DETERMINATION OF THE EFFECT OF NaOH ON THE RHEOLOGICAL PROPERTIES BENEFICIATED GUM ARABIC

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CERTIFICATION

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DEDICATION

This project work is dedicated to the Almighty God, the giver of life for seeing me through this phase and journey. To my beloved parents, Mr. & Mrs. Okpede for their unwavering love, care and support throughout my undergraduate years.

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ABSTRACT

This research examines how Sodium Hydroxide (NaOH) influences the flow characteristics of purified gum Arabic-based drilling mud formulations, positioning them as eco-friendly substitutes for conventional synthetic additives. The experiment involved developing seven initial formulations combining bentonite with different polymer systems: xanthan gum, gum Arabic, and mixtures of gum Arabic with either cocoyam starch or ginger extract in proportions of 50/50 and 75/25. Subsequently, selected formulations underwent alkaline modification using NaOH at measurements of 3.0g, 7.5g, and 15.0g to replicate varying pH environments.

Flow behavior parameters encompassing plastic viscosity (PV), yield point (YP), gel strength, and mud weight were determined through Fann viscometer measurements and evaluated against three mathematical model frameworks: Bingham Plastic, Power Law, and Herschel-Bulkley models. Experimental findings demonstrated that 50g of gum Arabic delivered comparable rheological characteristics to 1g of xanthan gum under neutral conditions. The introduction of alkaline treatment produced substantial modifications in fluid behavior, with response patterns dependent on both the specific polymer-starch pairing and alkalinity level.

The most remarkable transformation occurred in the gum Arabic-cocoyam (50/50) formulation treated with 7.5g NaOH, which demonstrated PV of 65 cp and YP of 180 lb/100ft^2 corresponding to increases of 261% and 1025% respectively relative to the 3.0g NaOH variant. The gum Arabic-ginger combination displayed considerable viscosity enhancement (PV = 108 cp with 7.5g NaOH) yet revealed temporal degradation of gel structure at elevated alkalinity levels. Every alkaline-treated system manifested pseudoplastic (shear-thinning) characteristics with flow behavior indices (n) spanning 0.3 to 0.948, validating their appropriateness for drilling fluid applications.

Comparative model analysis indicated that the Herschel-Bulkley model most accurately characterized the behavior of alkaline-modified natural polymer systems, whereas both Bingham Plastic and Power Law models exhibited substantial prediction errors, especially under high-alkalinity conditions. These results established that purified gum Arabic, when strategically combined with indigenous starches, (cocoyam & ginger) and subjected to pH optimization, represents a viable, environmentally degradable, and economically advantageous alternative to synthetic drilling fluid components, delivering ecological advantages while preserving operational performance standards required for petroleum drilling activities.

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CHAPTER 1

1.1 BACKGROUND TO THE STUDY

In petroleum engineering, drilling is the process of producing vertical or deviated boreholes in the Earth to get access to underground geological formations containing oil and gas. This process is a critical component of petroleum engineering, requiring the design, planning, execution, and optimization of well building in order to extract hydrocarbons safely and efficiently.

Drilling Fluids (Mud) are an important part of drilling in petroleum engineering. They use specialized fluids to lubricate and cool the drill bit, remove cuttings, and maintain wellbore stability. The effectiveness of these fluids is primarily affected by their rheological and filtration characteristics, which determine their flow behavior and the volume of fluid lost to the formation. Recently, there has been an increase in interest regarding the incorporation of natural, biodegradable polymers in the formulation of drilling fluids, driven by environmental concerns and the rising costs of synthetic option. Gum Arabic, a natural substance derived from Acacia trees, exhibits promising rheological properties when modified or blended with other bio-based materials. Modifying the alkalinity of the system with sodium hydroxide (NaOH) impacts the polymer structure and its relationships with other elements. This research examines how gum Arabic performs when mixed with xanthan gum, ginger extract, cocoyam starch, and guar gum at different NaOH conc. to mimic variations in pH.

The drilling-fluid system, often referred to as the "mud system," is the sole component of the well-construction process that maintains continuous contact with the wellbore throughout the entire drilling operation. These systems are meticulously designed and formulated to function efficiently under anticipated wellbore conditions. Recent advancements in drilling-fluid technology have facilitated the implementation of cost-effective, purpose-specific systems for each interval of the well-construction process. The active drilling-fluid system consists of a volume of fluid that is circulated using specially designed mud pumps from the surface pits, through the drill string, exiting at the bit, and ascending through the annular space in the wellbore, before returning to the surface for solids removal and necessary maintenance treatments. The capacity of the surface system is typically determined by the rig size, which in turn is selected based on the well design. For instance, the active drilling-fluid volume for a deep water well may amount to several thousand barrels. Much of that volume is required to fill the long drilling riser that connects the rig floor to the seafloor. By contrast, a shallow well on land might only require a few hundred barrels of fluid to reach its objective.

The three primary functions of a drilling fluid; the transport of cuttings out of the wellbore, prevention of fluid influx, and the maintenance of wellbore stability depend on the flow of drilling fluids and the pressures associated with that flow. For example, if the wellbore pressure exceeds the fracture pressure, fluids will be lost to the formation. If the wellbore pressure falls below the pore pressure, fluids will flow into the wellbore, perhaps causing a blowout. It is clear that accurate wellbore pressure prediction is necessary. To properly engineer a drilling fluid system, it is necessary to be able to predict pressures and flows of fluids in the wellbore. Drilling fluid is considered as a vital part of the drilling system for the prevention of formation damage and the removal of cuttings. Such fluids must be engineered so that they will not lose their properties at various downhole conditions and it must be ensured that they do not damage the formations which are being drilled. Mud filtrate invasion is one of the most common causes of formation damage (Amaefule et. Al 1988). Such an invasion can result in significant formation damage around the wellbore and decrease well productivity and subsequently reservoir recovery. During drilling, the resultant differential pressure between wellbore pressure and reservoir pressure causes the fluid loss into the formation (Hoberock & Bratcher 1998). A filter cake is formed on the formation face due to the build-up of the mud solids. Filter cake properties, such as thickness, structure, particle size distribution, texture, permeability, and invasion into the formation are essential factors and identified and optimized.

Drilling additives are specialized chemicals or substances that are incorporated into drilling fluids to optimize their performance, stability, and efficiency. These additives play a vital role in adjusting viscosity, filtration and pH levels to ensure optimal drilling fluid performance. There are various types of additives namely;

- Viscosity modifiers: Control fluid thickness and flowability
- Filtration control agents: Prevent shale swelling and dispersion
- Lubricants: Reduce friction between the drill string and wellbore
- pH control agents: Help maintain a stable pH level, even in the presence of acidic or basic contaminants; they adjust the pH level of the drilling fluid to the optimal range, thereby enhancing its performance.

Polymers are complex molecules made up of repeating units, and they have numerous uses across the energy industry; they are used in drilling fluids to improve viscosity, reduce fluid loss, and stabilize shale formations with increase in oil displacement and recovery.

It can be broadly classified into: Natural and Synthetic, the use of polymers must be carefully managed to minimize environmental harm.

RHEOLOGY

Rheology is the science that deals with the flow and deformation of matter, particularly complex fluids and soft solids. Rheology primarily describes how materials respond to applied stress and strain. Two fundamental behaviors to be examined are: Viscosity- resistance to flow (fluid-like behavior) and Elasticity- ability to return to original form after deformation (solid-like behavior).

Several mathematical models are used to describe the flow behavior of complex fluids: Newtonian model, Bingham Plastic model, Power (Ostwald-de Waele) model, Hershley-Bulkley model.

GUM ARABIC AND ITS BENEFICIATION

Gum Arabic is a natural exudate obtained from Acacia species. It is primarily composed of polysaccharides and glycoproteins. Beneficiation, or the purification and enhancement of gum Arabic, typically involves removal of impurities and partial hydrolysis to improve its solubility and interaction with other additives. Several studies have examined the role of natural gums in improving mud properties. Beneficiated gum Arabic, due to its enhanced purity and functional groups, has shown promising behavior in terms of viscosity control and fluid loss reduction. It is a versatile natural gum with wide industrial relevance. However, its raw form requires beneficiation to meet the purity, functional, and consistency demands of modern industries. Various physical, chemical, and biotechnological methods have been developed to enhance its value. Future research is geared towards sustainable beneficiation and functionalization for advanced applications. (Williams & Phillips, 2000; Ali, Ziada & Blunden, 2009; Babiker et al., 2017; Abdalla et al., 2013)

1.2 PROBLEM STATEMENT

While gum Arabic has shown potential as a drilling fluid additive, there is limited scientific data on how it behaves under varying pH conditions, especially with other natural or semi-synthetic polymers. There is also a knowledge-gap regarding its compatibility with commonly used drilling fluid models such as Bingham Plastic, Power Law, and Hershley-

Bulkley models. Without this information, its practical application in drilling operations remains limited. Hence, there is a need for experimental investigation to determine the rheological behavior of gum Arabic-based formulations under different alkaline conditions.

1.3 AIMS AND OBJECTIVES OF THE STUDY

Aim:

To investigate the effect of pH (through NaOH variation) on the rheological and filtration properties of beneficiated gum Arabic-based polymer formulations and classify them under appropriate drilling models.

Objectives:

- To determine the rheological properties (e.g viscosity, yield stress) of each gum Arabic formulation (with cocoyam, ginger, xanthan gum, guar gum) under varying NaOH concentrations.
- To access the filtration characteristics of each formulated systems.
- To evaluate and classify the flow behavior of each formulation samples using standard rheological models.

1.4 SCOPE OF STUDY

This study focuses on four different polymer formulations involving beneficiated gum Arabic:

- Gum Arabic + Cocoyam starch
- Gum Arabic + Ginger extract
- Gum Arabic + Xanthan gum
- Xanthan gum + Ginger Extract

Each formulation will be tested at different NaOH concentrations to simulate pH variation. Experimental analysis will be conducted to measure:

- Rheological parameters such as plastic viscosity, yield point.
- Rheological model fitting; of the fluid behavior aligns with Bingham plastic, Power law, or Hershley-Bulkley models).

1.5 SIGNIFICANCE/RELEVANCE OF THE STUDY

The study contributes to sustainable drilling practices by investigating natural polymer-based mud systems as alternatives to synthetic drilling fluid additives. It offers:

- Environmental benefits through the use of biodegradable, non-toxic polymers.
- Economic relevance by promoting the use of locally available resources like gum Arabic, cocoyam and ginger.
- Scientific insight into how pH influences polymer behavior in drilling environments.
- Operational advantage by identifying which polymer systems fit desired flow models, aiding in better drilling fluid designs.

The findings can help drilling engineers, researchers and fluid design specialists make data-driven decisions in selecting cost-effective, eco-friendly, and efficient drilling fluid systems.

CHAPTER 2

LITERATURE REVIEW

Drilling fluids, commonly referred to as drilling muds, are critical components in every drilling operation; they are an essential component of the drilling process in oil and gas exploration. Their primary functions include, cooling and lubricating the drill bit, transporting cuttings to the surface, maintaining hydrostatic pressure, and stabilizing the borehole (Caenne et al., 2011). The rheological behavior of drilling fluids i.e. how they deform and flow under stress, is a key parameter influencing their performance, especially under varying downhole conditions. The composition and characteristics of drilling fluids vary depending on the drilling environment and the desired performance outcomes and the type and formulation of the drilling fluid used can significantly impact the efficiency, safety, and environmental sustainability of drilling operations.

Rheology is significantly affected by the type of polymers used and the pH of the fluid system. Natural polymers like gum Arabic are increasingly being investigated as environmentally friendly, biodegradable, and cost-effective alternatives to synthetic additives in drilling fluids. When treated with alkaline substances such as NaOH, these natural gums may exhibit altered molecular structures that affect their viscosity and flow behavior. The drilling fluids are the most important component in the drilling process, and the success of a drilling operation is closely related to its efficiency.

The drilling fluids has several purposes which must be adjusted to ensure safety and minimize hole problems. Some of these functions include the removal of the cuttings downhole, providing wellbore stability, cooling and lubricating the drill string and bit, controlling the downhole formation pressures, and preventing formation damage by creating a filter cake that seals the rock pores (Caenne & Chilllingar, 1996). Any failure of the drilling mud to meet its required function can prove extremely costly and jeopardize the success of the drilling operation; their composition, density, and rheological properties are continuously adjusted to optimize costs and performance.

Modern research has led to the development of nano-enhanced, bio-polymer-based, and aerated drilling fluids. Nanoparticles are used to improve the thermal conductivity and rheological behavior of the fluids, enhancing filtration control and shale stability. Meanwhile, bio-based additives from natural polymers like xanthan and guar gum offer biodegradable and non-toxic alternatives (Isa & Jimoh, 2019). Environmental regulations have also driven innovation in drilling fluid design, with emphasis on reducing the ecological impact while maintaining efficiency and safety in complex drilling environments.

The selection of fluids depend on several key factors; Formation type, Temperature and Pressure Conditions, Environmental constraints, and drilling depth and direction. Optimizing fluid properties like viscosity, gel strength, and pH is crucial to prevent formation damage, improve rate of penetration (ROP), and maintain well integrity (Caenne et al., 2011).

2.1 TYPES OF DRILLING FLUIDS

Drilling fluids can be classified into three main categories based on their base fluid:

i. **WATER-BASED MUDS (WBMs):** They are the most commonly used type of mud due to their cost- effectiveness and ease of disposal, accounting for approximately 80% of all wells drilled worldwide (Caenne et al., 2011). They use water as the continuous phase and include additives like bentonite clay, barite, and polymers. WBMs are especially favored in environmentally sensitive locations.

ii. **OIL-BASED MUDS (OBMs):** They use diesel, mineral oil, or synthetic oil as the base fluid. These fluids offer superior lubricity, thermal stability, and resistance to contamination. They are ideal for high-pressure wells and for drilling through shale formations and offer superior performance in demanding drilling conditions. They do not interact with shale, thus minimizing swelling. Their high tolerance to contaminants and ability to function under extreme conditions make them essential in certain drilling scenarios (Gray & Darley, 1980).

iii. **SYNTHETIC-BASED MUDS (SBMs):** They were developed to combine the benefits of OBMs with reduced environmental risks. The base fluids are synthetically produced esters, olefins, or paraffin, offering biodegradability and low toxicity. Here, a synthetic organic liquid, serves as the continuous phase in an emulsion; designed to be more environmentally acceptable than traditional oil-based muds while still offering comparable performance. SBMs can result in less dispersion of cuttings into the environment, as the synthetic oil tends to coat the cuttings and allow them to settle more quickly.

Drilling fluids are central to the success of drilling operations. Understanding the types, compositions, applications of different drilling fluid system is vital for effective well design and execution. While traditional WBMs and OBMs remain widely used, there is a growing emphasis on environmentally sustainable and high-performance alternatives such as SBMs, nanofluids, and biopolymer-based systems. Ongoing research continues to improve fluid performance while minimizing their ecological footprint.

iv. **PNEUMATIC DRILLING FLUIDS:** These systems use gases such as air, nitrogen, or natural gas as the drilling fluid. They are particularly useful in formations with low pressure or where conventional fluids might cause formation damage. These drilling systems operate by injecting gas at high pressure and flow rates down the drill string and out through the drill bit. The expanding gas creates high velocity flow that carries rock cuttings to the surface through the annular space between the drill string and wellbore walls.

Rheology studies the flow and deformation of matter, focusing on how materials respond to applied stress; rheology determines how these fluids behave under various flow conditions encountered during drilling operations. Some factors that affect rheological properties include: Temperature, Pressure, Composition of additives, and contamination due to influx of formation fluids.

