling fluid samples

	pure bentonite dispersion	commercial HDD drilling fluid
Base Fluid Concentration (wt.%)	5	3
Base Fluid Density (g/mL)	1.038	1.025
Sand Volumetric Fraction (%)	0%-50%	0%-50%
Sand Particle Size Range (μm)	80-160, 160-315	160-315
Temperature (°C)	22	22
Sand Particle Specific Gravity	2.675	2.675

The values of the generalized Reynolds numbers are summarized in Table 11 below, along with the critical Reynolds, it can be concluded that for this simplified HDD project, all flow regimes are laminar.

Table 20. Generalized Reynolds numbers for mixtures of sand particles in different suspending fluids

Sand Volumetric Fraction	N_{ReG} for 5% pure bentonite dispersion	N_{ReG} for 3% commercial HDD drilling fluid
0%	149.188	73.041
5%	158.378	78.471
10%	157.951	77.777
15%	157.881	71.17042
20%	150.867	64.066
25%	139.934	58.849
30%	123.633	50.827
35%	90.108	37.346
40%	62.205	23.402
45%	39.739	14.326
50%	28.524	10.576

4.3.9. Laminar Flow Friction Factor

Annular pressure loss during HDD is one of the most important factors to address to maintain borehole annular pressure and to evaluate the risk of hydrofracture (Pilehvari, 1999). It is thus necessary to estimate the laminar flow friction factor, which is an input to the calculation of the annular friction pressure loss, which will be presented in the next section.

As the flows in this case study are all laminar, the laminar flow friction factor can be calculated using Equation 9 and summarized in the following table (API RP 13D 2017).

$$f_{lam} = \frac{16}{N_{ReG}} \qquad [13]$$

Table 21. Laminar flow friction factor for the mixtures of sand particles in different suspending fluids

Sand Volumetric Fraction	f_{lam} for 5% pure bentonite dispersion	f_{lam} for 3% commercial HDD drilling fluid
0%	0.107	0.219
5%	0.101	0.204
10%	0.101	0.206
15%	0.101	0.225
20%	0.106	0.250
25%	0.114	0.272
30%	0.129	0.315
35%	0.178	0.428
40%	0.257	0.684
45%	0.403	1.117
50%	0.561	1.513

It can be seen from Equations 13 that the laminar flow friction factor is influenced by the density of the mixture as well as the wall shear stress.

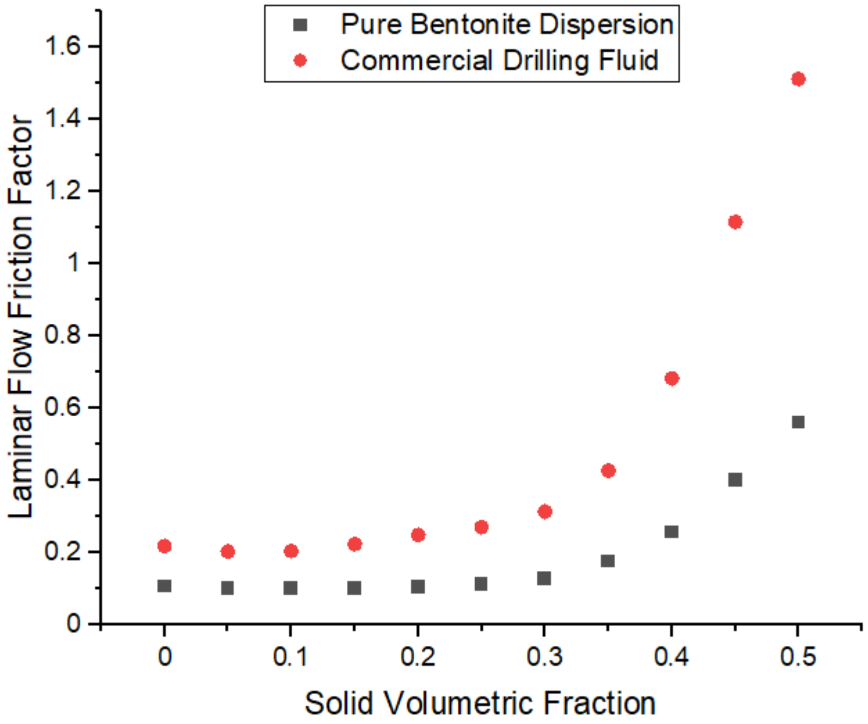

Figure 5. Relationship between laminar flow friction factor and the solid volumetric fractions

