DETERMINATION OF THE EFFECT OF DIVALENT SALT ON RHEOLOGICAL PROPERTIES BENEFICIATED GUM ARABIC

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CERTIFICATION

we certify that this project work was carried out by **OWOBU-FRIDAY DANIEL OSEMUDIAMEN** with matriculation number **ENG2002632** and **EDWIN OSARETIN OSAZEE** with matriculation number **ENG2002631** in the Department of Petroleum Engineering, in partial fulfillment of the requirements for the Award of the Degree, Bachelor of Engineering.

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DEDICATION

This project is dedicated to the Almighty God, whose grace and guidance made this journey possible. We also dedicate this project to our beloved parents for their unwavering love, prayers, and support throughout this endeavor.

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ABSTRACT

This research focuses on determining the effect of divalent salts on the rheological properties of beneficiated gum Arabic, with the aim of assessing its suitability as a vicosifying and filtration control agent in drilling fluids. Gum Arabic, a natural biopolymer, was beneficiated to enhance its purity and performance before being exposed to varying concentrations of divalent salts such as calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$). Rheological analyses were conducted to evaluate parameters including plastic viscosity, yield point, and gel strength under different shear rates and aging conditions. The results showed that the presence of divalent salts significantly altered the flow behavior of the gum Arabic-based fluids. Increasing salt concentration led to ionic cross-linking between the salt cations and the polymer's functional groups, improving viscosity and gel strength at lower concentrations but causing flocculation and viscosity reduction at higher concentrations. The interaction also affected the thixotropic behavior and structural stability of the fluid. Overall, the study demonstrates that divalent salts play a crucial role in modifying the rheological characteristics of gum Arabic solutions. The beneficiated gum Arabic exhibits potential as an eco-friendly, biodegradable, and cost-effective alternative to synthetic polymers for drilling fluid formulation, contributing to sustainable petroleum engineering operations.

CHAPTER ONE

INTRODUCTION

In the petroleum industry, drilling fluids (also known as drilling muds) are crucial to the success of any drilling operation. They perform several key functions, including carrying cutting to the surface, cooling and lubricating the drill bit, maintaining hydrostatic pressure, stabilizing the wellbore. One of the most critical properties of drilling mud is its rheology (the flow behavior under applied stress) which determines how effectively it performs these functions.

Drilling fluid is a heterogeneous fluid consisting of multiple chemical additives which is employed during drilling process in the petroleum industry. Its important physical properties are viscosity and water holding properties (crowo, 1990). Drilling fluid circulates in a loop from the building platform, where forced down into the formation system by entering the drill string and pushed into the surface again via the drill bit. The fluid characteristics such as density and temperature are variables that need to be regularly monitored for the perfect drilling performance according to the condition of the formation.

Drilling fluids are commonly known for gel or thixotropic characteristics, in which they can go through a reversible transformation from high to low viscosity status when being subjected to shear stress force. These transformations ruin the microstructure of the bit but will be gradually recovered when the fluid is in resting condition.

Usually the industry capability of wells is impaired by multifaceted interfaces between rocks and fluid, which decrease permeability to oil and gas. For that reason, drilling fluids should be continuously formulated to diminish these undesirable effects. Depth, pressure and mechanical/impact resistance of the wellbore are key parameters that determine which type of the mud is the most relevant. Inspite of their differences in categories, that main purposes and function remain mutual. They function to preserve hole reliability, convey the rock cuttings, managing the pressure of the mud system along with lubricating and cooling the drill bit (Baba hamed and Belhachi; Brazzel, 2009; caenn and chillinger, 1996; Gonzalez et sl, 2011). At the current time drilling mud are categorized by their external phase or basic material into five major group, which are oil based drilling mud (OBM), synthetic base drilling mud (SBM), water drilling mud (WBM), Gas based.

Drilling mud (GBM) and Nano based drilling mud (Davis et al, 1984; van dyke and baker, 1998). The significant factors for distinguishing the assets of a drilling fluid are gel strength, viscosity (apparent and plastic viscosity), explicit weight, PH, thermal stability and the filtration function. Untreated colloids, basically starch and its modified types, were used in drilling fluid industry for a longtime to defeat the hazardous effect of anhydrite and saline on drilling fluids. Managing the fermentation made by micro-organism in drilling muds, which are composed of gums, starches and tenants additives is on of the most important problems in drilling mud formation. In an effective stated drilling mud, depending on the PH, heat, ventilation group of enzymes get activated which assist microorganisms to fermentation dilemma in starch based drilling muds is generally challenged by adding an antiseptic like paraformaldehyde, which is fairly economical(myers, 1962; soepenberg et al, 1983). In drilling mud composition different polymer and chemical are used for various applications, these chemicals mostly influence the rheological and fluid loss properties of the mud (Austin, 1983).

1.1 BACKGROUND STUDY

Natural polymers like gum Arabic are increasingly being explored as environmentally friendly and biodegradable additives in drilling fluids. Extracted primarily from the Acacia tree, gum Arabic is a complex polysaccharide known for its film-forming, emulsifying, and thickening capabilities traits that make it a promising viscosifier in water-based mud systems. However, the effectiveness of natural polymers such as gum Arabic can be impacted by the presence of salts in the drilling environment, especially divalent salts like calcium chloride ($CaCl_2$) and magnesium sulfate ($MgCl_2$),which are commonly found in formation brines and drilling water. These salts can influence the polymer’s rheological behavior through ionic interactions, potentially causing flocculation, viscosity reduction, or gel formation. This study focuses on evaluating the impact of divalent salts on the rheological properties of beneficiated gum Arabic to determine its viability and performance as an additive in water-based drilling fluids.

1.1.1 GUM ARABIC

Gum Arabic, the natural exudates from acacia Senegal, a high molecular weight heteropolysaccharide (hydrolysis result D-galactose with lesser amount of 4-o-methyl-d-glucoronic acid), shows unusual solution behavior compared to other polysaccharides of similar molecular weight. The rheology of Arabic gum has been extensively studied. Gum solution 30% shows higher solution viscosity and exhibit pseudo plasticity. Some reports are available on shear thickening behavior of Arabic gums while recently mothe and rao reported that the gun shows shear thinning behavior at low shear rate (1-50s). the instrumental measurement of low viscosity fluids like Arabic gum solutions has been difficult task; however, with the advent of controlled stress rheometer, it is now possible to characterize the exact flow behavior of fluids with viscosities less than ImPas. The reports on the rheology of Arabic gum are contradictory and need further investigation.