2.2 DRILLING FLUID PERFORMANCE OPTIMIZATION

Drilling mud is a mixture of base fluid and other materials combined in specified amounts for the purpose of cleaning a drilled well. Some of its functions during drilling include but are not limited to the following: transport cuttings, cooling and lubrication of drill string, consolidating wellbore walls and controlling formation pressure. These functions are executed concurrently. In order to improve the drilling process, a robust mud rheological model is needed to capture the dynamics of the mud flow. Drilling fluid performance is crucial for achieving operational efficiency, safety, and environmental compliance in drilling operations. The goal of optimization is to tailor the physical, chemical, and thermal properties of the drilling fluid to suit specific subsurface conditions. Properly optimized drilling fluids improve rate of penetration (ROP), minimize formation damage, reduce costs, and ensure wellbore stability. Rheology is the study of how materials move or flow. This movement, flow, or perhaps deformation of materials is applicable to a number of disciplines, but has been studied extensively for flow through pipes, annuli, and other conduits of liquids such as drilling fluids. Drilling optimization in the oil and gas field is formulated by using mathematical models; hence the optimization targets the following key parameters:

2.2.1 RHEOLOGICAL PROPERTIES

i. **Plastic Viscosity:** It is a measure of the internal resistance of a drilling fluid to flow due to the presence of solids and the base fluid's viscosity. It represents part of the fluid's viscosity that is independent of the applied shear rate once flow has started. This affects hydraulic efficiency and pressure losses. Plastic viscosity is a fundamental rheological parameter that characterizes the flow behavior of non-Newtonian fluids, particularly those that follow the Bingham plastic model: it represents the resistance to flow that remains constant once a material begins flowing after exceeding its yield stress threshold and can be measured using rotational viscometers, Rheometers, Specialized drilling fluid testing equipment, and Flow-based measurement techniques. Plastic viscosity is essentially described as the resistance of a fluid to flow (Davoodi et al., 2018). It is used as an indicator of the size, shape, distribution and quantity of solids, and the viscosity of the liquid phase (Idress and Hasan, 2020). In order to increase plastic viscosity, the size of solids in the fluid should be decreased. A fluid with high plastic viscosity is undesirable and could result in increased equivalent circulating density due to increased pump pressures to pump the fluid in the wellbore (Nicora et al., 2001). Another negative effect of a fluid with high plastic viscosity is decreased rate of penetration (Beck et al., 1995). A low plastic viscosity and high yield point results in a high YP/PV ratio which improves cuttings transport (Okrajni and Azar, 1986). The energy required to pump the fluid increases with increased viscosity. Pumping power and pressure drop are two important parameters that depend on the viscosity (Shahsavani et al., 2018). The plastic viscosity is a key parameter in the Bingham plastic model: The Bingham plastic model is used as a common mathematical model of mud flow in drilling engineering, and in handling of slurries. In drilling applications, plastic viscosity should be as low as possible for fast drilling and is best achieved by minimizing colloidal solids, while yield point must be high enough to carry cuttings out of the hole.

The Bingham plastic model can be expressed as:

$$\tau = \tau_0 + \mu_p * \gamma$$

Where: $\tau =$ shear stress

τ_0 = yield stress (yield point)

μ_p = plastic viscosity

γ = shear rate

ii. **Yield point:** This represents the minimum shear stress required to initiate flow in a fluid. It is the threshold stress below which a material behaves as a solid and above which it flows as a liquid. Yield point finds application in drilling fluids in controlling hole cleaning efficiency, affecting pump pressure requirements and influencing wellbore stability. The yield point is the stress necessary to start the flow of a fluid and symbolizes resistance to early movement. If the applied stress is less than the yield stress, the fluid will restore its shape once the tension is removed. The yield point is controlled by electrical charges on or near the particles' surfaces, which impact frictional pressure losses and the equivalent circulation density. The Power law model is a fundamental mathematical framework for describing non- Newtonian fluid behavior, particularly for fluids that exhibit shear-thinning and shear-thickening characteristics. Yield point is a key parameter that determines how effectively a drilling fluid can carry and hold cuttings in suspension, thereby supporting borehole stability. In contrast, gel strength refers to the fluid's ability to rebuild its internal structure during periods of no circulation, which is essential for minimizing particle settling and ensuring the structural integrity of the wellbore.

The basic power law equation is given as:

$$\boldsymbol{\tau = K(\frac{dy}{dt})^n}$$

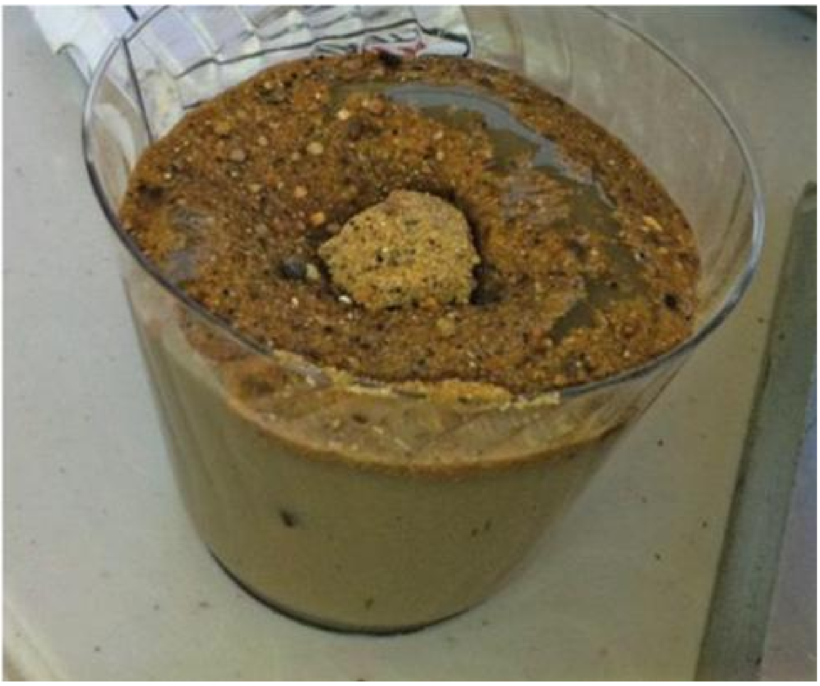
Where: $\boldsymbol{\tau}$ = shear stress (Pa)

$\boldsymbol{K}$ = consistency index (Pa.s^n)

$\boldsymbol{\frac{dy}{dt}}$ = shear rate (s^{-1})

$\boldsymbol{n}$ = flow behavior index (dimensionless)

iii. **Gel strength:** This indicates the fluid's ability to suspend solids when static. It is the shear stress required to initiate flow in a mud sample after it has rested undisturbed, typically measured after 10 seconds and 10 minutes per API standards. (SLB Energy glossary, 2025). A mud lacking gel strength would make a day’s worth of drilling result in solids build up down hole and/or cuttings settling once fluid circulation is stopped (Trenchless Technology, 2013). Both can cause significant downhole problems. Whether the mud is at rest or is in circulation and cuttings are suspended, it enhances a clean wellbore by enabling the drill bit to cut new formation rather than unnecessarily re-grinding cuttings that were not cleaned. This leads to an increase in the rate of penetration. Despite being an essential mud property, a delicate balance has to be struck between using mud with very low gel strength and one with very high gel strength. While low gel strength would lead to the accumulation of cuttings downhole, barite sagging (Annis and Smith, 1996), high gel strength leads to pressure losses, formation fracture and a solids control problem.



Demonstrating a fluid mixture's gel strength for suspending sand for transport. (Trenchless Technology (2013).

Gel strength is often treated as a low-shear plateau in models like Herschel–Bulkley or Bingham, manifesting in the yield term or initial stress response. The Herschel–Bulkley model, also known as the Modified Power Law is a widely used three-parameter rheological model that describes non-Newtonian fluids featuring both a yield stress and power-law flow behavior. It is well suited for a range of soil additives and conditions, though parameter validity may vary across different shear rates. The Herschel-Bulkley fluid can be mathematically described by:

$$\tau = \tau 0 + k(\gamma)n,$$

Where: τ = shear stress

$\tau 0$ = yield stress

k = consistency factor

γ = shear rate

n = flow index, a power law exponent.

Flow won't occur until τ exceeds $\tau 0$; beyond that, stress grows with shear rate raised to the nth power.

This model offers a refined, yet flexible tool for capturing the complex flow behavior of drilling fluids from solid-like rest to dynamic shear response.

In other words, gel strength is vital for drilling fluid performance, balancing the need of solid suspension during circulation downtime and the need of minimal resistance when circulation resumes. It is measured using organized tests, influenced by fluid chemistry and environmental factors, and described through rheological data-based models, it remains a basic parameter requiring careful monitoring and design control. The performance of drilling fluids directly impacts the safety and efficiency of drilling operations. Among the various performance attributes of drilling fluids, rheological modification and fluid loss control are the two key properties that ensure safe drilling (Abdullah et al., 2024; Guo et al., 2023; Yahya et al., 2023). During drilling operations, the rheological properties of the fluid determine its ability to suspend solid weighting materials and transport drill cuttings (Al-Shargabi et al., 2024; Ma, Yin, et al., 2024; Pedrosa et al., 2023), while fluid loss control properties affect borehole stability and formation protection (Davoodi, Al-Shargabi, Wood, Minaev, & Rukavishnikov, 2024; Orun et al., 2023; Yang et al., 2022). Therefore, improving the rheological and fluid loss control properties of drilling fluids is vital for enhancing the safety and efficiency of drilling operations.

2.3 EVOLUTION OF DRILLING FLUID ADDITIVES IN OIL-BASED AND WATER-BASED MUDS

Over a period of time, the composition and functionality of the oil and water based fluids have evolved significantly, especially with the advancement of additives that enhance their performance.

2.3.1 EVOLUTION IN WATER-BASED ADDITIVES

Water-based muds have traditionally been favored for their environmental compatibility and cost-effectiveness. However, their limitations in thermal stability, lubricity, and shale inhibition have driven continuous improvements through additive development. Early WBMs used basic additives like bentonite clay for viscosity and filtration control, and barite for weighting. These traditional additives were relatively simple and relied on physical properties rather than chemical interaction with formation. (Caenne, Darley & Gray, 2017).

The challenge of shale swelling and dispersion led to the introduction of inhibitive additives. These include potassium chloride (KCl), which suppresses shale hydration, and more recently, polyamine-based inhibitors, glycols, and nano-silica particles for superior inhibition and wellbore stability. (Yan et al., 2013; Zhao et al., 2014).

Modern developments have introduced bio-based and green additives, including modified gums (like xanthan and guar gum), gum Arabic, and biopolymers, which are biodegradable and sustainable while maintaining rheological efficiency. (Abdulraheem et al., 2019).

2.3.2 EVOLUTION IN OIL-BASED ADDITIVES

Oil-based muds were developed to combat the limitations of WBMs in high temperature, high pressure (HTHP) wells and reactive formations. OBMs with oil as the continuous phase and brine as the dispersed phase offer superior lubricity, thermal stability, and inhibition.

Early OBMs used diesel or mineral oils with lime and organophilic clay as primary additives. These organophilic clays, e.g. amine treated bentonite, enabled viscosity control in the oil medium. (Caenne et al, 2017). The evolution of OBMs saw the emergence of emulsifiers and wetting agents, such as fatty acid soaps and amine derivatives, to stabilize the water-in-oil emulsion and enhance oil-wetting of solids. Dual emulsifier systems i.e. primary and secondary emulsifiers have improved emulsion stability (Fink, 2012).

Although, recent advancements focus on synthetic base oils like olefins and esters, which offer lower toxicity and better biodegradability, addressing environmental concerns.

Furthermore, organophilic lignite, resin-based filtration reducers, and advanced rheology modifiers have enhanced the performance of oil based muds in deep wells. (Gbolami et al, 2014).

2.3.3 NANOTECHNOLOGY AND SMART ADDITIVES

A contemporary advancement in both WBMs and OBMs is the application of nanoparticles to enhance filtration, lubrication, and thermal resistance. Additives such as nano-silica, nano-clay, and graphene derivatives provide extensive surface areas and reactivity, facilitating a dynamic response to downhole conditions. (Contreras et al, 2014). Research is ongoing on smart fluids that integrate responsive polymers or temperature- sensitive gels to achieve controlled viscosity and sealing.

The evolution of drilling fluid additives in WBMs and OBMs reflects a trend towards higher performance, environmental sustainability, and adaptability to complex environments. The integration of biotechnology and nanotechnology in additive formulation signifies a transformative phase in drilling fluid engineering, offering promising solutions for future drilling challenges.

2.4 OVERVIEW OF NATURAL POLYMERS IN DRILLING FLUIDS AND PH SENSITIVITY

2.4.1 INTRODUCTION TO NATURAL POLYMERS IN DRILLING FLUIDS

Natural polymers, such as gum Arabic, xanthan gum, guar gum, and other biopolymers, have gained increasing interest in petroleum drilling operations due to their biodegradability, renewability, and environmentally friendly profiles. These polymers serve as rheology modifiers, stabilizers, and fluid loss reducers in water-based drilling fluids, contributing to safer and more sustainable drilling practices. (Fink, J.K 2012)

Some advantages of Natural Polymers are:

i. Biodegradability: They break down naturally, minimizing environmental impact.
ii. Low Toxicity: Safer for workers and ecosystems.
iii. Cost-Effectiveness: Often locally available and renewable.
iv. Functional Versatility: Capable of modifying viscosity, gel strength, and filtration properties.

2.4.2 RHEOLOGY AND ITS DEPENDENCE ON PH

The rheological behavior of these polymers is critical to their performance in drilling fluids. Rheology describes how the fluid deforms and flows under applied stress or shear, influencing cutting transport, wellbore stability, and mud removal efficiency.

Natural polymers are pH-sensitive because their molecular structures, specifically functional groups like carboxyl, amino, and hydroxyl groups, can undergo protonation or deprotonation depending on the pH level. These molecular changes significantly influence chain conformation, Intermolecular interactions, solubility, pH Effects on Molecular Structure and Rheology, Acidic Conditions (Low pH): Protonation of functional groups (e.g., carboxyl groups become –COOH) leads to increased intermolecular hydrogen bonding and potential chain contraction, decreasing viscosity and gel strength, Alkaline Conditions (High pH): Deprotonation (e.g., –COOH to –COO−) enhances negative charges along the polymer backbone. This causes electrostatic repulsion, chain extension, and increased viscosity. The increased negative charge also stabilizes the polymer in solution, enhancing gel strength and suspension capacity. For example: Gum Arabic exhibits increased viscosity at higher pH due to deprotonation of its carboxyl groups, leading to chain extension. Xanthan gum shows similar behavior, becoming more viscous with increasing pH until a threshold beyond which hydrolysis or degradation could occur.

2.4.3 IMPLICATIONS FOR DRILLING OPERATIONS

In actual well conditions, downhole pH can vary widely, often influenced by formation lithology, the presence of salts, and chemical additives. The ability to tune the rheological properties of drilling fluids via pH adjustment allows engineers to optimize performance:

i. Enhance suspension of cuttings.
ii. Increase gel strength during static periods to prevent settling.
iii. Control fluid viscosity for efficient cuttings transport.

Furthermore, natural polymers like gum Arabic undergo structural changes upon pH variation that can either improve or impair fluid stability, affecting the overall success of drilling operations. Understanding the pH sensitivity of natural polymers such as gum Arabic is essential for designing effective, eco-friendly drilling fluids. Adjusting pH with agents like NaOH allows control over polymer conformation and solution behavior, enabling optimization of rheological properties for safe and efficient drilling operations.

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CHAPTER 3

METHODOLOGY

3.1 MAJOR MATERIALS USED

1. Xanthan Gum
2. Sodium Hydroxide (NaOH)

3.1.1 XANTHAN GUM

Xanthan gum is used as a high-efficiency, environmentally friendly viscosifier and suspension agent in water-based drilling fluids to carry cuttings and gravel, improve wellbore stability, and control fluid loss. It creates a strong gel structure that suspends solids, prevents them from settling, and enhances the rheology of the mud. Its ability to withstand high salinity, variable temperatures, and different pH levels makes it suitable for various drilling conditions and formations, though specialized modifications may be needed for extreme environments. Xanthan gum oil drilling grade is a polysaccharide. Xanthomonas produce it through monosaccharide fermentation. Xanthan gum oil drilling grade is a hydrocolloid polymer. So it can be dissolved in water. Because water is the basic carrier fluid in drilling mud, hydrophilicity is the basic characteristic of xanthan gum (oil drilling grade).

As a viscosifier, Xanthan gum (oil drilling grade) is widely used in drilling mud. It can increase the viscosity of the mud. In addition, Xanthan gum (oil drilling grade) is a good carrier for drill cuttings. When mixed into water, Xanthan gum (oil drilling grade) swells. As a result, the mixture exhibits a gel-like consistency. This viscous mixture can trap cuttings in suspension. Therefore, these cuttings will not fall on the drill pipe due to gravity.

In oil drilling, Xanthan fluid products can control the rheology of drilling fluids. Its main role is to enhance the strength of the gel, thereby improving the suspension. This helps to transport ordinary drill cuttings and heavier gravel and pebbles. This keeps the hole open and transports the cuttings outward.

Xanthan gum (oil drilling grade) has many other industrial uses. Including but not limited to glues, inks and etc.