As seen in Figure 6, the laminar flow friction factor is also heavily influenced by the volumetric fraction of solids in the mixture, and a significant increase is observed once it exceeds 30-35%.

4.3.10. Annular Frictional Pressure Loss

In addition to the hydrostatic pressure of the fluid, the annular frictional pressure is a critical component in estimating the annular fluid pressure in the borehole during HDD (ASTM F1962-11). The annular fluid pressure should be kept sufficiently low so that the risk associated with hydrofracture is minimized (Pilehvari, 1999). Since the hydrostatic pressure is related to the bore path design, this paper will only focus on the annular frictional pressure loss for the simplified case study.

The frictional pressure loss in the HDD borehole annulus can be estimated using Equation 10 (API RP 13D 2017).

$$P_a = \frac{1.076\rho V_a^2 f_{lam} L}{10^5 d_{hyd}} \quad [10]$$

The results calculated for annular friction pressure loss for drilling fluids with various solid volumetric fractions are summarized in Table 13.

Table 22. Annular friction pressure loss for mixtures of sand particles in different suspending fluids

Sand Volumetric Fraction	P_a for 5% pure bentonite dispersion ($lb_f/in^2/ft$)	P_a for 3% commercial HDD drilling fluid ($lb_f/in^2/ft$)
0%	0.009	0.019
5%	0.009	0.019
10%	0.010	0.020
15%	0.011	0.024
20%	0.012	0.028
25%	0.014	0.032
30%	0.016	0.040
35%	0.024	0.057
40%	0.036	0.010
45%	0.059	0.164
50%	0.086	0.232

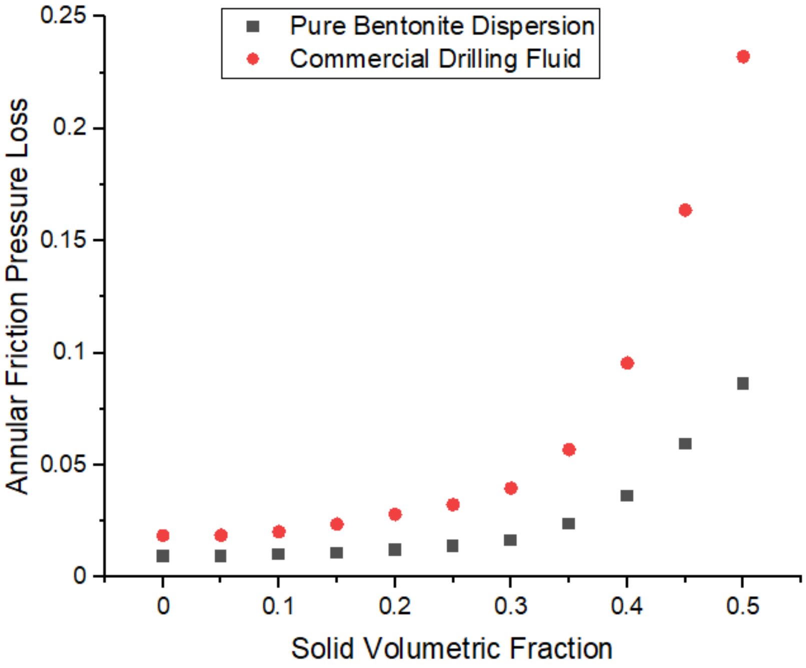

Figure 6. Relationship between annular friction pressure loss and volumetric fraction of solids

From Figure 7 above, it can be seen that the volumetric fraction of solids has an increasing influence on the annular friction pressure loss. It is also noted that this effect is much stronger for the commercial drilling fluid than the pure bentonite dispersion, possibly due to its much higher yield stress and consistency index.