Presently, considerably attention has been given to the study of various hydrocolloids and their combinations for thickening and texture modification in gravies, dairy products, food drinks and pet food because rheological and functional properties are complimentary. Recent applications have proved that such blends can produce new food formulations and ingredients. Gum Arabic is compatible with the most other gums due to its low viscosity characteristics. The structure of gum Arabic contains proteinaceous material (2%) covalently joined with polysaccharide moiety. It gives a smooth flow or sometimes flow or sometimes reduces high viscosity in combination with other gums like xanthan, gelatin, agar, guar gum and modified starches to produce various confections. The gum has been beneficial when a thin, pourable consistency is desired. The synergic effects of Arabic gum have also interested the food processing industries. The resulting rheological properties of various gums depends on the gum concentration molecular weight of the polysaccharides and functional groups, and the degree of interaction between two hydrocolloids. Associations of participating hydrocolloids occur if biopolymer the interaction is favorable while mixture of the repulsive hydrocolloids

1.1.2 DIVALENT SALT (CaCl2 AND MgCl2)

Divalent salts are compounds formed by a metal cation with a +2 charge and an anion. These salts often exhibit distinct sensory properties like astringency and bitterness, and play important roles in various biological and industrial processes.

Divalent salts are ionic compounds that are composed of divalent cations—positively charged ions with a charge of +2—and suitable anions. The term ―divalent‖ refers to the ability of the metal ion to form two ionic bonds due to the presence of two valence electrons. These salts are formed through the neutralization reaction between a divalent metal and an acid or a suitable anion. These salts are highly soluble in water and significantly influence the chemical and physical properties of solutions, especially in fields like drilling fluids, water treatment, rheology, and industrial processing. $CaCl_2$ and $MgCl_2$ help control fluid density, inhibit clay swelling, and stabilize shale formations during drilling operations. Their high solubility increases the density of drilling fluids, allowing the control of formation pressure and prevention of blowouts. These salts also minimize water invasion into reactive clays, reducing issues like wellbore instability and pipe sticking. $CaCl_2$ is used in foods like canned vegetables to maintain firmness, in tofu production to aid coagulation, and in sports drinks to replace lost electrolytes. It is recognized as safe for consumption in controlled quantities by food safety authorities.

1.2 PROBLEM STATEMENT

The petroleum industry is under increasing pressure to adopt sustainable and environmentally friendly drilling practices. Synthetic polymers, while effective, can be expensive and environmentally hazardous. Natural alternatives like gum Arabic offer potential, but their behavior under saline conditions, especially in the presence of divalent cations, is not fully understood.

Understanding how these salts influence the viscosity, gel strength, and flow properties of gum Arabic-treated muds is critical in determining whether it can be used effectively in saline or high-ion environments typically encountered in deep and offshore drilling.

1.3 AIM OF STUDY

To investigate the effect of divalent ($CaCl_2$ and $MgCl_2$) salts on the rheological properties of beneficiated gum Arabic to determine their usage as vicosifying or filtration control agents for drilling purposes.

1.4 OBJECTIVES OF STUDY

1. To beneficiate raw gum Arabic and prepare it for rheological analysis.

2. To characterize the baseline rheological properties of gum Arabic solutions.

3. To study the influence of selected divalent salts (e.g., $CaCl_2$, $Mgcl_2$) on gum Arabic's rheology.

4. To compare the results with standard requirements for water-based drilling fluid additives.

5. To evaluate gum Arabic’s potential as an eco-friendly viscosifier under high salinity conditions.

1.5 JUSTIFICATION OF THE STUDY

Drilling operations in regions with high brine concentration (e.g., offshore or deep wells) need robust fluid systems. Finding a natural additive like gum Arabic that performs well even in such environments is vital. Additionally, leveraging locally sourced gum Arabic (abundant in Africa) supports economic and sustainable development. Natural polymers are underutilized in petroleum drilling applications due to uncertainties regarding their performance in chemically aggressive environments. By focusing on divalent salt interactions, this study addresses a key limitation in the deployment of natural additives. Additionally, the beneficiation of gum Arabic ensures reproducibility and enhances its functional properties, making it a competitive candidate for widespread industrial application.

Major designs and production of drilling fluids in Nigerian oil and gas sector over the years has been faced with the challenges of either importing the materials to produce and in some cases imported, already designed and produced drilling fluids. In this case, industry in this sector adjust the properties of the drilling fluid with the aid of the right types of additives which are also imported to suit the formation requirements of the are to be drilled. This has not allowed them to compute effectively with their foreign counterparts. Research into this area is thus very necessary. This research provides a sustainable alternative to conventional viscosifier in drilling fluids. If gum Arabic shows good rheological stability in the presence of divalent salts it could; reduce environmental risks ,Lower drilling costs in saline environments, Promote the use of indigenous resources like gum Arabic in oil and gas operations.

Gum Arabic, a natural, biodegradable biopolymer, is abundant in regions like Nigeria and has the potential to serve as a green and sustainable alternative to synthetic additives. However in its raw form, gum Arabic may not meet all industrial requirements, which is why beneficiation (modification or purification) is essential to enhance its properties. Understanding the rheological behavior of beneficiated gum Arabic in the presence of divalent salts ($CaCl_2$ and $MgCl_2$) is crucial because these salts are commonly encountered in formation waters or added intentionally to drilling fluids. Divalent cations often affect the viscosity, gel strength, and stability of polymer based fluids.

1.6 SCOPE

This study is designed to examine how divalent salts, specifically calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$)**,** influence the rheological and filtration control properties of beneficiated gum Arabic**,** with the intent of evaluating its potential application in water-based drilling fluids. Divalent salts like calcium chloride (CaCl2) and magnesium chloride (MgCl2) negatively impact the rheological and filtration control properties of beneficiated gum arabic (GA) in drilling fluids. These salts can reduce viscosity, alter flow behavior, and increase fluid loss, potentially compromising the mud's ability to clean the wellbore and control formation pressure.

1.7 LIMITATION

The study is conducted under controlled laboratory settings and may not fully replicate complex downhole conditions such as extreme temperature and pressure. The investigation focuses solely on $CaCl_2$ and $MgCl_2$**.** Other potentially relevant divalent ions (e.g., Ba^{2+}, Zn^{2+}) are excluded from the scope. Only one type of gum Arabic (from a specific origin and after beneficiation) is tested, which may not represent all gum Arabic varieties. The tests do not assess the long-term stability of gum Arabic in saline environments or under thermal

CHAPTER TWO

LITERATURE REVIEW

Drilling Engineering is one of the challenging disciplines in the petroleum industry, significant advancements have been made in past decades which have allowed the petroleum industry worldwide to economically and successfully exploit underground reserves that were not been possible before. Considerable research studies have been done in drilling fluid technology to understand drilling fluid properties for successful and economical completion of an oil well. The cost of the drilling fluid itself is relatively small, but the maintenance of the right properties while drilling profoundly influence total well costs. American petroleum institute has a recommended practice for testing liquid drilling fluid properties; regular testing of drilling fluid properties help mud engineers determine proper functioning of drilling fluid. Bourgoyne Jr. (1986) mentioned that drilling fluid is related directly or indirectly to most of drilling problems. The complex drilling fluid plays several functions simultaneously. They are intended to clean the well, hold the cuttings in suspension, prevent caving, and ensure the tightness of the well wall, flood diesel oil or water and to form an impermeable cake near the wellbore area. Moreover, they also have to cool and lubricate the drill bit, transfer the hydraulic power and carry information about the nature of the drilled formation by raising the cutting from the bottom of the surface.