3.1.2 SODIUM HYDROXIDE (NAOH)

Also known as Caustic soda is a common additive in drilling engineering, especially in water-based drilling fluids. It plays several important roles in maintaining fluid properties and ensuring successful drilling operations. It is mainly used to control pH, reduce corrosion, precipitate hardness ions, and improve clay/polymer hydration, and support additive performance. However, careful monitoring is required to prevent over-treatment. A higher pH helps to reduce corrosion of drilling equipment by neutralizing acidic species like CO_2 and H_2 S. It stabilizes clays and prevents excessive hydration and swelling.

Fig. 3.1.2: NaOH pellets

3.2 INSTRUMENTATION

1. Scout Pro Weighing Balance
2. Hamilton Beach Mud Mixer
3. Fann Viscometer
4. Measuring Cylinder
5. Spatula

3.2.1 SCOUT PRO WEIGHING BALANCE

It is a compact, reliable, and versatile digital balance widely used for quick and accurate measurements in labs, classrooms, fieldwork, and industries for accurate weight measurement. It is designed for precision, durability, and portability. It has multiple measurement units: grams (g), milligrams (mg), ounces (oz), carats (ct), pounds (lb), etc. It could be either manual or digital; the one used during the experiment was the manual model.

Fig. 3.2.1: Scout pro weighing balance

3.2.2 HAMILTON BEACH MUD MIXER

3.2.3 FANN VISCOMETER

3.2.4 MEASURING CYLINDER

3.2.5 SPATULA

3.3 SAMPLES AND SAMPLING TECHNIQUES

3.3.1 PREPARATION OF THE COCOYAM POWDER

The cocoyam tubers were purchased in large quantities; it was then peeled and sliced thinly in order to make the drying process faster, it was measured at a weight of about 1500g before drying. The sliced cocoyam was then dried in sunlight for about a week and the air-dried for another week due to constant rainfall. After the 2 weeks had elapsed, the cocoyam was then measured at a weight of 430g; as a result of fluid and moisture loss. This sample was then grinded and ready to be used for the experiment.

3.3.2 PREPARATION OF THE GINGER POWDER

Fresh ginger was purchased, peeled and sliced; its initial measurement before drying was about 450g. It was also dried under sunlight for about a week, and air-dried for another week. After the 2-week period elapsed, the ginger sample weighed about 40g. It was then grinded and ready for use for the experiment.

Fig. 3.2.2: Ginger Powder

3.4 EXPERIMENT ONE

3.4.1 GENERAL BASELINE EXPERIMENTS WITHOUT SALT OR PH

RPM	**Bentonite**	**Xanthan Gum**	**Gum Arabic(GA)**	**GA-CO 50/50**	**GA-CO 75/25**	**GA-Ginger 50/50**	**GA-Ginger 75/25**
600	9	46	45	45	30	48	44.5
300	6.5	35.5	34.5	28	24	30	28.0
200	5.5	31.0	31	22.5	19	24	21.5
100	4.5	25.0	25	16	13	27	15.5
Gel strength							
10`	5.5	29.0	28	15	16	20	19.0
10``	7	35	30	20	19	24	18
Yield point	4.0	24	24	11	18.0	12	11.5
Plastic viscosity	2.5	11.5	10.5	17	6.0	18	16.5
Density (g/cc)	8.6	8.7	8.6	8.1	8.2	8.1	8.0

Table 3.4.1: Table of values for baseline experiments without salt or pH

3.4.2 EXPERIMENTAL PROCEDURE FOR BENTONITE AND WATER MIXTURE ONLY

1. 500ml of water was measured using the measuring cylinder and placed in the mixing cup.
2. 30g of bentonite using the weighing balance and add the powder into the mixing cup containing the water and stir using the mud mixer for 3mins on medium speed.
3. After mud mixing, part of the mixture was placed into the viscometer and its viscosity and gel strength was measured at 600rpm, 300rpm, 200rpm, and 100rpm. Measure the maximum deflection at 15secs and 10mins.
4. The second part of the mixture that was reserved was placed in the mud cup and its density was measured.

Table 3.4.1:Baseline experiments (Bentonite only)

3.4.3 EXPERIMENTAL PROCEDURE FOR BENTONITE AND XANTHAN GUM

1. 30g of bentonite and 500ml of water were measured.
2. The mixture was stirred using the mud mixer at medium speed for 3mins
3. 4g of xanthan gum was then measured and added to the mixture; but the resulting mixture was too viscous to be stirred and had to be discarded.
4. Another fresh batch of bentonite and water mixture was measured and mixed at medium speed for 3mins and this time around, 1g of xanthan gum was measured instead and added to the mixture and stirred at high speed. (The resulting mixture was less viscous than the previous and it was able to be worked with).
5. Its viscosity, gel strength and density were then measured.

Table 3.4.1: Baseline experiments (Bentonite and Xanthan gum)

3.4.4 EXPERIMENTAL PROCEDURE FOR BENTONITE AND GUM ARABIC

1. 30g of bentonite and 500ml of water were measured and then stirred using the mud mixer at medium speed for 3mins.
2. 50g of gum arabic was then measured and added to the mixture and stirred for another 3mins.

3. The resulting mixture was then measured for viscosity, gel strength and density. (Observation: 1g of xanthan gum is equivalent to 50g of gum Arabic as a result of the nature of their resulting mixture).

   Table 3.4.1: Baseline experiments (Bentonite and Gum Arabic)

3.4.5 EXPERIMENTAL PROCEDURE FOR BENTONITE, GUM ARABIC AND COCOYAM (50/50)

1. 30g of bentonite and 500ml of water were measured and stirred at medium speed for 3mins.
2. 25g of gum Arabic was then measured and added to the mixture and stirred for another 3mins.
3. Finally, 25g of cocoyam was measured and added to the mixture and stirred for another 3mins still at medium speed.
4. The resulting mixture was then measured for density, gel strength and viscosity.

   Table 3.4.1: Baseline experiments (Bentonite, Gum Arabic & Cocoyam 50/50)

3.4.6 EXPERIMENTAL PROCEDURE FOR BENTONITE, GUM ARABIC AND COCOYAM (75/25)

1. 30g of bentonite and 500ml of water were measured and stirred for 3mins at medium speed.
2. 37.5g of gum Arabic was then measured and added to the mixture and was stirred at medium speed at 3mins.
3. 12.5g of cocoyam was then measured and added to the mixture and stirred at medium speed for 3mins. (It was important that the mixture was properly stirred in order to prevent the formation of fish-eye).
4. The resulting mixture was then measured for its density, viscosity and gel strength.

   Table 3.4.1: Baseline experiments (Bentonite, Gum Arabic & Cocoyam 75/25)

3.4.7 EXPERIMENTAL PROCEDURE FOR BENTONITE, GUM ARABIC AND GINGER (50/50)

1. 30g of bentonite and 500ml of water was measured and stirred for 3mins at medium speed.
2. 25g of gum Arabic was then measured and added to the mixture, stirred for 3mins at medium speed.
3. 25g of ginger was measured and added to the mixture, stirred for another 3mins still at medium speed.
4. The resulting mixture was then measured for its viscosity, density and gel strength.

Table 3.4.1: Baseline experiments (Bentonite, Gum Arabic & Ginger 50/50)

3.4.8 EXPERIMENTAL PROCEDURE FOR BENTONITE, GUM ARABIC AND GINGER (75/25)

1. 30g of bentonite and 500ml of water was measured and stirred for 3mins at medium speed.
2. 37.5g of gum Arabic was then measured and added to the mixture and stirred at medium speed for 3mins.
3. 12.5g of ginger was measured and added to the mixture while stirring at medium speed for 3mins.
4. The resulting mixture was then measured for its viscosity, gel strength and density.

Table 3.4.1: Baseline experiments (Bentonite, Gum Arabic & Ginger 75/25)

3.5 EXPERIMENTAL PROCEDURES (WITH NaOH)

3.5.1 EXPERIMENTAL PROCEDURE WITH BENTONITE, XANTHAN GUM (1G), NAOH (7.5 G).

This experiment was considered immiscible due to the formation of a lot of “fish eye”.

3.5.2 EXPERIMEMTAL PROCEDURE WITH BENTONITE, GUM ARABIC (50G), NAOH (7.5G & 15G)

1. 30g of bentonite and 500ml of water were measured and then stirred using the mud mixer at medium speed for 3mins at low speed.
2. 50g of gum arabic was then measured and added to the mixture and stirred for another 3mins.
3. 7.5g of NaOH was then measured and added into the mixture and stirred for another 3mins at medium speed.
4. The resulting mixture was then measured for viscosity, gel strength and density and its pH was also tested using the litmus paper.
5. The same procedure was then repeated, but using 15g of NaOH.

3.5.3 EXPERIMENTAL PROCEDURE USING BENTONITE, GUM ARABIC (25G), COCOYAM (25G), NAOH (3.0G & 7.5G)

1. 30g of bentonite and 500ml of water were measured and then stirred using the mud mixer at medium speed for 3mins at low speed.
2. 50g of gum arabic was then measured and added to the mixture and stirred for another 3mins.
3. 50g of cocoyam was also added to the mixture and stirred for 3mins on medium speed.
4. 3.0g of NaOH was then measured and added into the mixture and stirred for another 3mins at medium speed.
5. The resulting mixture was then measured for viscosity, gel strength, density and pH.
6. The procedure is then repeated, but using 7.5g of NaOH.

3.5.4 EXPERIMENTAL PROCEDURE USING BENTONITE, GUM ARABIC (25G), GINGER (25G), NAOH (3.0G & 7.5G)

1. 30g of bentonite and 500ml of water were measured and then stirred using the mud mixer at medium speed for 3mins at low speed.
2. 50g of gum arabic was then measured and added to the mixture and stirred for another 3mins.
3. 50g of cocoyam was also added to the mixture and stirred for 3mins on medium speed.

4. 3.0g of NaOH was then measured and added into the mixture and stirred for another 3mins at medium speed.
5. The resulting mixture was then measured for viscosity, gel strength, density and pH.
6. The procedure is then repeated, but using 7.5g of NaOH.

3.5.5 PRECAUTIONS

1. During the test for viscosity, it was ensured that the pointer settled on the scale before the reading was taken.

2. During the test for mud weight, it was ensured that the mud balance came to rest and built-in spirit level was at the middle of the scribed mark

3. It was ensured that the weight balance was placed on a flat working surface.

4. It was ensured that no external force acted on the weigh balance before taking reading.

5. It was ensured that errors due to parallax were avoided while taking the reading from the instrument.

3.6 EXPERIMENTAL RESULTS USING BENTONITE &WATER (MUD)

RPM	**Bentonite**
600	9
300	6.5
200	5.5
100	4.5
Gel strength	
10`	5.5
10``	7
Yield point	4.0
Plastic viscosity	2.5
Density (g/cc)	8.6

Table 3.6: Bentonite and water mixture reading

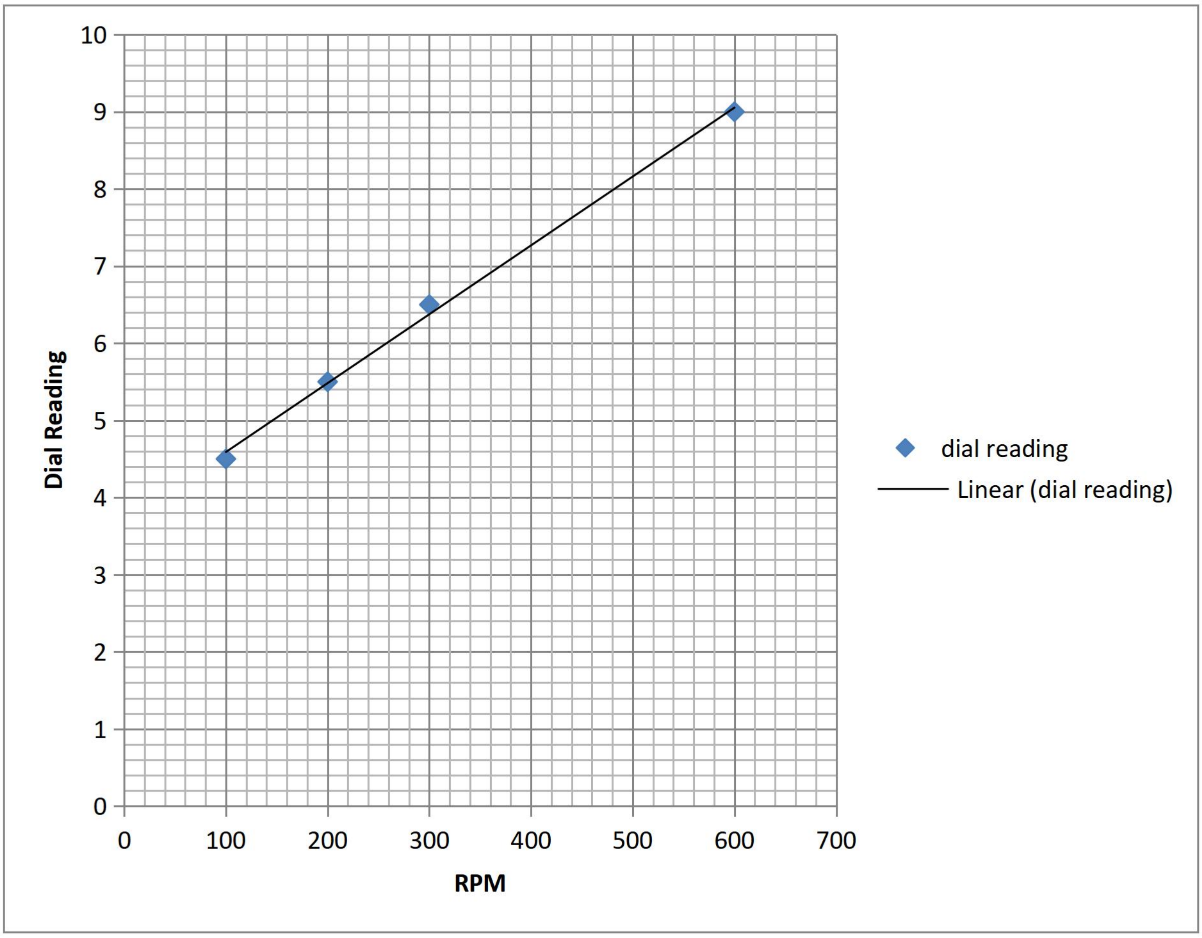

Fig. 3.6: Plot of Dial Reading vs RPM (Bentonite & Water)

3.6.1 EXPERIMENTAL RESULTS USING BENTONITE MIXTURE & XANTHAN GUM

RPM	**Xanthan Gum**
600	46
300	35.5
200	31.0
100	25.0
Gel strength	
10`	29.0
10``	35
Yield point	24
Plastic viscosity	11.5
Density (g/cc)	8.7

Table 3.6.1: Mud mixture +1g of Xanthan Gum

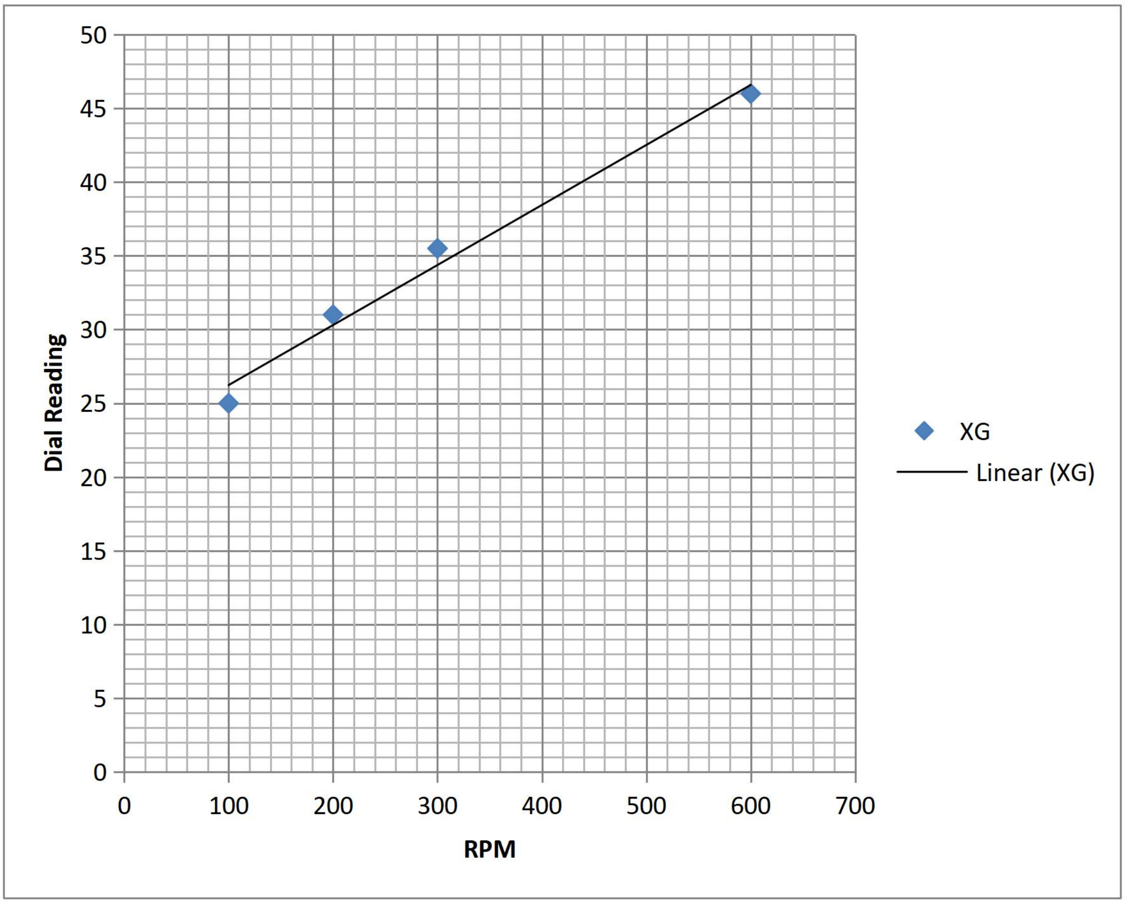

Fig. 3.6.1: Plot of Dial Reading vs RPM (1g of Xanthan Gum)