4.3.11. Annular Plug Width

The annular plug width, h_p, is a measure of the flatness of the velocity profile for fluid flow in the annular space (Kelessidis, 2006). This value represents the height of the plug region where the local shear rate is low or near zero, thus giving the fluid a high viscosity, which is very beneficial in suspending the drilled cuttings (Leising, 2002; Powell, 1991; Zamora, 1993).

The annular plug width can be calculated as in Equation 11 (Kelessidis, 2006):

$$h_p = \frac{2\tau_M}{Pa} \qquad [11]$$

In order to evaluate the plug width for various operational conditions, it is necessary to define a dimensionless annular plug width, h_{pD}, as shown in Equation 12, to provide a basis for comparison:

$$h_{pN} = \frac{h_p}{H} \qquad [12]$$

where H is the total annular gap width.

The results of h_{pN} for different drilling fluids containing various volumetric fractions of solids are summarized in Table 14 below:

Table 23. Dimensionless annular plug width for mixtures of sand particles in different suspending fluids

Sand Volumetric Fraction	h_{pN} for 5% pure bentonite dispersion	h_{pN} for 3% commercial HDD drilling fluid
0%	0.666	0.690
5%	0.665	0.688
10%	0.666	0.685
15%	0.664	0.685
20%	0.663	0.685
25%	0.663	0.681
30%	0.663	0.680
35%	0.659	0.679
40%	0.659	0.680
45%	0.661	0.680
50%	0.661	0.683

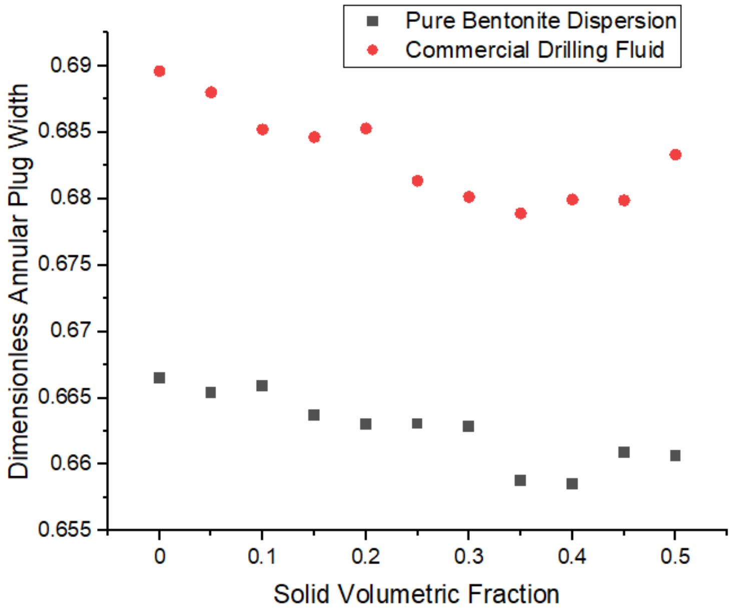

Figure 7. Relationship between dimensionless annular plug width and volumetric fraction of solids

It can be seen from Figure 8 above that the increasing solid volumetric fraction generally has a negative impact on the annular plug width, and the commercial drilling fluid has a much higher annular plug width compared with the pure bentonite dispersion, indicating a much higher solid suspension capacity (Deng, 2018).

4.3.12. YP/PV Ratio

The YP/PV ratio is another important parameter that can be used to estimate the condition of the drilling fluid, as well as its hole cleaning capacity (Okrajni, 1986; Chilingarian, 2007). It is one of the most commonly used parameters to compare the hole cleaning performance of different drilling fluids, and has been demonstrated to correlate closely with cutting transportation performance (Becker, 1991). A lower value of the YP/PV ratio is often an indication of a greater tendency of cutting settlement. Based on experimental results, drilling fluids with higher values of YP/PV exhibit better hole cleaning performance (Okrajni, 1986; Chilingarian, 2007).