Drilling fluid went through major technological evolution, since the first operations performed in the US, using a simple mixture of water and clays, to complex mixtures of various specific organic and inorganic products used nowadays. These products improve fluid rheological poperies and filtration capability, allowing to penetrate heterogeneous geological formations under the best conditions. In fact, borehole stability and fluid loss remains the main problem during drilling and the selection of drilling fluid type and composition was at the origin of successful drilling. Numerous studies have analyzed shale problems and several methods have been proposed to improve fluid performance for clay swelling inhibitions and to evaluate the scattered results already published in the literature. The majority of the procedures recommend to compare initial and final sizes (or weight) of cuttings for inhibition estimation after fluid contact.

In drilling fluid technologies , two main tendencies are currently developed in parallel: i) the search for new additives increasing the performance of water based muds (WBM) and ii) the development and introduction of new compounds into oil-based muds (OBM). Some pendent questions will be discussed in this chapter such as filtration, viscosity, effects of divalent salts on polymers.

2.1 DRILLING FLUID: COMPOSITION AND FUNCTION

DRILLING FLUID COMPOSITION:

The complexity of the problem met in petroleum drilling has led to emerging techniques for the formulation of appropriate fluids. Generally, drilling modes may be classified in the following three families:

1. The WBM family, in which the fresh salt or seawater is the continuous phase. It is the most used (90-95%). The WBM are mainly composed of aqueous solutions of polymers and clays in water or brines, with different types of additives incorporated to the aqueous solution.

2. The OBM family is less used (5-10%). These drilling fluids have been developed for situations where WBM may form inadequate (Chiligarian and vorabur, 1981). The OBM are usually gas-oil based modes. Generally, they are inverse emulsions of brine into an oil-major continuous Phase, stabilized by surfactants. Also, other additives are often added to the organic phase, such as organophilic modifiers of the clay surface. However, although OBM often give better performances, there have been major drawbacks such as to be generally more expensive and less ecologically friendly than WBM. Consequently, although OBM give greater shale stability than WBM, these latter systems have also been developed by many researchers in order to respond to environmental regulations (Simpsons, et al. in 1994, and Friedheim, et al. in 1999, and Young Maas, 2001; Patel et al. Schlemmer, 2002)

3. The third family of drilling fluids comprises gas-aerated muds, (classical muds with nitrogen) or aqueous foams. These drilling fluids are used when their pressure is lower than that exerted by the petroleum located in the pores of the rock formation. These fluids are called under-balanced fluids. This under-balanced drilling technology is generally adopted for poorly consolidated or fractured formations.

Controlled drilling tests in various rocks have confirmed that air or gas is a faster drilling fluid than water or oil. Water should be the faster drilling fluid, however, in this case, drilling tests show that the most commonly used additives have detrimental effects on the drilling rate. Choosing a mode system begins with the selection of a mode family, according to the nature of the rock formation, and should take into account environmental and economic constraints. The choice of the mode formulation will be the second step, where one has to decide on the range of desired properties, leading to use minimal amounts of additives.

FUNCTIONS OF DRILLING FLUID

The main functions of liquid drilling fluids are to exert hydrostatic pressure to prevent formation fluids from entering into the well bore, and carrying out drill cuttings as well as suspending the drill cuttings while drilling is paused such as when the drilling assembly is brought in and out of the hole. The drilling fluid also keeps the drill bit cool and clears out cuttings beneath it during drilling. The drilling fluid used for a particular job is selected to avoid formation damage and to limit corrosion.

2.2 IMPORTANCE OF RHEOLOGICAL PROPERTIES ON DRILLIJNG FLUID

The rheological properties characterize the flow behavior of the drilling fluids, including the resistance to movement of some bodies in the fluid mass. These properties allow to evaluate the pressure and pumping energy of the drilling fluids, the washing conditions as well as the evacuation of the detritus, the danger of erosion of the walls.

Importance of rheological properties:

1. Hole Cleaning:

Cuttings Transport: Drilling fluid's rheology dictates its ability to lift and carry rock cuttings from the wellbore to the surface.

Annular Velocity: Adequate viscosity and yield point help maintain sufficient annular velocity to transport cuttings effectively.

Gel Strength: Gel strength allows the fluid to suspend cuttings when circulation stops, preventing them from settling and causing issues.

2. Wellbore Stability:

Hydrostatic Pressure: Rheological properties contribute to maintaining the required hydrostatic pressure to counteract formation pressure and prevent wellbore collapse.

Fluid Loss: Controlling fluid loss is crucial for maintaining wellbore stability, and rheology plays a role in this by affecting filter cake formation.

3. Hydraulic Optimization:

Pressure Losses: Rheological properties influence pressure drop in the drill string and annulus, impacting pumping requirements and hydraulics.

ECD: Equivalent circulating density (ECD), a critical parameter for well control, is directly affected by rheology, particularly the fluid's viscosity and yield point.

Swab and Surge: Rheological properties impact swab and surge pressures, which can cause instability or formation damage if not managed properly.

4. Drilling Efficiency:

Penetration Rate: Optimized rheology can improve drilling efficiency by reducing friction, enabling faster penetration.

Torque and Drag: Viscosity and other rheological parameters affect torque and drag, influencing the efficiency of drilling and tripping operations.

5. Fluid Performance:

Lubrication: Proper rheology ensures adequate lubrication of the drill bit and drill string, reducing friction and wear.

Cooling: Drilling fluids help cool the drill bit, and rheology impacts how effectively this is achieved.

Cementing: Rheological properties of drilling fluids impact the success of cementing operations by affecting the displacement of drilling fluid from the annulus.

2.3 ROLES OF POLYMERS IN DRILLING FLUID

Polymers are used in drilling fluids to control properties such as viscosity, fluid loss and shale inhibition. Polymers are large macromolecules composed of repeating monomer units, and their properties depend on factors like molecular weight and structure. Polymers play several crucial roles in drilling fluids, primarily focusing on controlling fluid properties and wellbore stability. They act as viscosity modifiers, fluid loss control agents, and shale stabilizers, helping to optimize drilling operations and minimize issues like lost circulation and borehole instability.