3.6.2 EXPERIMENTAL RESULTS USING BENTONITE &WATER MIXTURE + 50G GUM ARABIC

RPM	**Gum Arabic(GA)**
600	45
300	34.5
200	31
100	25
Gel strength	
10`	28
10``	30
Yield point	24
Plastic viscosity	10.5
Density (g/cc)	8.6

Table 3.6.2: Result of mud with 50g of Gum Arabic

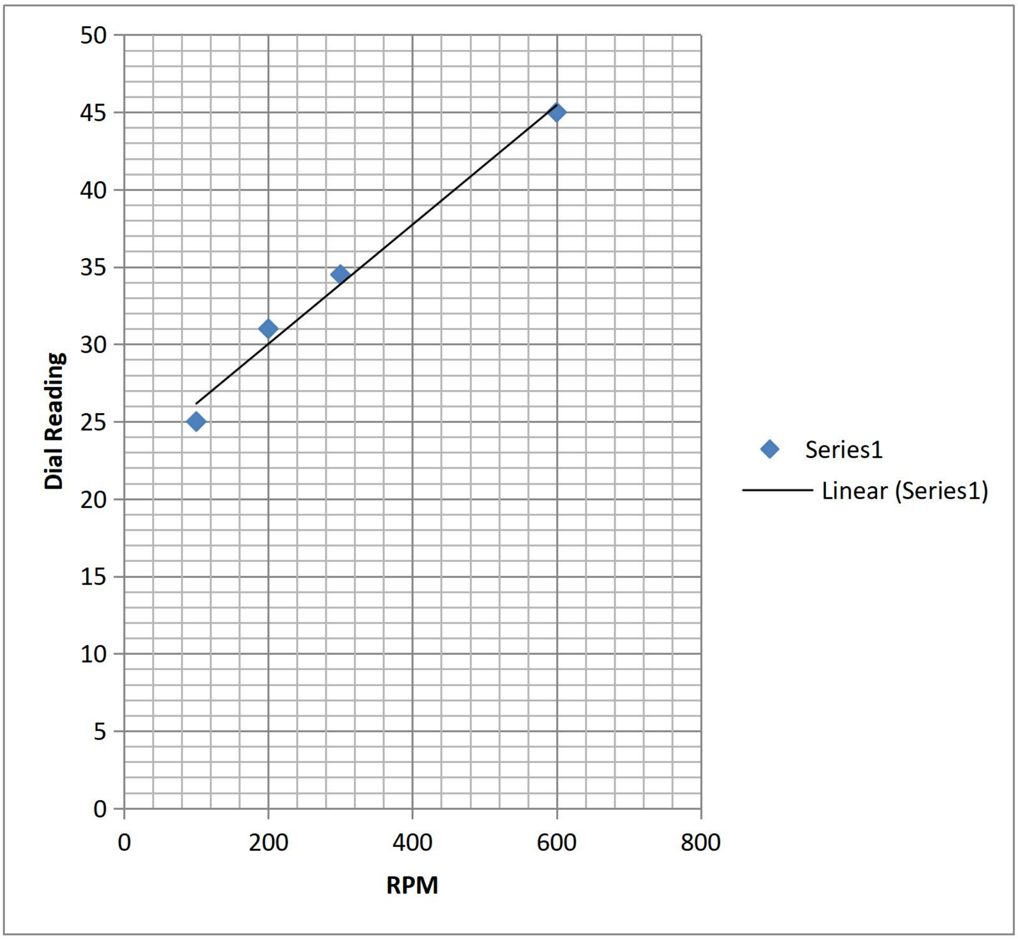

Fig. 3.6.2: Plot of Dial Reading vs RPM (Gum Arabic)

3.6.3 EXPERIMENTAL RESULTS USING MUD MIXTURE + GUM ARABIC & COCOYAM (50/50)

RPM	GA-CO (25g & 25g)
600	45
300	28
200	22.5
100	16
Gel strength	
10`	15
10``	20
Yield point	11
Plastic viscosity	17
Density (g/cc)	8.1

Table 3.6.3: Results of mud mixture with gum Arabic & cocoyam (50/50)

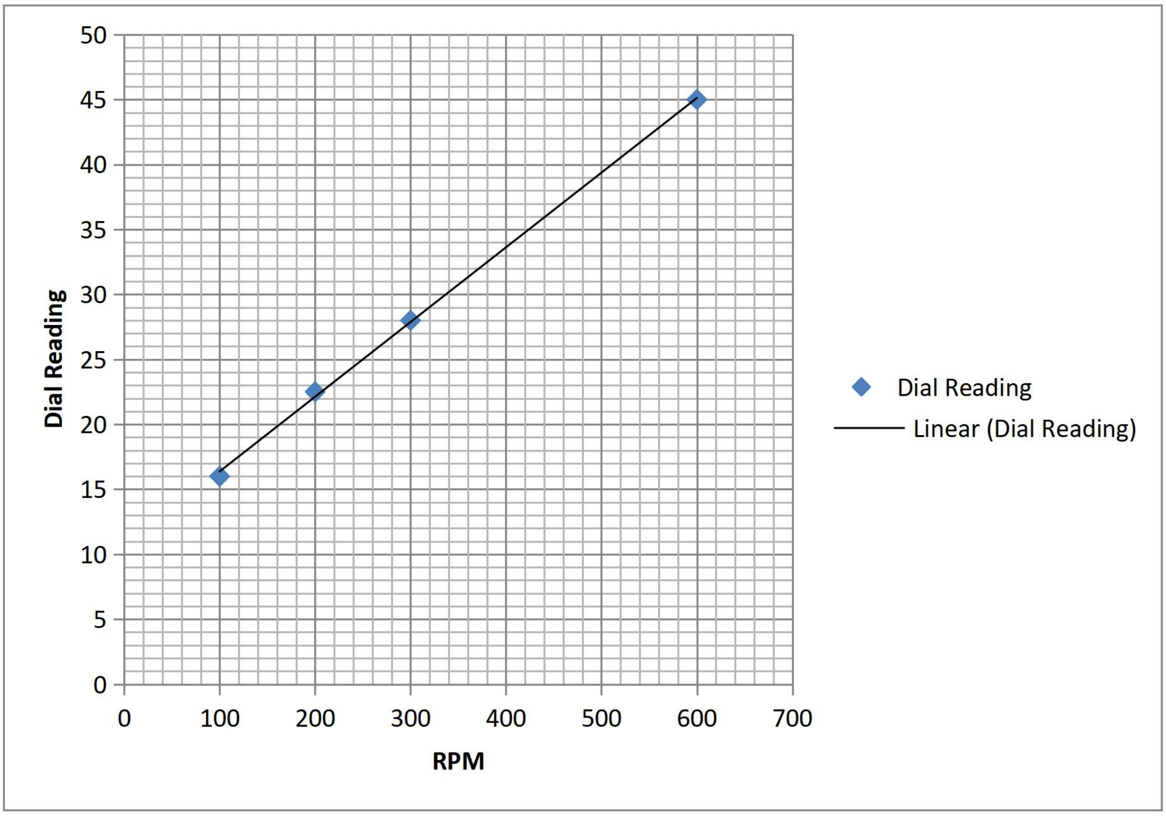

Fig. 3.6.3: Plot of Dial Reading vs RPM (Gum Arabic-Cocoyam; 50/50)

3.6.4 EXPERIMENTAL RESULTS OF MUD MIXTURE + GUM ARABIC & COCOYAM (75/25)

RPM	**GA-CO (37.5g & 12.5g)**
600	30
300	24
200	19
100	13
Gel strength	
10`	16
10``	19
Yield point	18.0
Plastic viscosity	6.0
Density (g/cc)	8.2

Table 3.6.4: Results of mud mixture with gum Arabic& cocoyam

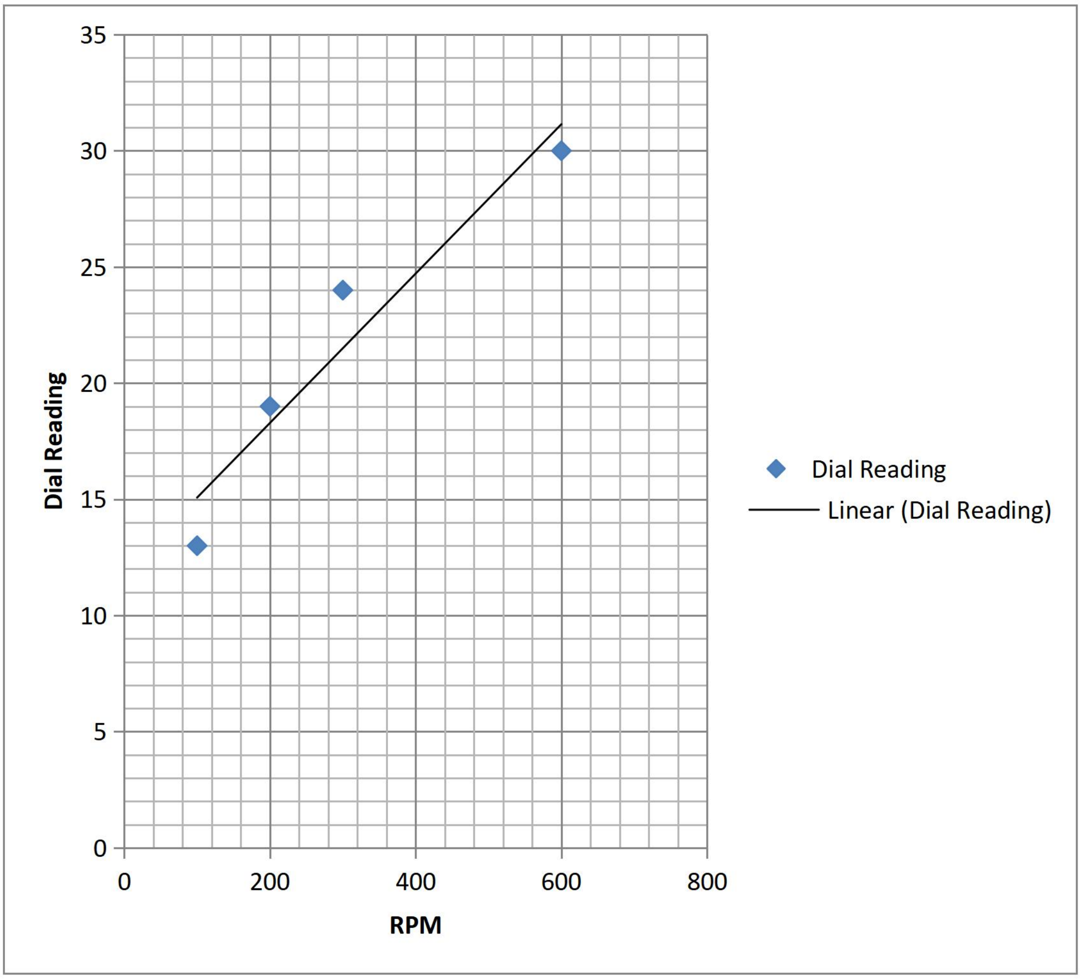

Fig. 3.6.4: Plot of Dial Reading vs RPM (Gum Arabic-Cocoyam; 75/25)

3.6.5 EXPERIMENTAL RESULTS FOR MUD MIXTURE + GUM ARABIC & GINGER (50/50)

RPM	GA-Ginger (25g &25g)
600	48
300	30
200	24
100	27
Gel strength	
10`	20
10``	24
Yield point	12
Plastic viscosity	18
Density (g/cc)	8.1

Table 3.6.5: Results of mud mixture with gum Arabic and ginger (50/50)

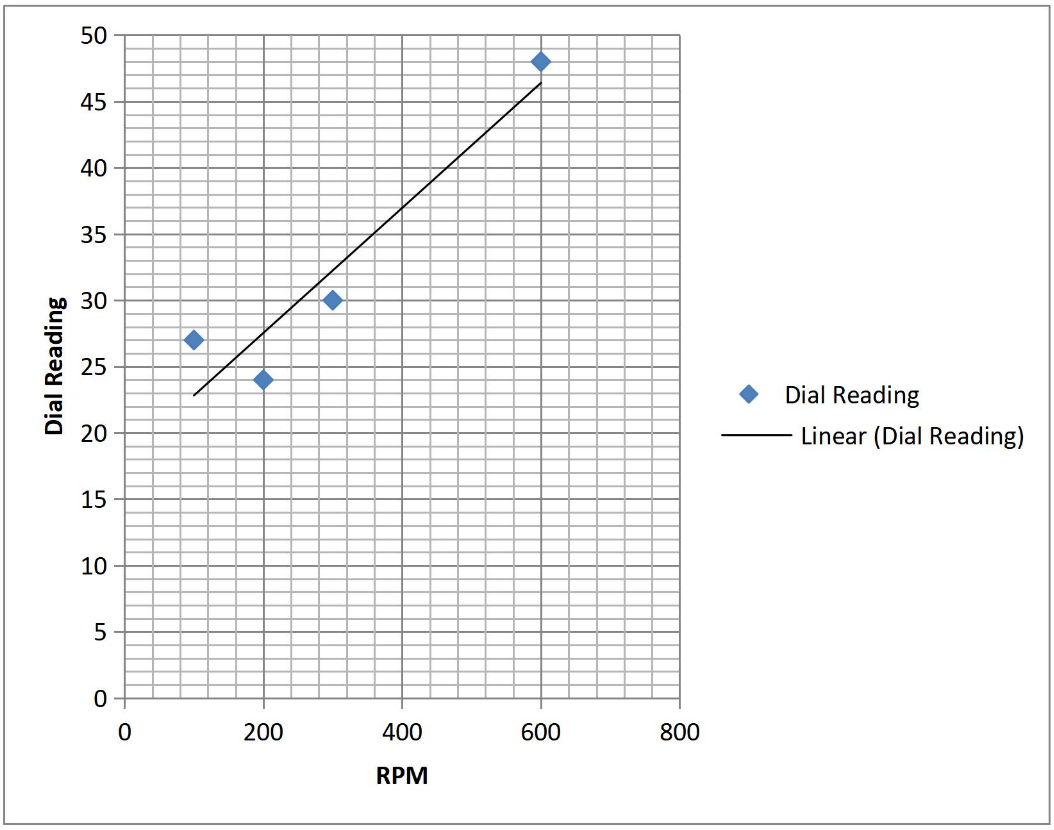

Fig. 3.6.5: Plot of Dial Reading vs RPM (Gum Arabic-Ginger; 50/50)

3.6.6 EXPERIMENTAL RESULTS OF MUD MIXTURE + GUM ARABIC & GINGER (75/25)

RPM	**GA-Ginger (37.5g & 12.5g)**
600	44.5
300	28.0
200	21.5
100	15.5
Gel strength	
10`	19.0
10``	18
Yield point	11.5
Plastic viscosity	16.5
Density (g/cc)	8.0

Table 3.6.6: Results of mud mixture with gum Arabic & ginger (75/25)