Table 24. YP/PV ratio for mixtures of sand particles in different drilling fluids

Sand Volumetric Fraction	YP/PV for Pure Bentonite Dispersion ($lb_f/100ft^2/cP$)	YP/PV for commercial HDD drilling fluid ($lb_f/100ft^2/cP$)
0%	1.482	2.237
5%	1.447	2.154
10%	1.460	2.047
15%	1.375	2.005
20%	1.358	2.057
25%	1.374	1.874
30%	1.374	1.820
35%	1.261	1.844
40%	1.268	1.842
45%	1.328	1.828
50%	1.303	1.953

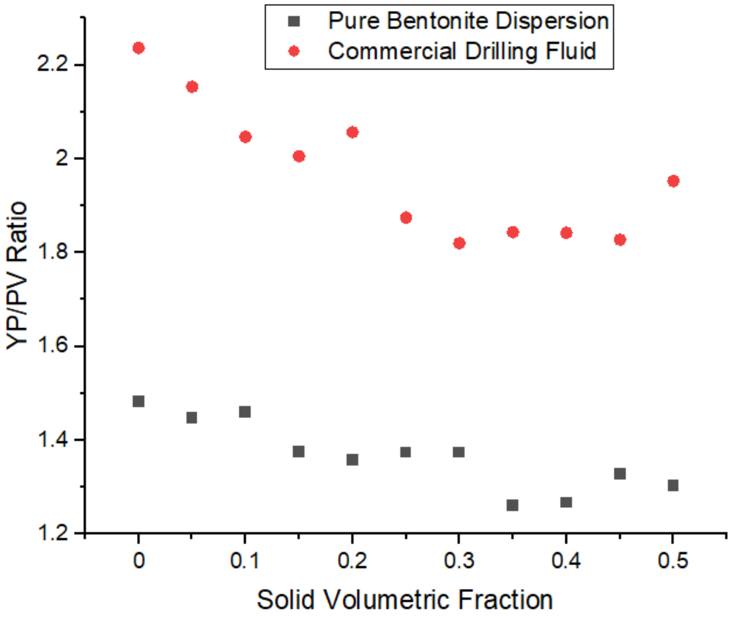

Figure 8. Relationship between YP/PV ratio and solid volumetric fractions

Based on Figure 9 above, it can be seen that the increasing solid volumetric fraction generally has a negative impact on the condition of the drilling fluid and its cutting carrying capacity. Overall, the mixtures containing 3% commercial drilling fluid have a much higher YP/PV ratio than the 5% pure bentonite dispersion, and thus the commercial drilling fluid has a higher cutting carrying capacity.

4.4. Discussion

4.4.1. Impact of Suspended Cuttings on the Drilling Fluid's Cutting Carrying Capacity

As previously mentioned, the annular plug width is considered to be one of the most important parameters to evaluate the cutting carrying capacity of a drilling fluid. It was found that increasing the volumetric fraction of solids within the mixtures generally decreases the annular plug width for both of the drilling fluid samples analyzed in this paper, which implies that the volumetric fraction of solids should be kept to a minimum if possible. However, considering that the difference between the maximum and minimum values of the dimensionless annular plug width is only 1.2% and 1.6% for both drilling fluid samples, it can be concluded that the impact of the volumetric fraction of solids on the annual plug width is not obvious, and that the base fluid itself has a higher influence on the annular plug width. As a result, the 3% commercial drilling fluid seems to be superior compared to the 5% pure bentonite dispersion in terms of annular plug width.