Key roles:

1. Viscosity Modification: Polymers can be added to drilling fluids to increase or decrease viscosity, depending on the specific needs of the drilling operation, higher viscosity fluids are better at suspending and removing drill cuttings from the wellbore. Some polymers, like xanthan gum, are viscosifiers that help control the flow of drilling fluid. Others, like starch, can also thicken the fluid and aid in transporting cuttings.

2. Fluid Loss Control: Polymers can reduce the amount of drilling fluid that leaks into the surrounding formation, a process known as fluid loss. This is crucial for maintaining borehole stability and preventing issues like lost circulation, where the fluid is lost into large fractures or voids in the formation. Different types of polymers, including synthetic, natural, and modified natural polymers, are used for this purpose.

3. Shale Stabilization: Shale formations can be prone to swelling and instability when exposed to water-based drilling fluids. Polymers, particularly anionic polymers, can help stabilize these formations by interacting with the shale and preventing it from disintegrating. This is essential for preventing borehole collapse and ensuring smooth drilling operations.

4. Other Roles:

- **Filtration control:** Polymers can help reduce the amount of solids that pass through the filter cake, which is a layer of solids that forms on the borehole wall.
- **Flocculation:** Some polymers can cause particles in the drilling fluid to clump together, which can be useful for separating solids from the fluid.

- **Bridging:** Polymers can help create a bridge across fractures or voids in the formation, preventing fluid loss.

2.4 VISCOSITY

Most fluids offer some resistance to motion, and we call this resistance ―viscosity.‖ Viscosity arises when there is relative motion between layers of the fluid. More precisely, it measures resistance to flow arising due to the internal friction between the fluid layers as they slip past one another when fluid flows. Viscosity can also be thought of as a measure of a fluid’s thickness or its resistance to objects passing through it. A fluid with large viscosity resists motion because its strong intermolecular forces give it a lot of internal friction, resisting the movement of layers past one another. On the contrary, a fluid with low viscosity flows easily because its molecular makeup results in very little friction when it is in motion. Gases also exhibit viscosity, but it is harder to notice in ordinary circumstances. The viscosity of liquids decreases rapidly with an increase in temperature, and the viscosity of gases increases with an increase in temperature. Thus, upon heating, liquids flow more easily, whereas gases flow more slowly. Also, viscosity does not change as the amount of matter changes, therefore it is an intensive property.

Polymers generally increase the viscosity of fluids. This is because polymer molecules, when added to a liquid, create a more complex and interconnected structure, leading to increased resistance to flow. The extent of the viscosity increase depends on factors like polymer concentration, molecular weight, and the specific type of polymer and solvent. Polymer molecules, especially long chain polymers, can become entangled with each other and with the solvent molecules. This entanglement increases the intermolecular forces, making it harder for the fluid to flow and thus increasing its viscosity. Many polymer solutions exhibit shear-thinning behavior, meaning their viscosity decreases as the shear rate (how quickly the fluid is being deformed) increases. This is because at higher shear rates, the polymer chains can align themselves with the flow direction, reducing the entanglement and resistance to flow. The viscosity of polymer solutions can be affected by temperature. Some polymers, particularly those used as viscosity index improvers in lubricants, increase viscosity more at higher temperatures due to the expansion of their molecular coils. This expansion increases the resistance to flow, contributing to a more stable viscosity across a range of temperatures.

2.5 FILTRATION CONTROL

Filtration is the process of separating a fluid-solid system by passing the volume of the suspension through a porous medium while retaining a fraction of the solid particles in the mixture.

During the drilling process, fluids enter into the formation in the following different ways (Federer-Kovacs and Matrai, 2013);

1. Filtration below the bit where the fluid is pushed into the formation

2. Dynamic filtration in the well bore in the annulus from circulation

3. Static filtration under the trips or any operation where circulation is stopped

Fluid loss results during the drilling process as fluid penetrates the formation around the wellbore. It is an undesirable phenomenon because it raises the processes expenses and puts the formation at risk of damage. The severity of these issues increases with the increase in the temperature of the well (Browning, 1976; Minaev *et al*., 2018). A properly designed drilling fluid should have an optimum viscosity and the potential to create a compact filter cake of low permeability to reduce fluid losses. Biopolymers, such as starches and cellulose-based additives, may help solve this problem by bridging, bonding, deflocculation, and viscosity, which are four important factors that influence filtration.

Filtration-control additives decrease the amount of filtrate that flows into the exposed formation from the drilling mud. Numerous additives including bentonite, polymers, starches, and thinners are all used as filtration-control agents. Polymer compounds were among the first and most widely applied drilling mud additives. Polymers are still employed as viscosifiers, flocculants, surfactants, and fluid loss control materials because of their structure and reactive groups (Harry *et al*., 2016; Vryzas and Kelessidis, 2017).

Another important requirement for efficient well completion is the mud's potential to seal permeable formations revealed by the bit with a thin and low permeability filter cake (Borges *et al.*, 2021). In overbalanced drilling, the mud column pressure is maintained higher than the formation pore pressure to avoid formation fluid infiltration. If an impermeable filter cake has not developed, the mud will continue to infiltrate permeable strata. In order for a filter cake to develop, the mud should include certain particles that are just slightly smaller than the formation's pore throats. Such particles are called bridging particles, because they are retained in the surface pores, whereas finer particles get conveyed deeper into the formation. This bridged region in the surface pores continues to capture smaller particles until only liquid passes into the formation after a few seconds. Through this mechanism, the filter cake develops. Literature survey depicted that the thickness of the desirable filter cake should be 1 to 2/32″ and 3/32″ for OBM and WBM respectively (Kök and Bal, 2019). The thickness of thin filter cake is less than 2 mm API, while thicker filtercake is around 4–6 mm API (Kania *et al*., 2015).

If the cake's surface is exposed to fluid or mechanical erosion during the filtration, it determines the rate of filtration and the rise in cake thickness. For instance, in static conditions, the filtrate quantity and cake thickness develop in accordance with the square root of time (at a decreasing rate). The rate of fluid invasion is reduced by the growth of the mud cake due to cake compaction and thickness. However, in dynamic conditions, the cake's surface is exposed to continuous erosion, so when the filter cake's rate of growth equals the rate of erosion, the cake's thickness and filtration rate become constant. Filtration is regarded as dynamic during well drilling owing to cake erosion by the mud and mechanical wear by the drill string; however, it is considered static (dead end filtration) during round trips. All filtration characteristic testing is done at the well site under static conditions. As a result, filtration rates and cake thicknesses reported in surface experiments only roughly correspond to those found downhole.