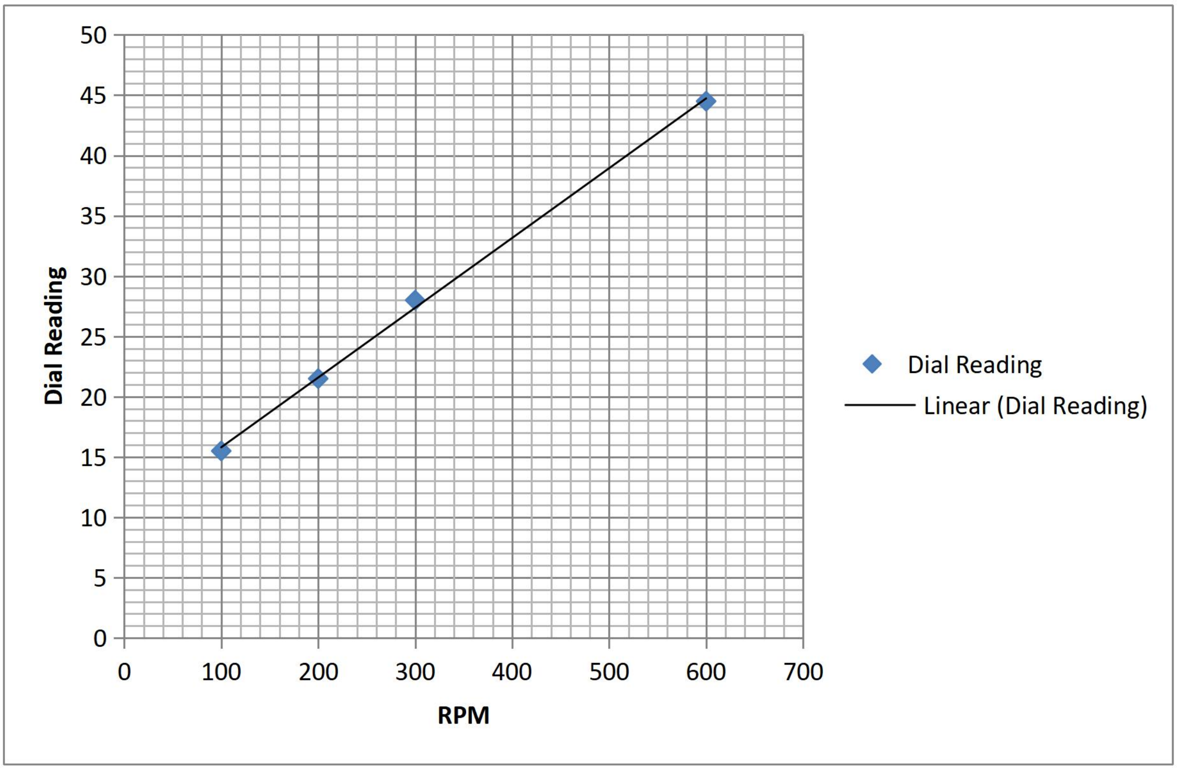

Fig. 3.6.6: Plot of Dial Reading vs RPM (Gum Arabic-Ginger; 75/25)

3.7 EXPERIMENT TWO (USING ALKALINE)

- The experiment on the mixture using NaOH and 1g of Xanthan gum was concluded to be Immiscible as its mixture resulted in a lot of "fish eye".

3.7.1 EFFECTS OF NAOH ON GINGER (25G) & GUM ARABIC (25G)

RPM	**NaOH 3.0g**	**NaOH 7.5g**
600	85	225
300	54	117
200	43	120
100	30	85
Gel Strength		
10secs	45	90
10mins	50	10
Density	6.7	8.2
pH	11	11

Table 3.7.1: Results of NaOH (3.0g &7.5g) with mud mixture & ginger

3.7.2 EFFECTS OF NAOH (7.5G & 15.0G) ON GUM ARABIC (50G)

RPM	**7.5g**	**15.0g**
600	54	56.5
300	31	33
200	25.5	21
100	15	11
Gel strength		
10 secs	20	20
10 mins	24	16
Density (g/cc)	7.85	7.7
pH	10	11

Table 3.7.2: Results of NaOH with mud mixture & gum Arabic

- Observation: During the 10 mins wait, there was formation of foam and an increase in temperature when mixing with the mud mixer.

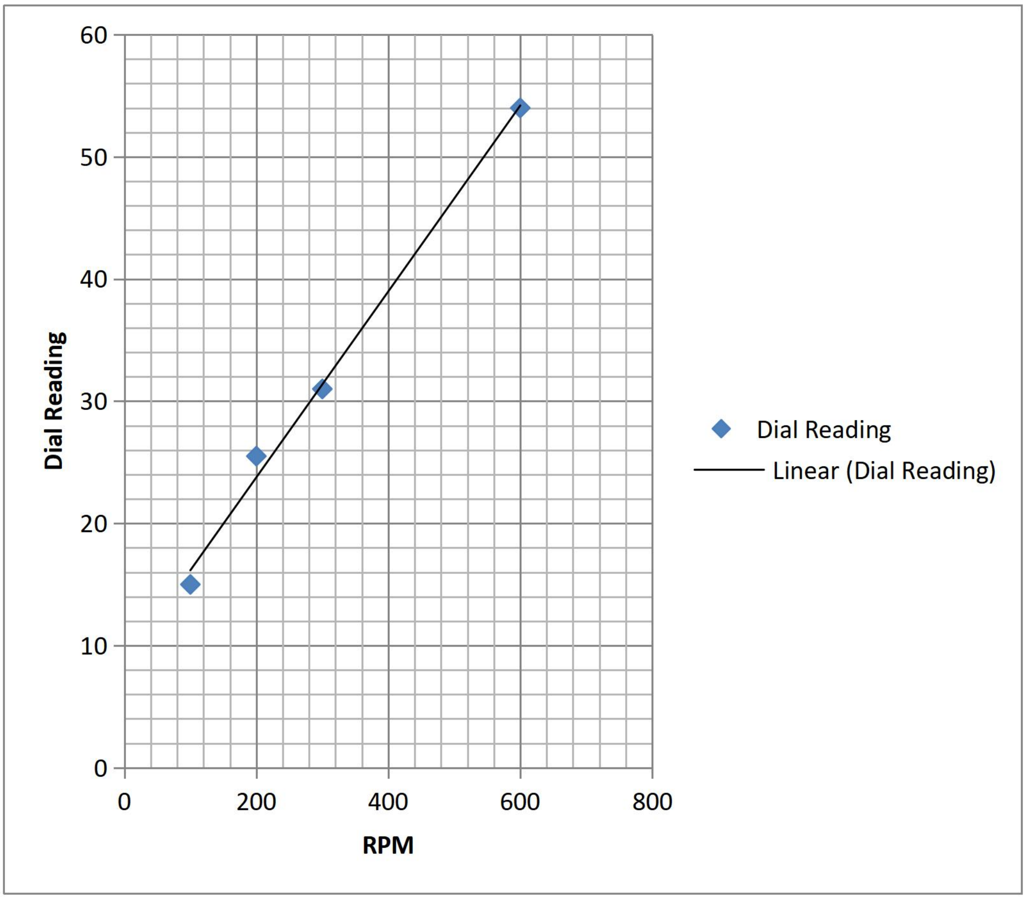

Fig. 3.7.2: Dial Reading vs RPM (NaOH-Gum Arabic)

3.7.3 EFFECTS OF NAOH (3.0G & 7.5G) ON GUM ARABIC (25G) AND COCOYAM (25G)

RPM	**NaOH 3.0g**	**NaOH 7.5g**
600	52	310
300	34	245
200	26	50
100	19	45
Gel Strength		
10 secs	18	90
10 mins	32	112
Density (g/cc)	8.2	8.5
pH	10	11

Table 3.7.3: Results of NaOH, gum Arabic & cocoyam

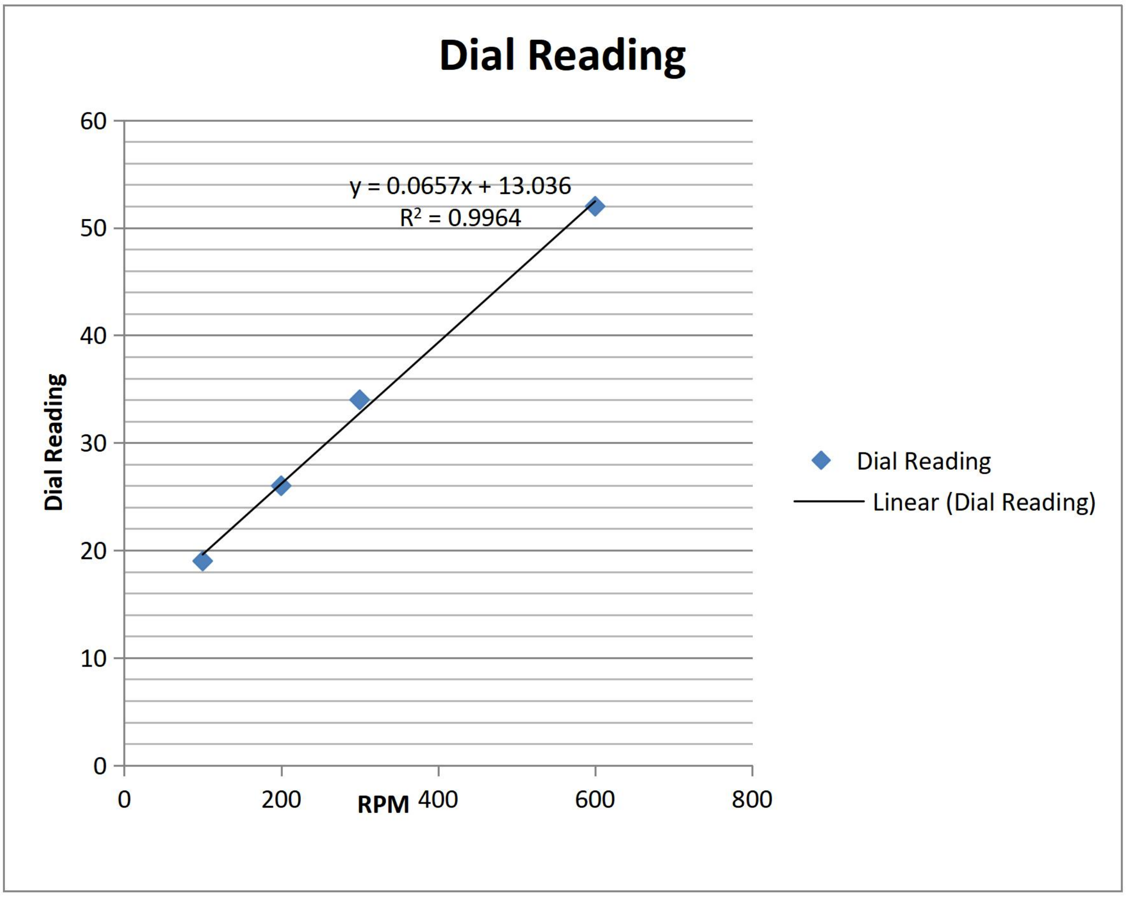

Fig. 3.7.3: Plot of Dial Reading vs RPM (NaOH, 3.0g- GA-CO; 25g/25g)

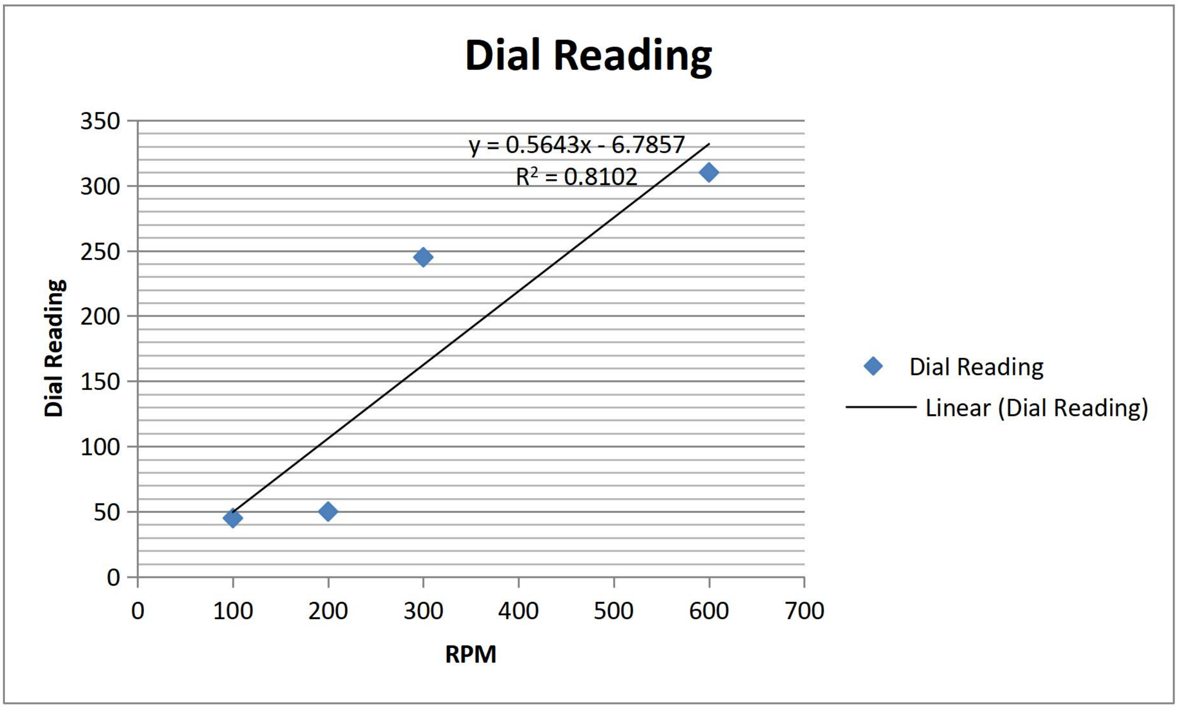

Fig. 3.7.4: Plot of Dial Reading vs RPM (NaOH, 7.5g-GA-CO; 25g/25g)

3.7 CALCULATIONS

PLASTIC VISCOSITY (PV)

PV= Ø600 - Ø300

YIELD POINT (YP)

YP= Ø300 – PV

n = 3.32 Log Ø600/ Ø300

K = 5.11* Ø300/ $(511)^n$

τ = 1.067 * dial reading ($lbf/100ft^2$)

γ = 1.703 * rpm (sec^{-1})

3.8.1 EFFECT OF 7.5G OF NAOH ON THE RHEOLOGICAL PROPERTIES OF 50G OF GUM ARABIC

RPM	**7.5g of NaOH**	**15.0g OF NaOH**
600	54	56.5
300	31	33
200	25.5	21
100	15	11
Gel strength		
10 secs	20	20
10 mins	24	16
Density (g/cc)	7.85	7.7
pH	10	11
n	0.8	0.78
K	1.0	1.0
PV	23	23.5
YP	8	9.5

Table 3.8.1: Effect of Alkaline on 50g of Gum Arabic

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 50g OF GUM ARABIC

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	58	340	256	314
511	33	200	147	180
341	28	150	106	134
170	16	85	61	77