4.4.2. Impact of Suspended Cuttings on the Drilling Fluid’s Sweeping Capacity

The frictional pressure loss and the YP/PV ratio can be considered as parameters to evaluate drilling fluid’s sweeping capacity. As previously discussed, the frictional pressure loss is the main limitations for HDD drilling fluid evaluation, because it is directly related to the risk of hydrofracture. Based on the analysis, it can be seen that the volumetric fraction of solids has an increasing influence on the annular friction pressure loss, and this effect becomes especially obvious once the solid volumetric fraction exceeds 30-35%. For the YP/PV ratio, increasing the volumetric fraction of solids generally decreases the YP/PV ratio, indicating a decrease in the sweeping capacity of the drilling fluid.

4.4.3. Recommended Fluid-to-Soil Ration for HDD in Fine Sand Formations

Increasing the solid volumetric fractions will increase the yield stress of the drilling fluid, which is beneficial in terms of its cutting carrying capacity, to a certain extent. Another consideration is that excessive yield stress requires increased pump output in order to initiate fluid circulation, and which also results in a higher risk of hydrofracture. Due to the fact that the volumetric fraction of solids will have a significantly higher impact on the yield stress of the drilling fluid once this value exceeds 30-35%, the solid volumetric fraction should be kept below 30-35%, if site conditions such as geological factors and equipment condition permit. Increasing the volumetric fraction of solids will also decrease the annular plug width, which is another indicator of the cutting carrying capacity of the drilling fluid, but the impact of increasing volumetric solid content is only 1.2% and 1.6% for the 3% commercial drilling fluid and 5% pure bentonite dispersion, respectively, so this effect is considered to be relatively minor and may actually be negligible.

In terms of the sweep capacity of the drilling fluid, increasing the solid volumetric fraction will increase the annular friction pressure loss and decrease the YP/PV ratio. Both of these effects are considered detrimental to the sweeping capacity of the drilling fluid. However, the annular friction pressure loss, which is the major limitation related to the risk of hydrofractures, strongly depends on the solid volumetric fraction, and ideally the solid volumetric fraction should be kept below 30-35%.

In summary, the volumetric fraction of solids has negative impacts on the hole cleaning performance indices of the drilling fluid, and thus the solid content in the drilling should be kept as low as possible during HDD operations. However, this is not a practical or economical target, because drilling fluid being returned from the borehole will always carry a certain amount of cuttings. Typically, these cuttings are separated from the drilling fluid using equipment at the surface. However, to maintain a very low volumetric fraction of solids requires a very high fluid-to-soil ratio, and thus will result in higher operational costs to replace solid-loaded drilling fluid with freshly prepared mud. Despite this, it is recommended that the volumetric fraction of solids should be maintained below 30-35% wherever possible, in order to prevent excessively high annular friction pressure loss and to minimize the risk of hydrofracture. This recommended upper limit for the volumetric fraction of solids corresponds to a fluid-to-soil ratio of 2:1 to 3:1, which is consistent with the experience-based practice within the HDD industry of maintaining a fluid-to-soil ratio of 2:1 to 3:1 within fine sand formations (Vroom, 2018).

4.5. Conclusion

This paper analyzed the experimental results for the impact of the volumetric fraction of solids on the rheological and hydraulic parameters of two drilling fluids. Experimental results were presented for various hole cleaning performance indices of the drilling fluid, including. The effect of the volumetric fraction of solids on the cutting carrying capacity and sweeping capacity if the drilling fluid was discussed. Ideally, the volumetric fraction of solids should be maintained as low as possible in order to achieve the highest possible hole cleaning performance during HDD operations. However, a more practical and economical approach is to maintain the solid volumetric fraction below 30-35%, as geological and equipment conditions permit, since at higher solid volumetric fractions the drastically increasing friction pressure loss will significantly increase the risks associated with hydrofracuring.

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Chapter 5: SUMMARY AND CONCLUSIONS

5.1. Summary

Chapter 2 introduces the development of trenchless technologies with a focus on horizontal directional drilling, including different categories and stages of the operations. The topics of the impact of suspended drilled cuttings on the drilling fluids' rheological properties was also briefly discussed. Finally, the importance of understanding the impact of cuttings on drilling fluids' rheology and hole cleaning performance parameters was introduced.