Filter cake permeability is another fundamental filtration characteristic that can be calculated using Darcy's law utilizing static filtration test data. The cake permeability decreases as the number of colloidal particles increases. The presence of soluble salts in conventional muds dramatically increases the filter cake's permeability, whereas some organic particles allow for low cake permeabilities even in saturated salt solutions. For instance, thinners reduce the permeability of cakes by dispersing clay lumps into smaller particles. The permeability of the material has an impact on the fluid invasion depth. The filtration characteristics demanded for a well to be completed successfully are mostly controlled by the type of the formations to be drilled. The rate at which the water-based mud filtrate diffuses into formation water in the rock is determined by the pore size distribution and therefore the rock's permeability. In relatively high permeable formations, this diffusion rate may be higher than filtration at the borehole wall. As a result, the rate of filtration limits the invasion, and the formation of filter cake slows the process, lowering the invasion extent (Dewan and Chenvert, 1993).

2.6 BENEFICIATION OF GUM ARABIC

Beneficiation of gum Arabic involves processing the raw gum collected from acacia trees to improve its quality and suitability for various applications. This typically includes cleaning, grading, and sometimes further purification to remove impurities and standardize its properties. Gum Arabic is harvested from acacia trees, often during the rainy season, by making incisions in the bark. The hardened sap is collected, and the initial step in beneficiation involves removing large pieces of bark, dirt, and other debris. The gum is sorted based on size, color, and clarity.

Different grades of gum Arabic have varying properties and are suitable for different applications.

Beneficiation ensures that the gum Arabic meets the required quality standards for its intended application. It improves the functional properties of the gum, making it more effective and reliable, by removing impurities and standardizing properties, beneficiation expands the range of potential uses for gum Arabic. In regions where gum Arabic is produced, beneficiation can create more value-added products and improve the livelihoods of local communities.

2.7 EFFECTS OF DIVALENT SALTS ON POLYMERS IN DRILLING

Divalent salts like calcium and magnesium, commonly found in drilling fluids, can significantly impact the performance of polymers used in drilling operations. Generally, these salts reduce the viscosity of polymer solutions, affecting their ability to control fluid loss and stabilize the wellbore. The degree of impact depends on factors like the polymer type, salt concentration, and temperature.

Effects on Polymer Viscosity:

Viscosity Reduction:

Divalent ions can cause a decrease in polymer solution viscosity. This happens because the ions neutralize the charges on the polymer chains, causing them to coil up and reducing their ability to thicken the fluid.

Impact on Rheology:

Changes in viscosity due to divalent salts can affect the rheological properties (flow behavior) of the drilling fluid, potentially impacting its ability to carry cuttings and control fluid loss.

Dependence on Polymer Type:

Different polymers respond differently to divalent salts. Some are more susceptible to viscosity reduction than others.

Practical Implications:

Drilling Fluid Design:

Understanding the effects of divalent salts is crucial for designing effective drilling fluids.

Enhanced Oil Recovery:

In enhanced oil recovery (EOR) processes, the interaction between polymers and divalent ions is critical for optimizing polymer flooding and improving oil recovery.

Wellbore Stability:

Maintaining adequate viscosity in the drilling fluid is important for wellbore stability, and divalent salts can pose a challenge in this regard

2.8 GUM ARABIC IN THE PRESENCE OF DIVALENT SALTS

Gum Arabic's behavior in the presence of divalent salts is complex and depends on several factors, including the specific salt, its concentration, and the concentration of the gum Arabic itself. Generally, divalent cations like calcium and magnesium can interact with the gum Arabic molecules, potentially leading to changes in viscosity, gelation, or even precipitation. Divalent cations can form "salt bridges" between different gum Arabic molecules, effectively crosslinking them. This can lead to an increase in viscosity or even gelation, especially at higher concentrations of both the gum and the salt, Divalent cations can form "salt bridges" between different gum Arabic molecules, effectively crosslinking them. This can lead to an increase in viscosity or even gelation, especially at higher concentrations of both the gum and the salt. Gum Arabic is known for its ability to stabilize emulsions, but the presence of divalent salts can affect this property. Some studies have shown that calcium ions can reduce the negative charge on gum Arabic-emulsified particles, potentially impacting their ability to stabilize emulsions. The effects of divalent salts on gum Arabic are particularly relevant in food and pharmaceutical applications, where gum Arabic is often used as an emulsifier, stabilizer, or binder. The specific interactions between gum Arabic and divalent salts can influence the stability and properties of the final product. It's worth noting that different biopolymers can have varying sensitivities to divalent salts. For example, guar gum is known to be more stable and resistant to degradation in the presence of divalent salts compared to gum Arabic. While gum Arabic is a versatile and useful polysaccharide, its behavior in the presence of divalent salts is a complex interplay of factors that can lead to changes in viscosity, gelation, and emulsion stability.

CHAPTER THREE

METHODOLOGY

EQUIPMENT AND RAW MATERIAL

The following equipment were used in this work:

Viscometer

Mud cup

Electronic Weighing balance

Measuring cylinder

Spatula

Materials include: Ginger, Bentonite, Gum Arabic, Arabic Cocoyam, Xanthan Gum, $CaCl_2$ and NaCl.

The Arabic cocoyam and Ginger were dried using sunlight as a source of energy and weighted regularly using the electronic weighing balance until a constant weight was attained, indicating that both had dried properly.

EXPERIMENT 1

3.1.1 PROCEDURE FOR THE PREPARATION OF THE MUD

1. Measure 500ml of water

2. Water was allowed to stir using mud mixer at medium speed

3. Measure 30g of bentonite

4. Add the bentonite to the 500ml of water in the mud mixer and stir for 3 minutes

5. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

6. Rheological properties were then measured and the result is tabulated in Table 3.1.1

3.2.1 PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF GUM ARABIC AND COCOYAM

1. Measure 500ml of water, 30g of bentonite and mix for 3minutes.

2. various grams of gum Arabic and cocoyam (25g of coco yam and 25g of gum Arabic, 37.5g of gum Arabic and 12.5g of cocoyam) were added for different samples and allowed to mix for 3 minutes.

3. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

4. Rheological properties were then measured and the result is tabulated in Table 3.2.1

3.3.1 PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF GUM ARABIC AND GINGER

1. Measure 500ml of water, 30g of bentonite and mix for 3minutes.

2. Various grams of gum Arabic and ginger (25g of ginger and 25g of gum Arabic, 37.5g of gum Arabic and 12.5g of ginger) were added for different samples and allowed to mix for 3 minutes.

3. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

4. Rheological properties were then measured and the result is tabulated in Table 3.5.1

3.4.1 PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF XANTHAN GUM ON THE MUD SYSTEM

1. Measure 500ml of water, 30g of bentonite and mix for 3minutes.

2. Measure 1g of xanthan gum.

3. Add the 1g of xanthan gum to the mixture and stir for 3 minutes at high speed.

4. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

5. Rheological properties were then measured and the result is tabulated in Table 3.4.1

3.5.1 PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF GUM ARABIC

1. Measure 500ml of water, 30g of bentonite and mix for 3minutes.

2. Measure 50g of gum Arabic, add to the mixture and mix for 3 minutes

3. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

4. Rheological properties were then measured and the result is tabulated in Table 3.5.1

EXPERIMENT TWO

3.1.2 : PROCEDURE FOR DETERMINATION OF THE EFFECT OF DIVALENT SALT ($CaCl_2$) ON XANTHAN GUM MUD SYSTEM

1. Measure 30g of bentonite and 500ml of water and mix for 3 minutes

2. Add 1g of xanthan gum to the mixture and mix for 3 minutes

3. Then add 7.5g of $CaCl_2$ to the mixture and mix for another 3 minutes at high speed

4. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

5. Repeat the procedure for 15g of $CaCl_2$ and take readings

6. Rheological properties were then measured and the result is tabulated in Table 3.1.2

3.2.2 : PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF DIVALENT SALT ($CaCl_{2)}$ ON GUM ARABIC MUD SYSTEM

1. Measure 30g of bentonite and 500ml of water and mix for 3 minutes

2. Add 50g of gum Arabic to the mixture and mix for 3 minutes.

3. Then add 7.5g of $CaCl_2$ to the mixture and mix for another 3 minutes at high speed

4. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

5. Repeat the procedure for 15g of $CaCl_2$ and take readings

6. Rheological properties were then measured and the result is tabulated in Table 3.2.2

3.3.2 : PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF DIVALENT SALT ($CaCl_2$) ON GUM ARABIC AND COCOYAM MUD SYSTEM

1. Measure 30g of bentonite and 500ml of water and mix for 3 minutes

2. Add 25g of gum Arabic to the mixture and mix for 3 minutes.

3. Measure 25g of cocoyam and add to the mixture and mix for another 3 minutes

3. Then add 7.5g of $CaCl_2$ to the mixture and mix for 3 minutes

4. place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

5. Repeat the procedure for 15g of $CaCl_2$ and take readings

6. Rheological properties were then measured and the result is tabulated in Table 3.3.2

3.4.2 : PROCEDURE FOR THE DETERMINATION OF THE EFFECT OF DIVALENT SALT ($CaCl_2$) ON GUM ARABIC AND GINGER MUD SYSTEM

1. Measure 30g of bentonite and 500ml of water and mix for 3 minutes

2. Add 25g of gum Arabic to the mixture and mix for 3 minutes.

3. Measure 25g of Ginger and add to the mixture and mix for another 3 minutes

3. Then add 7.5g of $CaCl_2$ to the mixture and mix for 3 minutes

4. Place the mixture into the viscometer and take the reading for 600RPM, 300RPM, 200RPM AND 100RPM.

5. Repeat the procedure for 15g of $CaCl_2$ and take readings

6. Rheological properties were then measured and the result is tabulated in Table 3.4.2

RESULTS

EXPERIMENT ONE

RESULT TABLE:

TABLE 3.1.1: RESULT OF BENTONITE AND WATER (SPUD MUD)

RPM	**DIAL READING**
600	9.0
300	6.5
200	5.5
100	4.5
Gel	
10 SECONDS	5.5
10 MINUTES	7
PV	2.5
YP	4.0
DENSITY	8.6g/cc

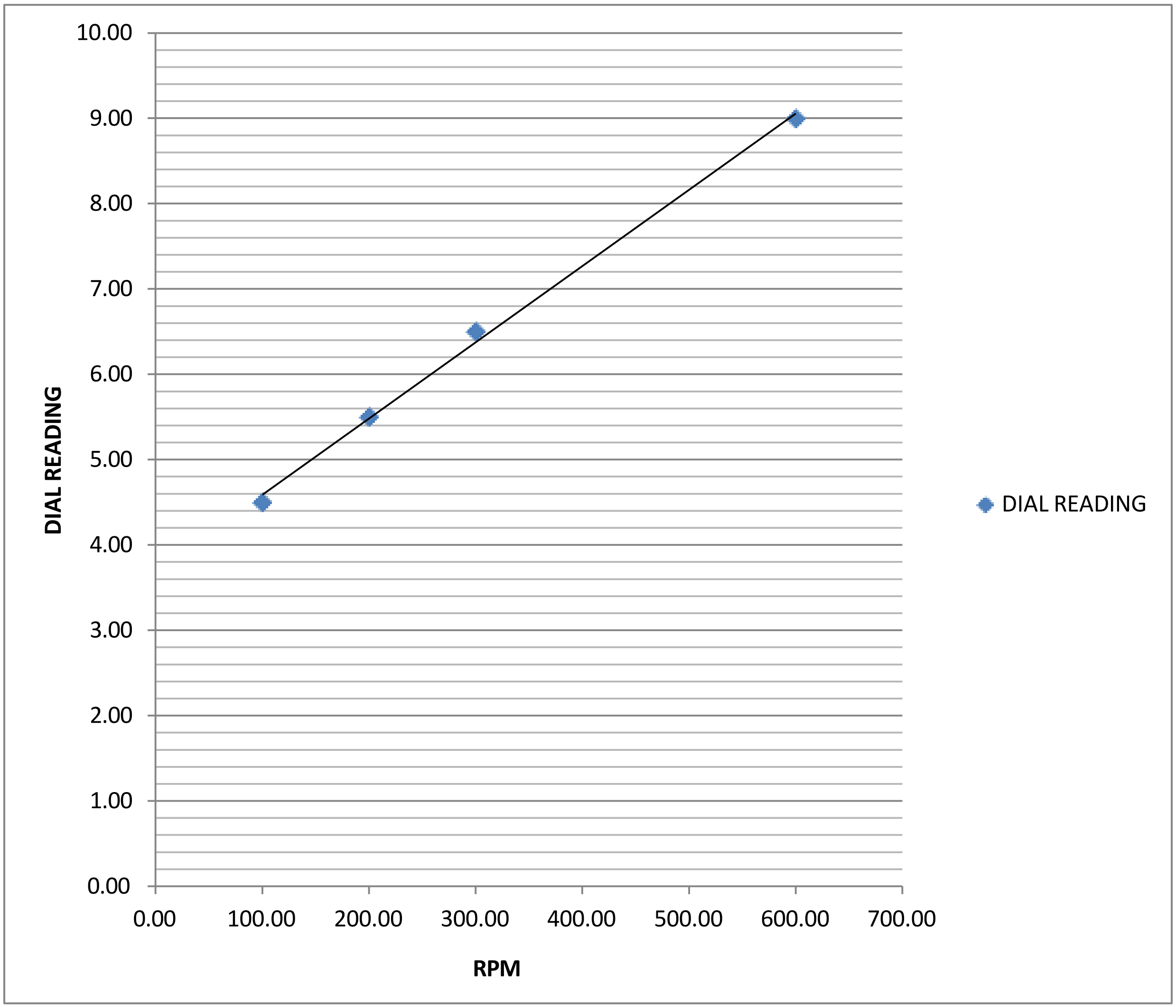

Fig 3.1.1 Plot of Dial reading versus RPM on bentonite and water (spud mud)