Table 3.8.1b: Model data of 7.5g of alkaline on 50g of Gum Arabic

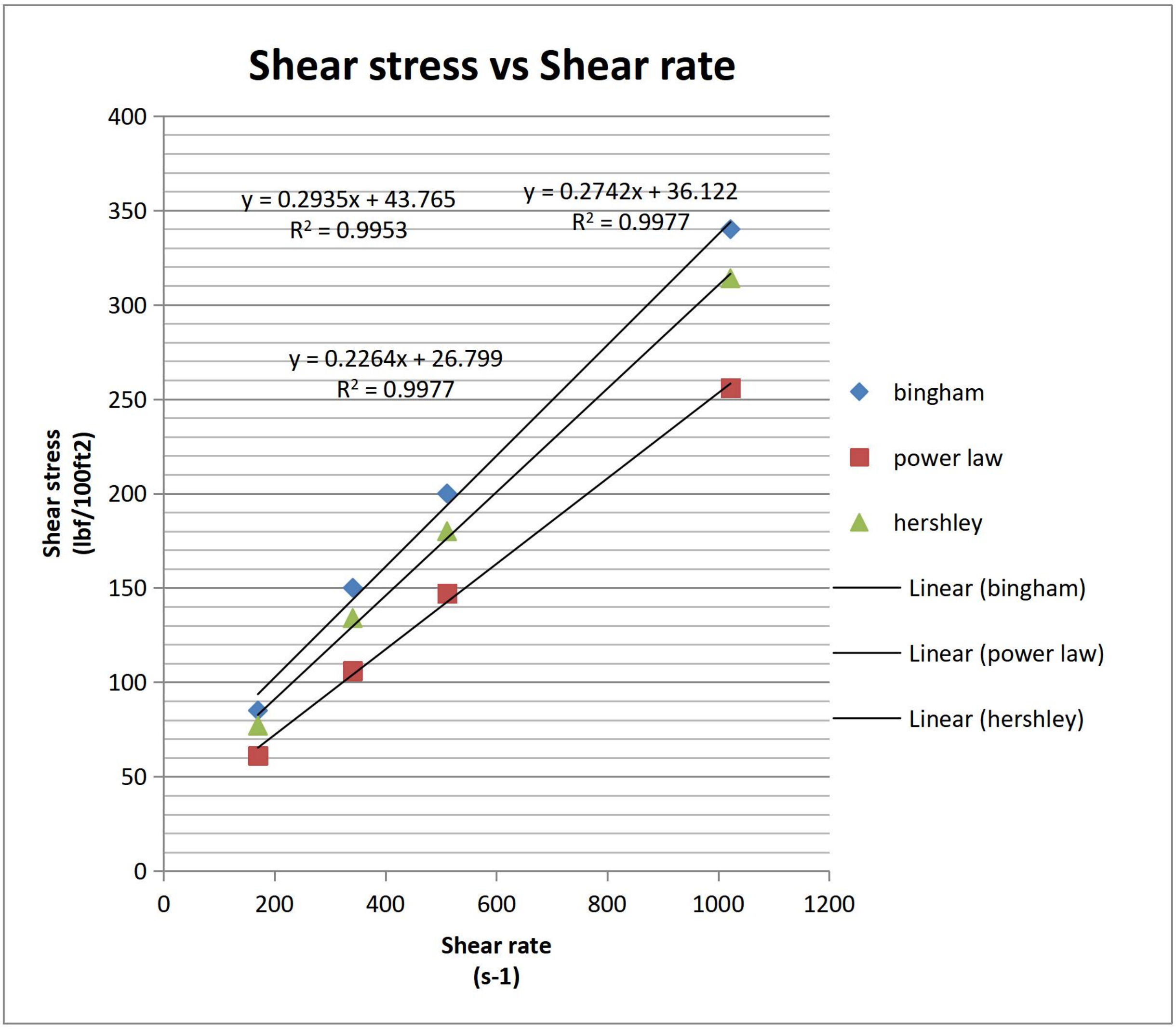

Fig 3.8.1b: Plot of Shear stress versus shear rate of the effect of 7.5g of NaOH on 50g of gum arabic mud system

MODEL DATA TO DETERMINE THE EFFECT OF 15g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 50g OF GUM ARABIC

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	61	312	223	284
511	33	180	130	163
341	22	135	95	117
170	12	75	55	67

Table 3.8.1c: Model data of 15.0g of alkaline on 50g of Gum Arabic

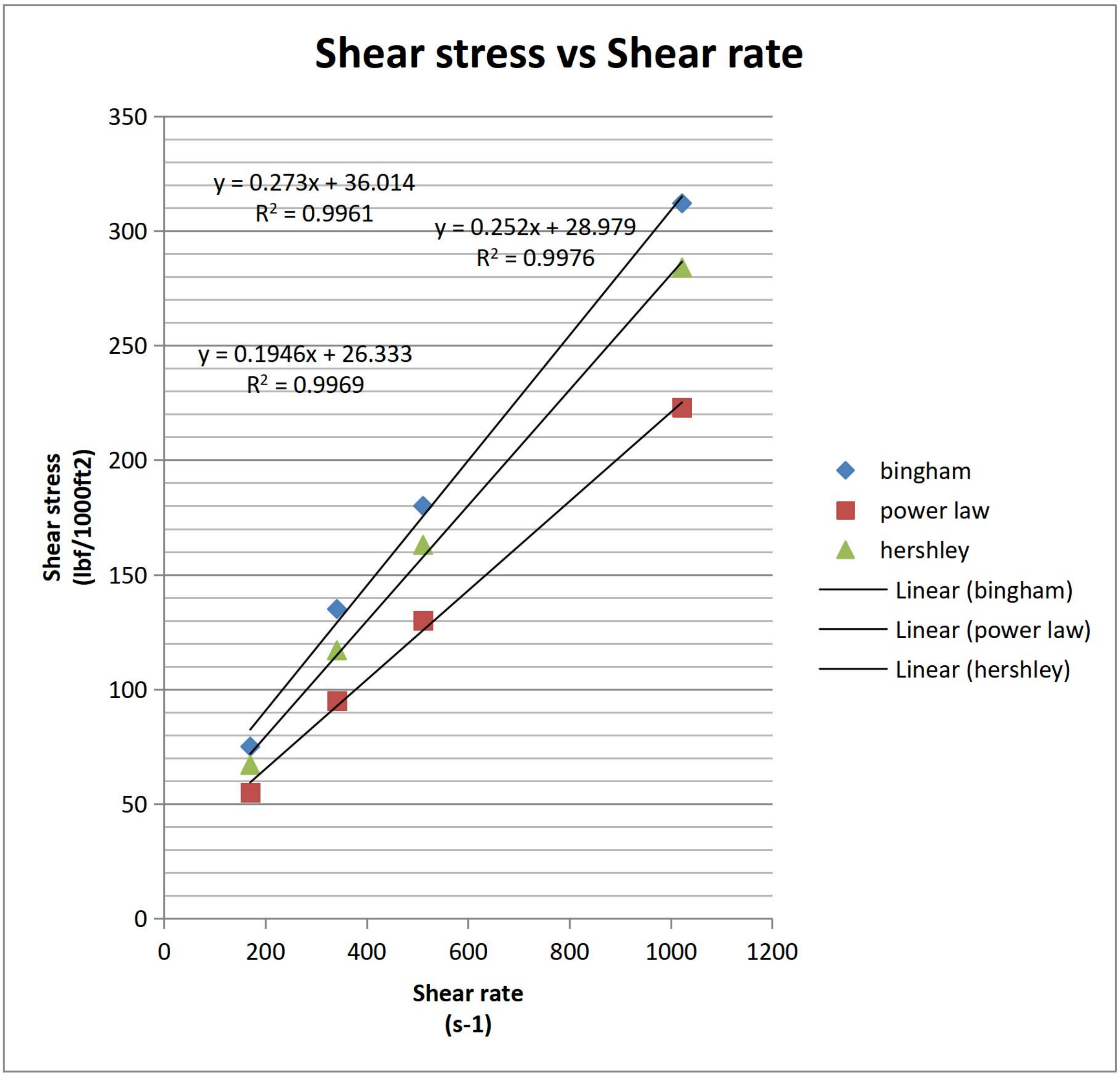

Fig. 3.8.1c: Plot of Shear stress versus shear rate of the effect of 15.0g of NaOH on 50g of gum arabic mud system

3.8.2 EFFECTS OF NAOH (3.0G & 7.5G) ON GUM ARABIC (25G) AND COCOYAM (25G)

RPM	**NaOH of 3.0g**	**NaOH of 7.5g**
600	52	310
300	34	245
200	26	50
100	19	45
Gel Strength		
10 secs	18	90
10 mins	32	112
Density (g/cc)	8.2	8.5
pH	10	11
n	0.948	0.3
K	0.4	0.8
PV	18	65
YP	16	180

Table 3.8.2: Effect of Alkaline on 25g of Gum Arabic & 25g of Cocoyam

MODEL DATA TO DETERMINE THE EFFECT OF 3.0g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC & 25g OF COCOYAM

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	55	302	285	340
511	36	155	148	186
341	28	122	101	129
170	20	66	52	72

Table 3.8.2b: Model data of 3.0g of alkaline on 25g of Gum Arabic & 25g of Cocoyam

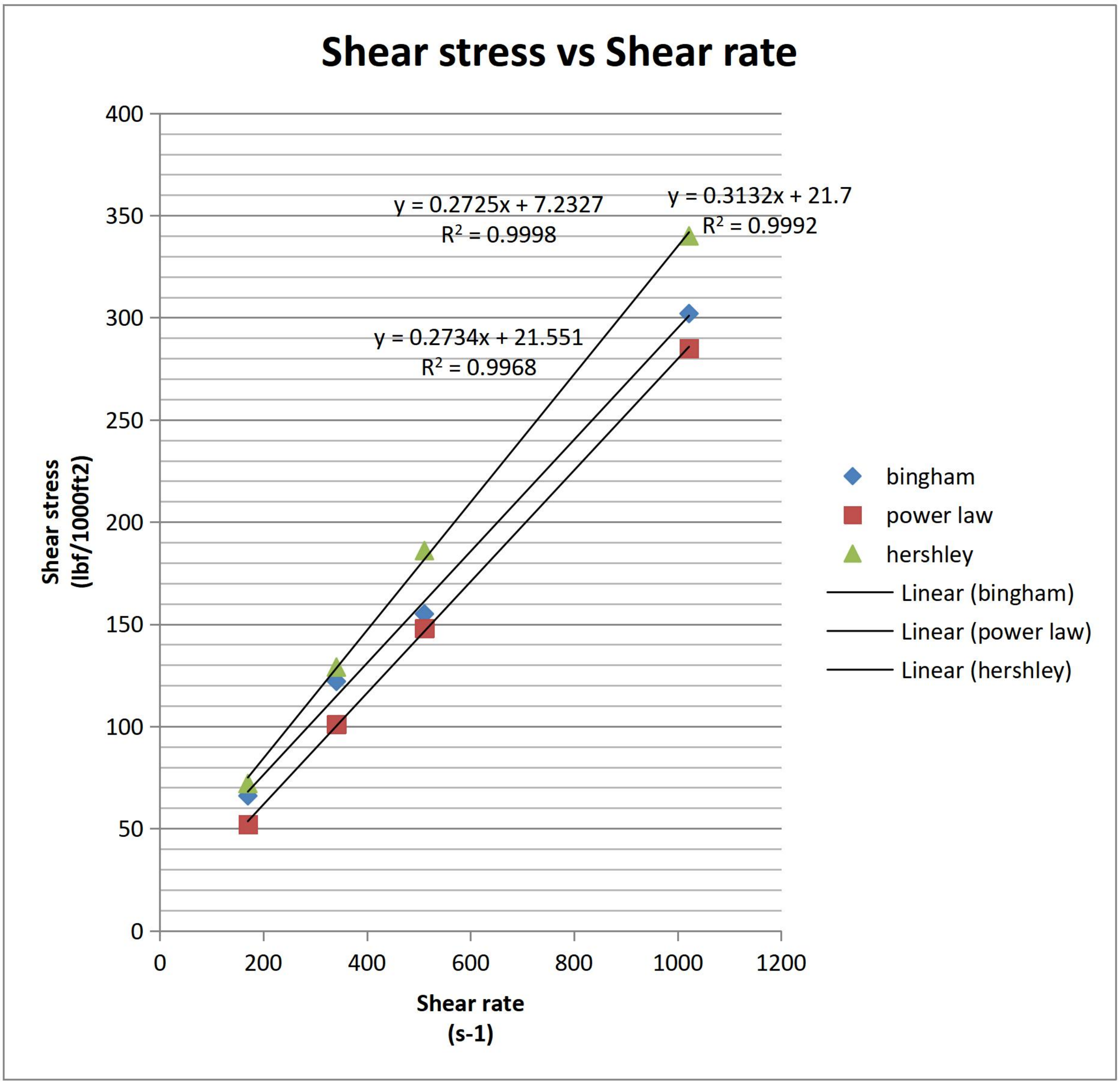

Fig. 3.8.2b: Plot of Shear stress versus shear rate of the effect of 3.0g of NaOH on 25g of gum arabic & 25g of cocoyam mud system

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC & 25g OF COCOYAM

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	331	66610	6	337
511	261	33395	5	266
341	53	22345	4	57
170	48	11230	3	51

Table 3.8.2c: Model data of 7.5g of alkaline on 25g of Gum Arabic & 25g of Cocoyam

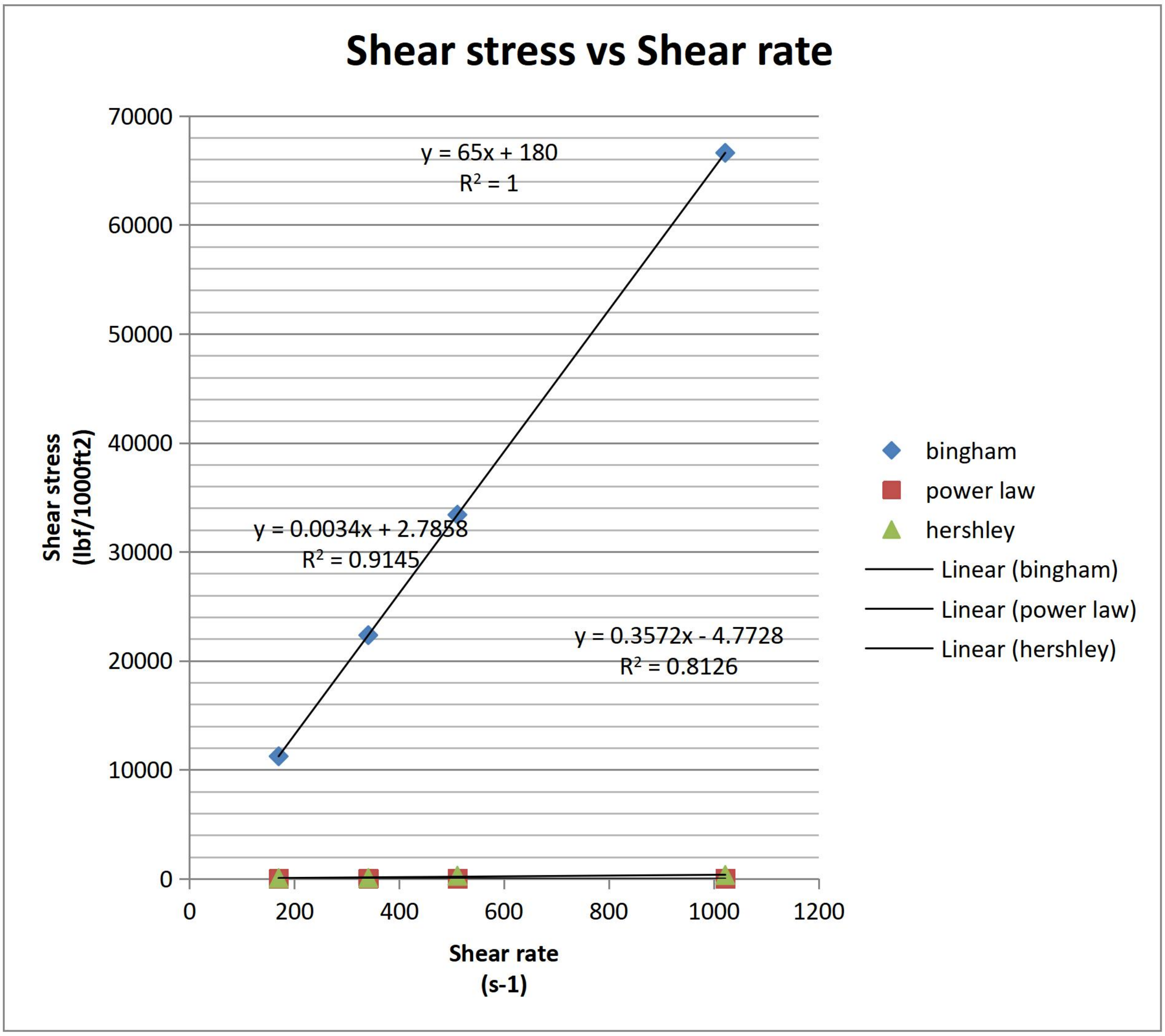

Fig. 3.8.2c: Plot of Shear stress versus shear rate of the effect of 7.5g of NaOH on 25g of gum arabic & 25g of cocoyam mud system

3.8.3 EFFECTS OF NAOH ON GINGER (25G) & GUM ARABIC (25G)

RPM	**NaOH of 3.0g**	**NaOH of 7.5g**
600	85	225
300	54	117
200	43	120
100	30	85
Gel Strength		
10secs	45	90
10mins	50	10
Density (g/cc)	6.7	8.2
pH	11	11
n	0.948	0.943
K	0.74	0.91
PV	31	108
YP	23	9

Table 3.8.3: Effects of alkaline on 25g gum arabic & 25g ginger mud system

MODEL DATA TO DETERMINE THE EFFECT OF 3.0g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC & 25g OF GINGER

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	91	412	527	618
511	58	172	273	331
341	46	96	186	232
170	32	74	96	128