In Chapter 3, the impact of suspended solid particles on the drilling fluids' overall rheology was presented. Drilling fluid samples were prepared with both pure bentonite dispersions and commercial HDD drilling fluid mixtures. The sample preparation process was carefully controlled to remove impurities and air bubbles, in order to obtain reproducible results. Solid volumetric fractions were varied from 0% to 50%, and the samples' rheological properties were measured using a rheometer. The experimental data was fitted with both the Herschel-Bulkley model and the Bingham Plastic model. It was found that the solid volumetric fraction has an increasing influence on the drilling fluids' rheological properties, and this effect becomes especially pronounced when the solid volumetric fraction exceeds 30-35%. The experimental procedures were repeated for different solid particle sizes, but no obvious differences were observed for the experimental settings.

In Chapter 4, the impact of solid volumetric fractions on the drilling fluids' hole cleaning performance parameters was investigated. By dividing the drilling fluids' hole cleaning performance parameters into 2 categories, it was found that the annular plug width, frictional pressure loss and the YP/PV ratio can be selected to evaluate the drilling fluids' cutting carrying capacity and sweeping capacity. Increasing solid volumetric fractions has a negative impact on the drilling fluid's cutting carrying capacity by decreasing the annular plug width, however this effect is rather small. Instead, the drilling fluid type seems to have a much higher impact. The 3% commercial HDD drilling fluid demonstrated superior characteristics compared with the 5% pure bentonite dispersion.On the other hand, the drilling fluids' frictional pressure loss is heavily influenced by the suspended solid volumetric fraction. This effect is also more significant when the solid volumetric fractions exceeded 30-35%. Similarly, increasing solid volumetric fractions will also decrease the YP/PV ratio, all of these impacts will decrease drilling fluids' hole cleaning performance.

5.2. Conclusions

The key conclusions of this work are highlighted below.

(1) Solid volumetric fractions have significant and increasing impact on the drilling fluids' rheological properties, which is more profound once the solid volumetric fractions exceed 30-35%. Following Chateau's approach, it was found that both the Herschel-Bulkley yield stress and consistency index can be described using the Krieger-Dougherty equation, as a function of the solid volumetric fraction.

(2) Increasing solid volumetric fractions will negatively affect the drilling fluids' hole cleaning performances, and the sweeping capacity is more significantly impacted.

(3) For HDD operations within fine sand formations, it was found that the solid volumetric fractions should be kept below 30-35% in order to maintain satisfactory hole cleaning performances, which is consistent with the commonly adopted practice for drilling in fine sand formations in the HDD industry.

(4). The exact relationship between the Herschel-Bulkley yield stress and consistency index is still unclear, and further research is necessary in order to better understand the origin of the rheological observations resulting from increasing volumetric fractions. In addition, actual hole cleaning experiments using the flow loop device is higher recommended to better understand the cutting transport processes and drilling fluids' hole cleaning performances in HDD operations.

5.3. Future Research

(1). The scope of the work should be expanded to account for other potential factors, including cutting types (e.g. clay), cutting shapes, wider cutting particle size distributions, mixtures of cuttings with different particle sizes, various concentrations of water-based drilling fluid samples, influence of impurities (instead of using deionized water), and the influence of different HDD drilling fluid additives.

(2). The flow loop device should be installed and utilized to perform cutting transportation experiments, especially at the curvature sections, in order to investigate the actual hole-cleaning performance of drilling fluids with different solid volumetric fractions.

(3). A field test can be conducted to measure and monitor the influence of different fluid-to-soil ratios on the hole cleaning performance of drilling fluids, as well as the resulting borehole fluid pressure.

(4). Various types of fluids, including different concentrations of drilling fluids, or different combinations of polymer fluids, can be tested to better understand the effect of fluid types and properties on their reactions to suspended solid particles.

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