TABLE 3.2.1: RESULT OF MUD WITH 1g OF XANTHAN GUM

RPM	**DIAL READING**
600	46.0
300	35.5
200	31.0
100	25.0
GEL	
10 SECONDS	25.0
10 MINUTES	29.0
PV	10.5
YP	25.0
DENSITY	8.7g/cc

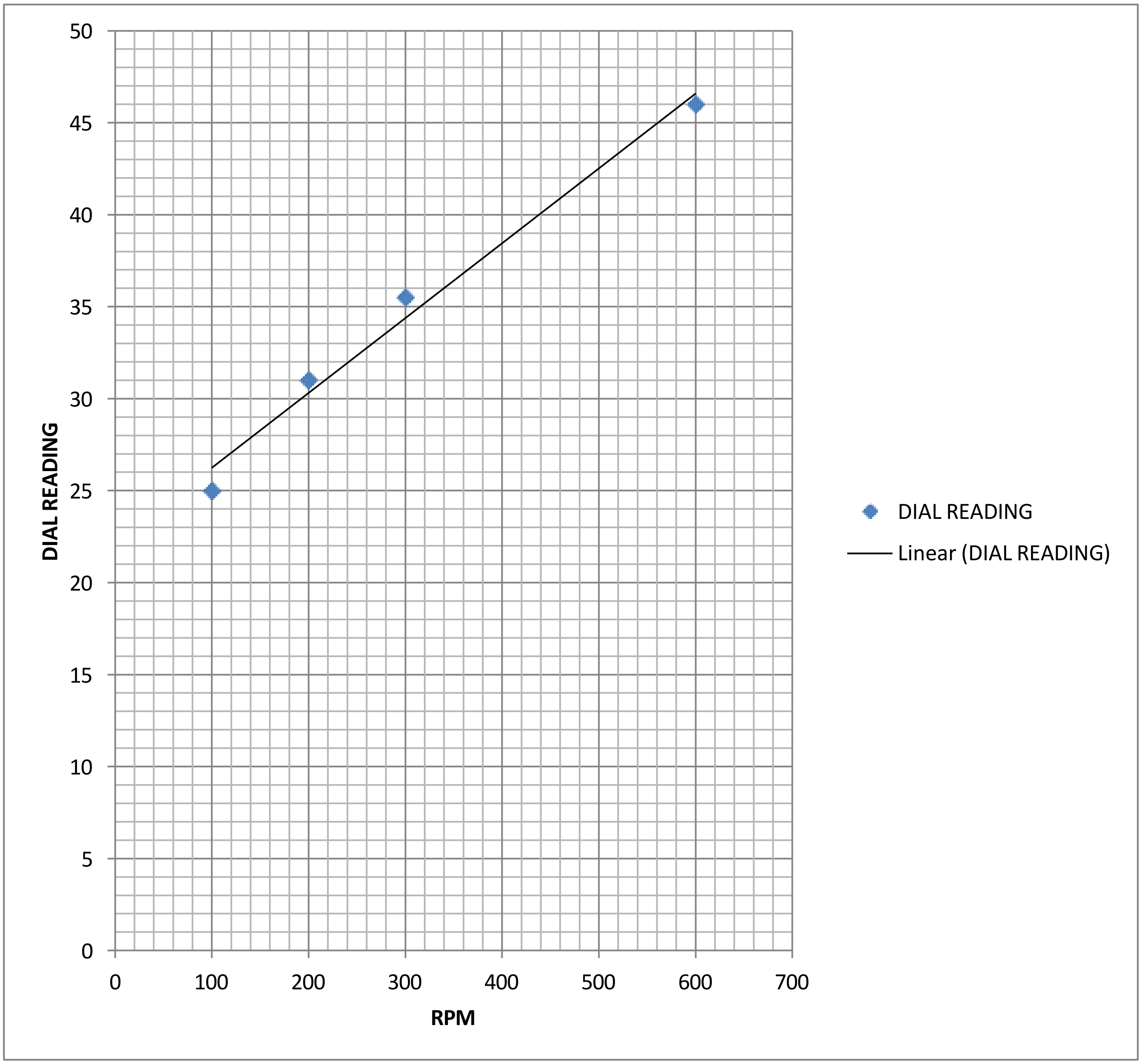

Fig 3.2.1 Plot of Dial reading versus RPM on 1g of Xanthan gum mud system

TABLE 3.3.1: RESULT OF MUD WITH 50g OF GUM ARABIC

RPM	**DIAL READING**
600	45.0
300	34.5
200	31.5
100	25.0
GEL	
10 SECONDS	28.0
10 MINUTES	30.0
PV	10.5
YP	24.0
DENSITY	8.6g/cc