Table 3.8.3b: Model data of 3.0g of alkaline on 25g of Gum Arabic & 25g of Ginger

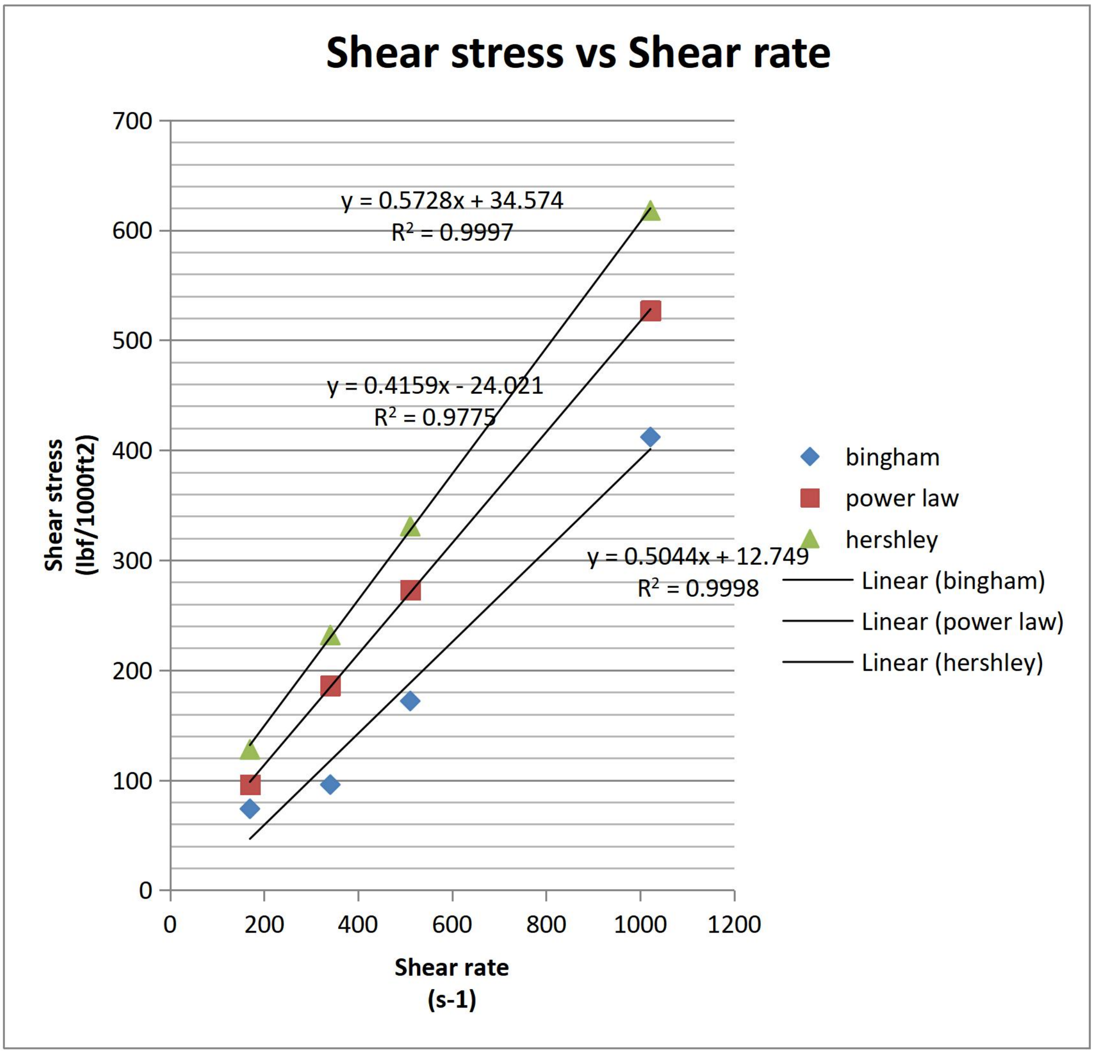

Fig. 3.8.3b: Plot of Shear stress versus shear rate of the effect of 3.0g of NaOH on 25g of gum arabic & 25g of ginger mud system

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF NaOH ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC & 25g OF GINGER

Shear rate (s^{-1})	**Shear stress(lbf/100ft^2)**	**Bingham plastic model (lbf/100ft^2)**	**Power law model (lbf/100ft^2)**	**Hershely Buckley model (lbf/100ft^2)**
1022	240	922	627	867
511	125	500	326	451
341	128	413	223	351
170	91	302	115	206

Table 3.8.3c: Model data of 7.5g of alkaline on 25g of Gum Arabic & 25g of Ginger

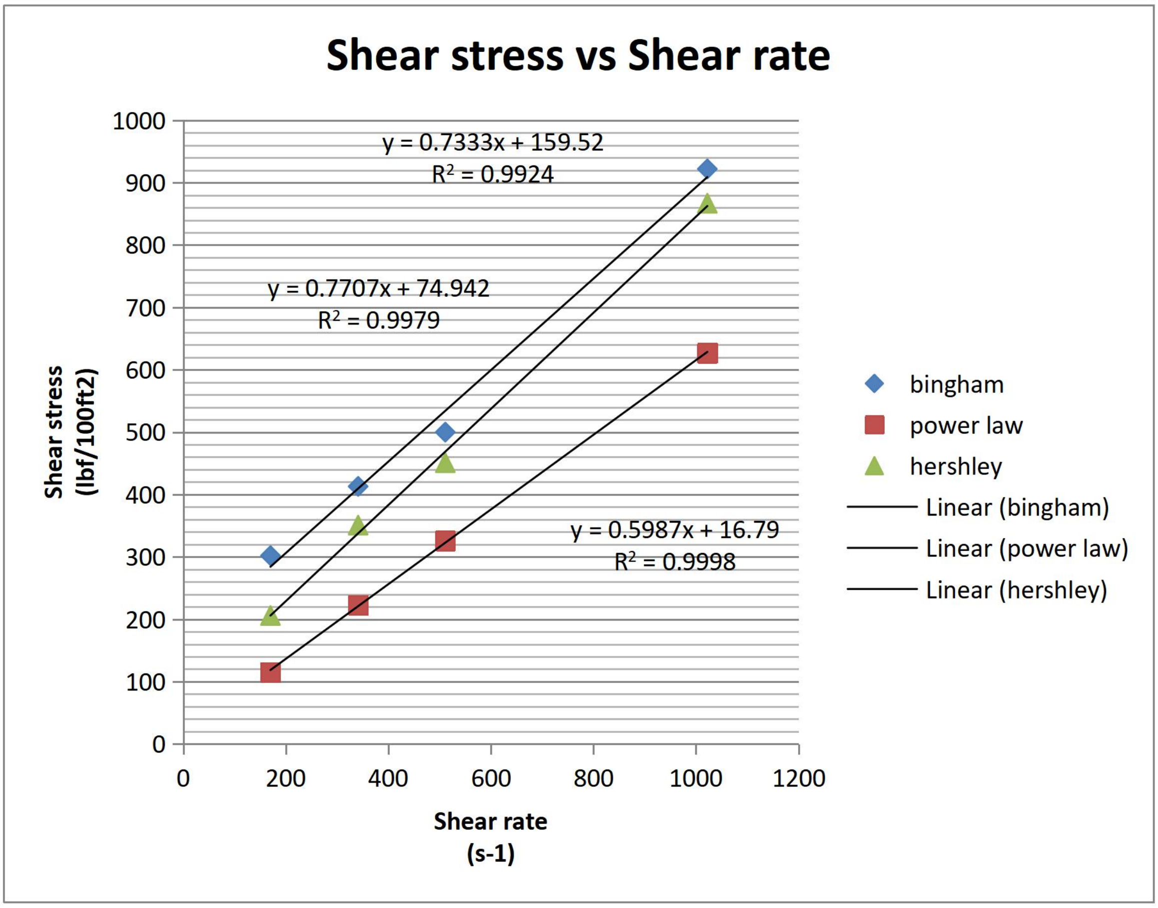

Fig. 3.8.3c: Plot of Shear stress versus shear rate of the effect of 7.5g of NaOH on 25g of gum arabic & 25g of ginger mud system

CHAPTER 4

ANALYSIS OF RESULTS

4.1 RESULT ANALYSIS

This chapter presents a comprehensive analysis of the experimental results obtained from the rheological investigation of beneficiated gum Arabic-based drilling fluid formulations. The analysis focuses on two major experimental phases: baseline experiments without pH modification and experiments with sodium hydroxide (NaOH) addition at varying concentrations. The rheological parameters evaluated include plastic viscosity, yield point, gel strength, and density, with subsequent classification of fluid behavior using standard rheological models (Bingham Plastic, Power Law, and Herschel-Bulkley models).

4.2 BASELINE EXPERIMENTAL RESULTS (WITHOUT NaOH)

4.2.1 COMPARISON OF POLYMER SYSTEMS

Table 3.4.1 presents the baseline rheological properties of seven different formulations: bentonite only, bentonite with xanthan gum, bentonite with gum Arabic, and four blended systems combining gum Arabic with cocoyam or ginger at different ratios (50/50 and 75/25).

PLASTIC VISCOSITY ANALYSIS:

The plastic viscosity (PV) values varied significantly across the formulations. Xanthan gum exhibited the highest PV of 11.5 cp, followed closely by gum Arabic at 10.5 cp. The bentonite-only system showed the lowest PV of 2.5 cp, which is expected given the absence of high-molecular-weight polymers. Among the blended systems, the gum Arabic-ginger (50/50) formulation demonstrated the highest PV of 18.0 cp, while the gum Arabic-cocoyam (75/25) showed the lowest at 6.0 cp. The elevated plastic viscosity in the ginger-containing formulations suggests enhanced internal resistance to flow, likely due to the starch content of ginger contributing to increased solid-liquid phase interactions.

YIELD POINT ANALYSIS:

Yield point (YP) values ranged from 4.0 lb/100ft^2 for bentonite to 24.0 lb/100ft^2 for both xanthan gum and gum Arabic systems. The blended formulations exhibited lower yield points, with values between 11.0 and 18.0 lb/100ft^2. Notably, xanthan gum and gum Arabic demonstrated identical yield points (24.0 lb/100ft^2), indicating comparable resistance to initial flow despite their different molecular structures. The gum Arabic-cocoyam (75/25) formulation showed a relatively high yield point of 18.0 lb/100ft^2, suggesting effective particle suspension capability.

GEL STRENGTH CHARACTERISTICS:

Gel strength measurements at 10 seconds and 10 minutes revealed the static suspension capacity of each formulation. Xanthan gum exhibited the highest gel strengths (29.0 and 35.0 lb/100ft^2 at 10 seconds and 10 minutes, respectively), indicating superior ability to suspend solids during circulation stoppages. The progression from 10-second to 10-minute gel strength was most pronounced in xanthan gum, with an increase of approximately 20.7%, suggesting rapid gel structure development. Conversely, the gum Arabic-cocoyam (50/50) system showed minimal gel strength progression (from 15.0 to 20.0 lb/100ft^2), indicating a more stable, less time-dependent gel structure.

DENSITY OBSERVATIONS:

Density values across all formulations ranged from 8.0 to 8.7 g/cc (equivalent to approximately 8.0 to 8.7 ppg). The variations were relatively minor, with xanthan gum showing the highest density (8.7 g/cc) and the gum Arabic-ginger (75/25) formulation the lowest (8.0 g/cc). The blended gum Arabic-cocoyam and gum Arabic-ginger systems exhibited lower densities (8.0-8.2 g/cc) compared to the pure polymer systems, likely due to differences in solid content and dispersion characteristics.

4.2.2 RHEOLOGICAL BEHAVIOR CLASSIFICATION

Analysis of the shear stress versus shear rate relationships *(Figures 3.6 through 3.6.6)* reveals distinct flow behaviors:

BENTONITE SYSTEM *(Fig. 3.6):*

The bentonite-water system exhibited relatively linear behavior with minimal yield stress, characteristic of a near-Newtonian to slightly pseudoplastic fluid. The low dial readings across all RPM values (4.5 to 9.0) indicate limited structural development.

XANTHAN GUM SYSTEM *(Fig. 3.6.1):*

The xanthan gum formulation displayed pronounced non-Newtonian behavior with substantial deviation from linearity. The dial readings ranged from 25.0 at 100 RPM to 46.0 at 600 RPM, demonstrating significant shear-thinning characteristics typical of pseudoplastic fluids. This behavior aligns with xanthan gum's known ability to form extensive intermolecular networks through hydrogen bonding and entanglement.

GUM ARABIC SYSTEM *(Fig. 3.6.2):*

Gum Arabic exhibited rheological behavior remarkably similar to xanthan gum, with dial readings of 25.0 at 100 RPM increasing to 45.0 at 600 RPM. This observation confirms that at the concentration tested (50g in 500ml), gum Arabic can effectively replicate the viscosifying properties of 1g xanthan gum, as noted in the experimental observations *(Section 3.4.4).*

BLENDED SYSTEMS *(Figures 3.6.3 through 3.6.6):*

The gum Arabic-cocoyam and gum Arabic-ginger blends demonstrated intermediate rheological behaviors. Notably, the 50/50 ratios generally produced higher viscosities and yield points compared to the 75/25 ratios, suggesting that optimal polymer-starch interactions occur at balanced concentrations. The gum Arabic-ginger (50/50) system showed the highest dial readings among blended formulations, reaching 48.0 at 600 RPM, indicating superior viscosification.

4.3 EFFECTS OF SODIUM HYDROXIDE ON RHEOLOGICAL PROPERTIES

4.3.1 GUM ARABIC WITH NAOH (7.5G AND 15.0G)

Table 3.7.2 and 3.8.1 present the effects of alkaline treatment on pure gum Arabic formulations.

RHEOLOGICAL PARAMETER CHANGES:

The addition of 7.5g NaOH resulted in dial readings of 54 and 31 at 600 and 300 RPM respectively, yielding a plastic viscosity of 23 cp and yield point of 8 lb/100ft^2. Increasing NaOH concentration to 15.0g produced minimal changes (PV = 23.5 cp, YP = 9.5 lb/100ft^2), suggesting that the rheological modification plateaus beyond a certain alkaline threshold. The pH values of 10 and 11 for 7.5g and 15.0g NaOH respectively confirm progressive alkalinization.

FLOW BEHAVIOR INDEX ANALYSIS:

The power law flow behavior indices (n) were 0.8 and 0.78 for 7.5g and 15.0g NaOH respectively, both indicating pseudoplastic (shear-thinning) behavior. The consistency indices (K) remained constant at 1.0 Pa·s^n^ for both concentrations. These values suggest that while NaOH modifies the polymer chain conformation through deprotonation of carboxyl groups, excessive alkalinity does not proportionally enhance rheological properties.

MODEL FITTING ANALYSIS *(Tables 3.8.1b and 3.8.1c):*

Comparison of experimental shear stress values with predicted values from three rheological models revealed:

BINGHAM PLASTIC MODEL: Significantly overestimated shear stress at all shear rates, particularly at higher RPM values (e.g., 340 lb/100ft^2 predicted vs. 58 lb/100ft^2 experimental at 1022 s^{-1} for 7.5g NaOH system).

POWER LAW MODEL: Provided better predictions but still overestimated shear stress, particularly at intermediate shear rates (e.g., 256 lb/100ft^2 predicted vs. 58 lb/100ft^2 experimental at 1022 s^{-1}).

HERSHLEY-BULKLEY MODEL: Showed intermediate predictions between Bingham Plastic and Power Law models, suggesting partial applicability but still with considerable deviation from experimental values.

The graphical representations *(Figures 3.8.1b and 3.8.1c)* clearly demonstrate that none of the classical models perfectly describe the alkaline-modified gum Arabic system, with all models consistently overestimating shear stress. This discrepancy suggests that alkaline treatment induces complex structural changes in gum Arabic that are not fully captured by conventional two- or three-parameter rheological models.

4.3.2 GUM ARABIC-COCOYAM BLEND WITH NAOH (3.0G AND 7.5G)

Tables 3.7.3 and 3.8.2 reveal dramatic rheological changes upon alkaline treatment of the gum Arabic-cocoyam (50/50) system.

CONCENTRATION-DEPENDENT EFFECTS:

The addition of 3.0g NaOH produced moderate increases in rheological parameters (PV = 18 cp, YP = 16 lb/100ft^2, pH = 10). However, increasing NaOH to 7.5g resulted in extraordinary enhancement: PV increased to 65 cp and YP to 180 lb/100ft^2 (pH = 11). This represents a 261% increase in plastic viscosity and a 1025% increase in yield point compared to the 3.0g NaOH system. Such dramatic changes indicate synergistic interactions between alkaline-activated gum Arabic and cocoyam starch.

GEL STRENGTH DEVELOPMENT:

The 7.5g NaOH system exhibited remarkable gel strength progression from 90 lb/100ft^2 at 10 seconds to 112 lb/100ft^2 at 10 minutes, representing a 24.4% increase. This progressive gelation suggests time-dependent structural organization within the polymer-starch network, likely driven by hydrogen bonding and electrostatic interactions enhanced by the alkaline environment.

FLOW BEHAVIOR ANALYSIS:

The flow behavior index decreased dramatically from $n = 0.948$ (near-Newtonian) at 3.0g NaOH to $n = 0.3$ (highly pseudoplastic) at 7.5g NaOH. This shift indicates transformation from mildly shear-thinning to strongly shear-thinning behavior. The consistency index doubled from $K = 0.4$ to $K = 0.8$ Pa·s^n^, reflecting increased fluid consistency.

MODEL COMPARISON *(Tables 3.8.2b and 3.8.2c, Figures 3.8.2b and 3.8.2c)***:**

For the 3.0g NaOH system, all three models provided relatively close predictions, with the Hershley-Bulkley model showing the best agreement with experimental data. However, for the 7.5g NaOH system, the Bingham Plastic model drastically overestimated shear stress (e.g., 66,610 lb/100ft^2 predicted vs. 331 lb/100ft^2 experimental at 1022 s^{-1}), while the Power Law model severely underestimated it (6 lb/100ft^2 predicted). The Hershley-Bulkley model provided the most reasonable predictions, though still with notable deviations, suggesting it is the most appropriate model for highly alkaline gum Arabic-cocoyam systems.

4.3.3 GUM ARABIC-GINGER BLEND WITH NAOH (3.0G AND 7.5G)

Tables 3.7.1 and 3.8.3 present the rheological response of gum Arabic-ginger (50/50) formulations to alkaline treatment.

RHEOLOGICAL PARAMETER PROGRESSION:

The gum Arabic-ginger system showed substantial but less dramatic increases compared to the cocoyam blend. At 3.0g NaOH, the system exhibited PV = 31 cp and YP = 23 lb/100ft^2 (pH = 11). Increasing NaOH to 7.5g resulted in PV = 108 cp (248% increase) and YP = 9 lb/100ft^2 (61% decrease). The reduction in yield point at higher alkalinity is particularly noteworthy and suggests that excessive alkaline treatment may disrupt the gel structure developed by ginger polysaccharides.

GEL STRENGTH ANOMALY:

An unusual observation was the dramatic decrease in 10-minute gel strength from 50 lb/100ft^2 (3.0g NaOH) to 10 lb/100ft^2 (7.5g NaOH), representing an 80% reduction. This anomalous behavior, combined with the elevated 10-second gel strength (90 lb/100ft^2 at 7.5g NaOH), suggests rapid gel formation followed by structural breakdown over time. This phenomenon may indicate hydrolysis or degradation of ginger polysaccharides under highly alkaline conditions.

FLOW BEHAVIOR CHARACTERISTICS:

Both NaOH concentrations produced near-identical flow behavior indices (n = 0.948 for 3.0g and n = 0.943 for 7.5g), indicating stable pseudoplastic behavior regardless of alkalinity. The consistency index increased modestly from K = 0.74 to K = 0.91 Pa·s^n^, suggesting moderate enhancement of fluid consistency.

MODEL FITTING RESULTS *(Tables 3.8.3b and 3.8.3c, Figures 3.8.3b and 3.8.3c):*

For the 3.0g NaOH system, the Power Law model significantly overestimated shear stress at high shear rates (527 lb/100ft^2 predicted vs. 91 lb/100ft^2 experimental at 1022 s^{-1}), while the Hershley-Bulkley model provided the most accurate predictions. At 7.5g NaOH, all models overestimated shear stress, with the Bingham Plastic model showing the largest deviations. The Hershley-Bulkley model again performed best, though with increasing error at higher shear rates, confirming its general applicability to alkaline-modified natural polymer systems.

4.4 COMPARATIVE ANALYSIS OF ALKALINE EFFECTS

4.4.1 SYSTEM-SPECIFIC RESPONSES

The three systems investigated (gum Arabic alone, gum Arabic-cocoyam, and gum Arabic-ginger) demonstrated distinctly different responses to alkaline treatment:

GUM ARABIC: Showed moderate, plateau-limited response with minimal difference between 7.5g and 15.0g NaOH, suggesting saturation of available functional groups.

GUM ARABIC-COCOYAM: Exhibited explosive rheological enhancement at 7.5g NaOH, indicating strong synergistic activation between alkaline-modified gum Arabic and cocoyam starch gelatinization.

GUM ARABIC-GINGER: Demonstrated substantial viscosity increases but with compromised long-term gel strength stability, suggesting susceptibility to alkaline degradation.

4.4.2 PRACTICAL IMPLICATIONS FOR DRILLING OPERATIONS

OPTIMAL FORMULATIONS:

Based on the experimental results, the following observations are relevant for drilling fluid design:

CUTTING TRANSPORT EFFICIENCY: The gum Arabic-cocoyam system with 7.5g NaOH exhibited the highest plastic viscosity (65 cp) and yield point (180 lb/100ft²), suggesting superior cuttings suspension and transport capacity.

GEL STRENGTH STABILITY: The gum Arabic-ginger system with 3.0g NaOH provided balanced gel strength progression (45 to 50 lb/100ft²), beneficial for preventing barite sagging and maintaining wellbore cleanliness during circulation breaks.

SHEAR-THINNING BEHAVIOR: All alkaline-modified systems exhibited pseudoplastic behavior ($n < 1$), which is desirable for drilling operations as it ensures high viscosity at low shear rates (cuttings suspension) and low viscosity at high shear rates (pump efficiency).

DENSITY CONSIDERATIONS:

The alkaline-modified gum Arabic-ginger system (3.0g NaOH) showed reduced density (6.7 g/cc), which may be advantageous for drilling in low-pressure formations to minimize formation damage. Conversely, the gum Arabic-cocoyam system maintained higher density (8.2-8.5 g/cc), suitable for pressure control in higher-pressure environments.

4.5 RHEOLOGICAL MODEL APPLICABILITY

4.5.1 MODEL PERFORMANCE SUMMARY

Across all formulations tested, the Hershley-Bulkley model consistently provided the best fit to experimental data, particularly for alkaline-modified systems. This three-parameter model effectively captures both yield stress and power-law flow behavior, making it most suitable for describing natural polymer-based drilling fluids.

The Bingham Plastic model, while simpler, consistently overestimated shear stress, particularly at high shear rates and in highly alkaline systems. Its assumption of constant plastic viscosity beyond yield stress does not adequately represent the shear-thinning nature of these polymer systems.

The Power Law model, lacking a yield stress term, failed to predict low-shear-rate behavior accurately, particularly underestimating shear stress in systems with well-developed gel structures.

4.5.2 RECOMMENDATIONS FOR MODEL SELECTION

For baseline formulations (no NaOH): Power Law or Hershley-Bulkley models

For moderately alkaline systems (pH 10): Hershley-Bulkley model preferred

For highly alkaline systems (pH 11): Hershley-Bulkley model essential

For engineering calculations requiring simplicity: Modified Bingham Plastic with empirical correction factors

4.6 EXPERIMENTAL OBSERVATIONS AND ANOMALIES

4.6.1 PHYSICAL OBSERVATIONS

Several qualitative observations merit discussion:

Foam Formation: Noted during preparation of 15.0g NaOH systems, likely due to protein denaturation in gum Arabic and air entrainment.

Temperature Increase: Observed exothermic reactions during alkaline mixing, consistent with heat of dissolution and potential chemical modifications.

Fish-Eye Formation: Encountered with xanthan gum-NaOH combinations (Section 3.7.1), indicating poor hydration and necessitating formulation abandonment.

4.6.2 MEASUREMENT CHALLENGES

The extremely high viscosities achieved in some alkaline systems (particularly gum Arabic-cocoyam with 7.5g NaOH) approached the upper measurement limits of the Fann viscometer, potentially introducing uncertainty in the highest dial readings. Future work should employ rheometers with higher torque capacity for such systems.

4.7 MODEL DATA RESULTS

S/N	**Drilling Mud Form**	**Rheological Model**	**N**	**K**	**R^2**	**Functions**
1.	7.5g NaOH + 50g of gum arabic	Hershley-Bulkley	0.8	1.0	0.9977	Viscosity control, shear-thinning behavior, cuttings suspension.
2.	15g NaOH + 50g of gum arabic	Hershley-Bulkley	0.78	1.0	0.9976	Enhanced viscosity, improved yield stress, wellbore stability.
3.	3.0g NaOH + 25g of Gum Arabic + 25g Cocoyam	Power law	0.948	0.4	0.9998	Pseudoplastic behavior, natural polymer synergy, low shear viscosity.
4.	7.5g NaOH + 25g of Gum Arabic + 25g Cocoyam	Bingham	0.3	0.8	1	Yield stress fluid, constant plastic viscosity, hole cleaning, cuttings transport.
5.	3.0g of NaOH + 25g of Gum Arabic + 25g of Ginger	Power law	0.948	0.74	0.9998	Shear-thinning, lubricity enhancement, friction reduction, moderate viscosity.

6.	7.5g of NaOH + 25g of Gum Arabic + 25g of Ginger	Power law	0.943	0.91	0.9998	High consistency, enhanced lubrication, improved torque reduction, superior friction control.

Table 4.4.2: Model data analysis

4.8 SUMMARY OF KEY FINDINGS

Gum Arabic at 50g concentration effectively replicated the rheological performance of 1g xanthan gum in baseline formulations.

Alkaline modification dramatically enhanced rheological properties, with effects dependent on both NaOH concentration and polymer-starch combination. The gum Arabic-cocoyam (50/50) system with 7.5g NaOH exhibited the most pronounced rheological enhancement, achieving PV = 65 cp and YP = 180 lb/100ft^2.

The gum Arabic-ginger system showed concentration-sensitive behavior, with optimal performance at 3.0g NaOH and potential degradation at 7.5g NaOH.

All alkaline-modified systems exhibited pseudoplastic (shear-thinning) behavior, with flow behavior indices ranging from 0.3 to 0.948.

The Hershley-Bulkley model provided the best fit for describing the rheological behavior of alkaline-modified natural polymer drilling fluids. Gel strength development varied significantly among systems, with the gum Arabic-cocoyam formulation showing progressive gelation and the gum Arabic-ginger formulation exhibiting time-dependent structural changes.

These findings demonstrate that beneficiated gum Arabic, when appropriately blended with natural starches (like cocoyam and ginger) and pH-modified, can serve as an effective, environmentally friendly alternative to synthetic drilling fluid additives, with performance characteristics suitable for various drilling practices.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This experimental investigation has successfully demonstrated the potential of beneficiated gum Arabic, when formulated with natural additives and pH-modified with sodium hydroxide, as a viable and environmentally sustainable alternative to synthetic drilling fluid additives. The study systematically evaluated the rheological properties of multiple formulations and established clear relationships between alkaline treatment and fluid performance characteristics.

This research represents a significant step forward in the development of environmentally sustainable, economically viable, and technically effective drilling fluid systems based on natural polymers. The successful demonstration that beneficiated gum Arabic, when appropriately formulated and pH-modified, can deliver performance characteristics suitable for petroleum drilling operations opens new possibilities for reducing the environmental footprint of hydrocarbon exploration and production.

The journey from laboratory curiosity to field-proven technology requires continued research, careful optimization, rigorous testing, and collaborative effort among researchers, industry practitioners, regulators, and agricultural producers. The recommendations provided herein offer a roadmap for this continuing development, addressing both technical challenges and practical implementation considerations.

As the global petroleum industry increasingly embraces sustainability principles and environmental stewardship, natural polymer-based drilling fluids represent not merely a technical alternative but a philosophical alignment with responsible resource development. The convergence of environmental necessity, economic opportunity, and technical feasibility positions these natural polymer systems as promising contributors to the future of drilling technology.

The knowledge generated through this investigation provides a foundation upon which subsequent innovations can be built, advancing the broader objective of harmonizing industrial progress with environmental protection. Through continued research, thoughtful implementation, and unwavering commitment to both technical excellence and ecological responsibility, natural polymer drilling fluids can transition from promising laboratory results to standard field practice, benefiting the petroleum industry, natural ecosystems, and human communities alike.

5.2 RECOMMENDATIONS

Based on the findings and limitations of this study, the following recommendations are proposed for future research, practical implementation, and continued development of natural polymer-based drilling fluids:

1. **High-Temperature Stability Studies:** Future investigations should evaluate the rheological stability of these natural polymer formulations under elevated temperatures (up to 150-200°C) using high-pressure, high-temperature (HPHT) aging cells. The thermal degradation kinetics, polymer chain breakdown mechanisms, and strategies for thermal stabilization through crosslinking agents or protective additives should be systematically explored.

2. **Comprehensive Filtration Characterization:** Dedicated studies should assess the filtration properties of these formulations, including API fluid loss, HPHT fluid loss, filter cake thickness, permeability, and compressibility. The relationship between alkaline treatment, polymer concentration, and filtration control should be quantified to develop formulations that simultaneously optimize rheological and filtration properties.

3. **Salinity Tolerance Investigation:** The compatibility of these natural polymer systems with various salt concentrations, including sodium chloride, potassium chloride, calcium chloride, and mixed salt environments, should be evaluated. Understanding salt-induced polymer aggregation, viscosity reduction, and strategies for salt tolerance enhancement through chemical modification or protective colloids would significantly expand the application range of these formulations.

4. **Shale Inhibition and Wellbore Stability:** Systematic studies should evaluate the shale inhibition effectiveness of these natural polymer systems using linear swelling tests, dispersion tests, and capillary suction time measurements. The mechanisms by which alkaline-modified gum Arabic interacts with clay minerals and the comparative performance against commercial shale inhibitors would provide valuable insights for application in reactive shale formations.

5. Economic Optimization Studies: Detailed cost-benefit analysis should be conducted comparing natural polymer formulations with conventional synthetic systems. The analysis should incorporate raw material costs, processing expenses, performance-based value (e.g., drilling rate improvements, reduced lost circulation), and disposal costs to generate comprehensive economic models that can guide formulation selection decisions.

6. Real-Time Monitoring Systems: Implementation should be accompanied by enhanced real-time monitoring of rheological properties using automated marsh funnel measurements, pressure-while-drilling sensors, and equivalent circulating density calculations. Rapid detection of rheological deviations would enable prompt corrective actions and prevent hole problems.

5.3 CONTRIBUTIONS OF THE STUDY

This research contributes several important insights to drilling fluid technology:

NATURAL POLYMER EQUIVALENCY: The finding that 50g of gum Arabic replicates the performance of 1g xanthan gum establishes a quantitative basis for formulation design using locally available natural resources. This 50:1 mass ratio, while seemingly disadvantageous, may be economically favorable in regions where gum Arabic is abundantly available and xanthan gum must be imported.

pH-DEPENDENT PERFORMANCE OPTIMIZATION: The research demonstrated that optimal alkalinity varies depending on the specific polymer-starch combination. While gum Arabic alone showed plateau-limited response beyond pH 10, the blended systems exhibited concentration-sensitive behavior with distinct optimal pH ranges. This finding emphasizes the importance of system-specific pH optimization rather than universal alkaline treatment protocols.

PSEUDOPLASTIC BEHAVIOR CONFIRMATION: All alkaline-modified formulations exhibited shear-thinning behavior with flow behavior indices ranging from 0.3 to 0.948, confirming their suitability for drilling applications. This pseudoplastic character ensures high viscosity at low shear rates for cuttings suspension and lower viscosity at high shear rates for pump efficiency, addressing competing operational requirements.

The experimental findings have direct implications for drilling fluid engineering:

For applications requiring maximum cuttings transport capacity, the gum Arabic-cocoyam (50/50) system with 7.5g NaOH offers superior plastic viscosity (65 cp) and yield point (180 lb/100ft^2), though careful monitoring is required to manage the extremely high gel strengths that may increase pump startup pressures.

For operations prioritizing gel strength stability and balanced rheological properties, the gum Arabic-ginger (50/50) system with 3.0g NaOH provides reliable performance with progressive gel development (45 to 50 lb/100ft^2) suitable for preventing barite sagging during circulation interruptions.

For low-pressure formations where minimizing equivalent circulating density is critical, the reduced-density formulations (6.7-8.0 g/cc) achieved with certain alkaline-modified systems offer advantages in formation damage prevention while maintaining adequate rheological properties.

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