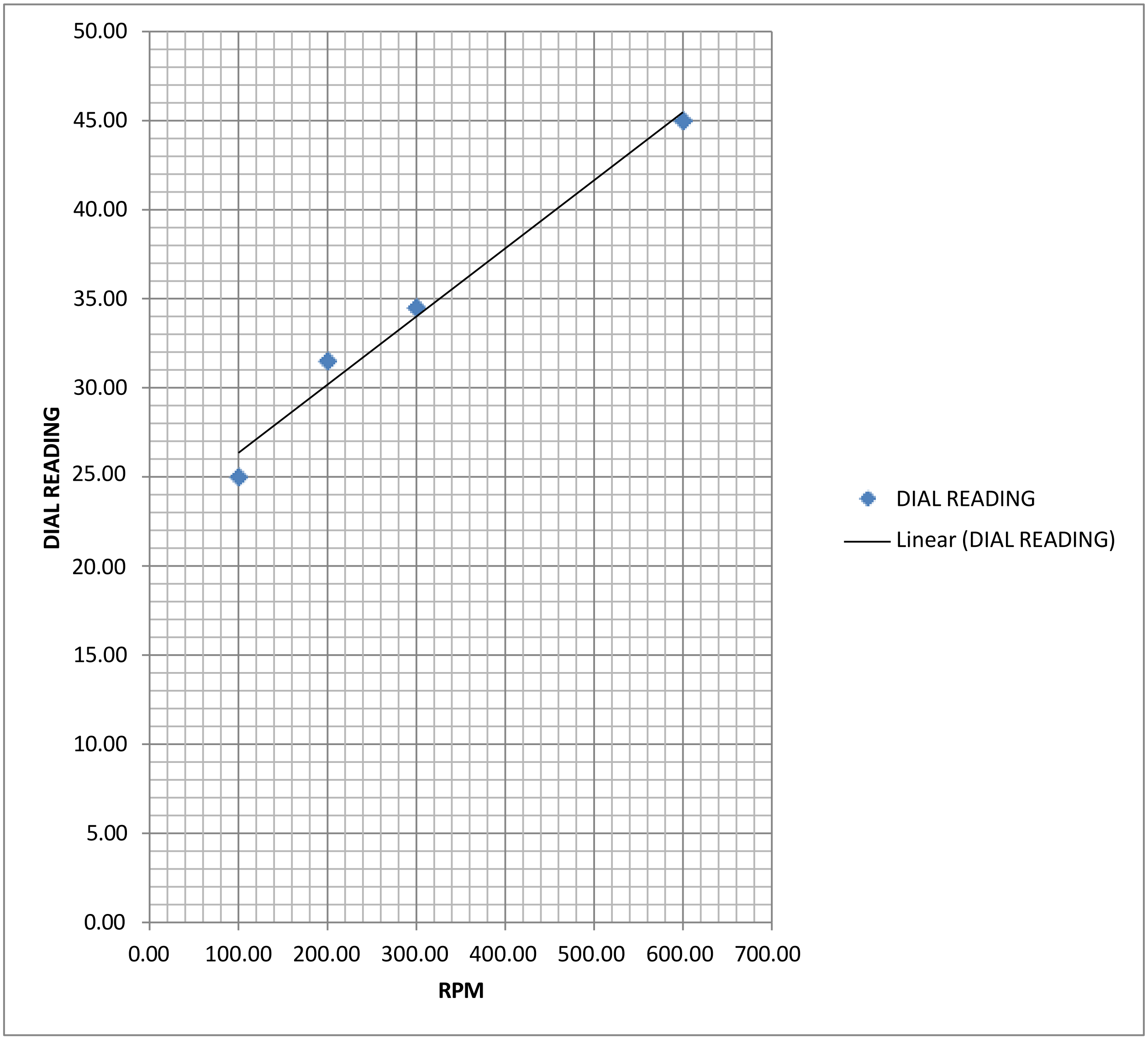

Fig 3.3.1 Plot of Dial reading versus RPM on 50g of Gum Arabic mud system

TABLE 3.4.1: RESULT OF MUD WITH GUM ARABIC AND COCOYAM

RPM	**25g of Gum Arabic +25g of cocoyam**	**37.5g of Gum Arabic + 12.5g of cocoyam**
600	30.0	30.0
300	22.0	24.0
200	19.0	19.0
100	14.0	13.0
GEL		
10 SECONDS	15.0	16.0
10 MINUTES	20	19.0
PV	8.0	6.0
YP	14.0	18
DENSITY	8.3g/cc	8.2g/cc

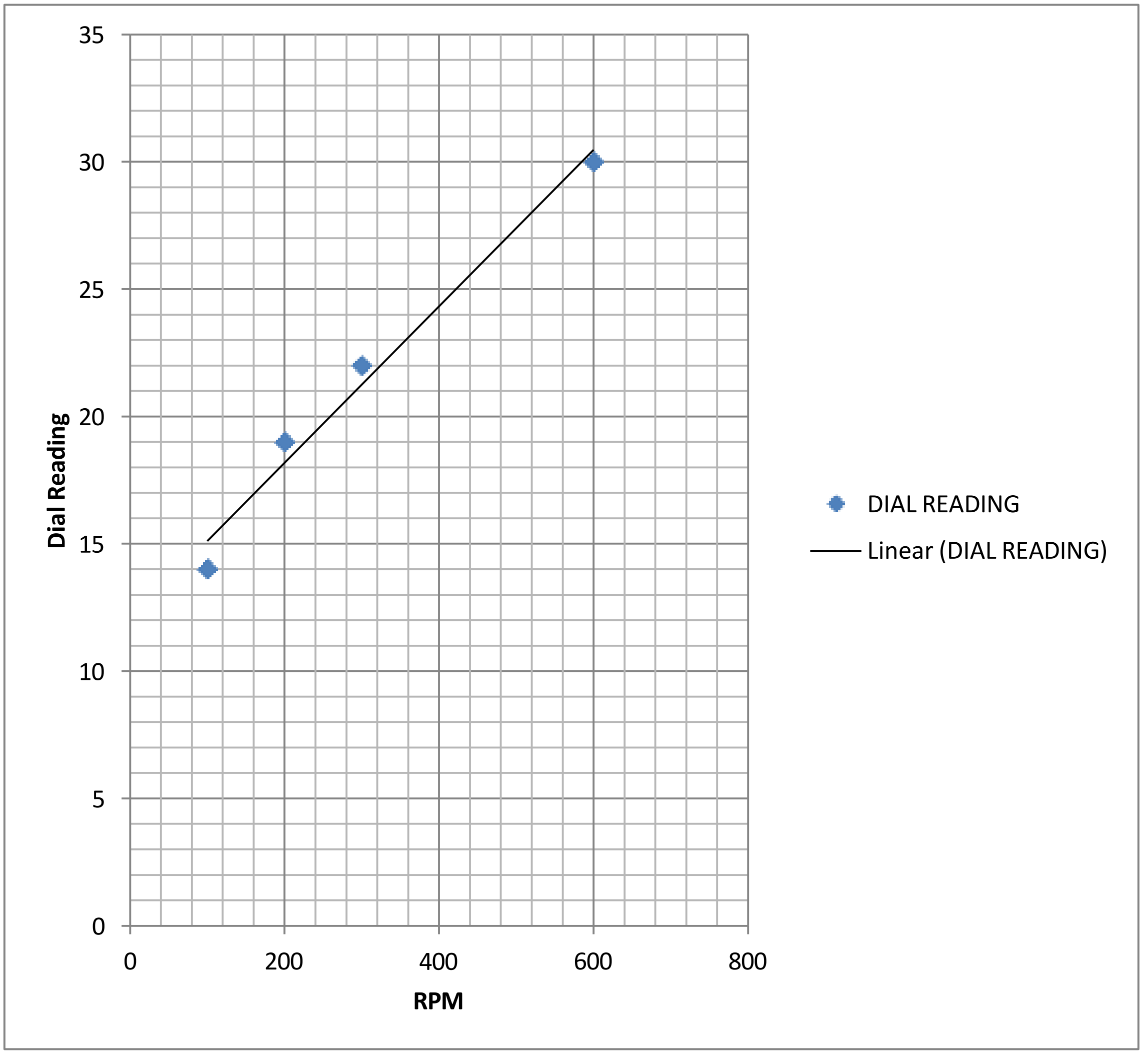

Fig 3.4.1 Plot of Dial reading versus RPM on 25g of gum arabic + 25g of cocoyam

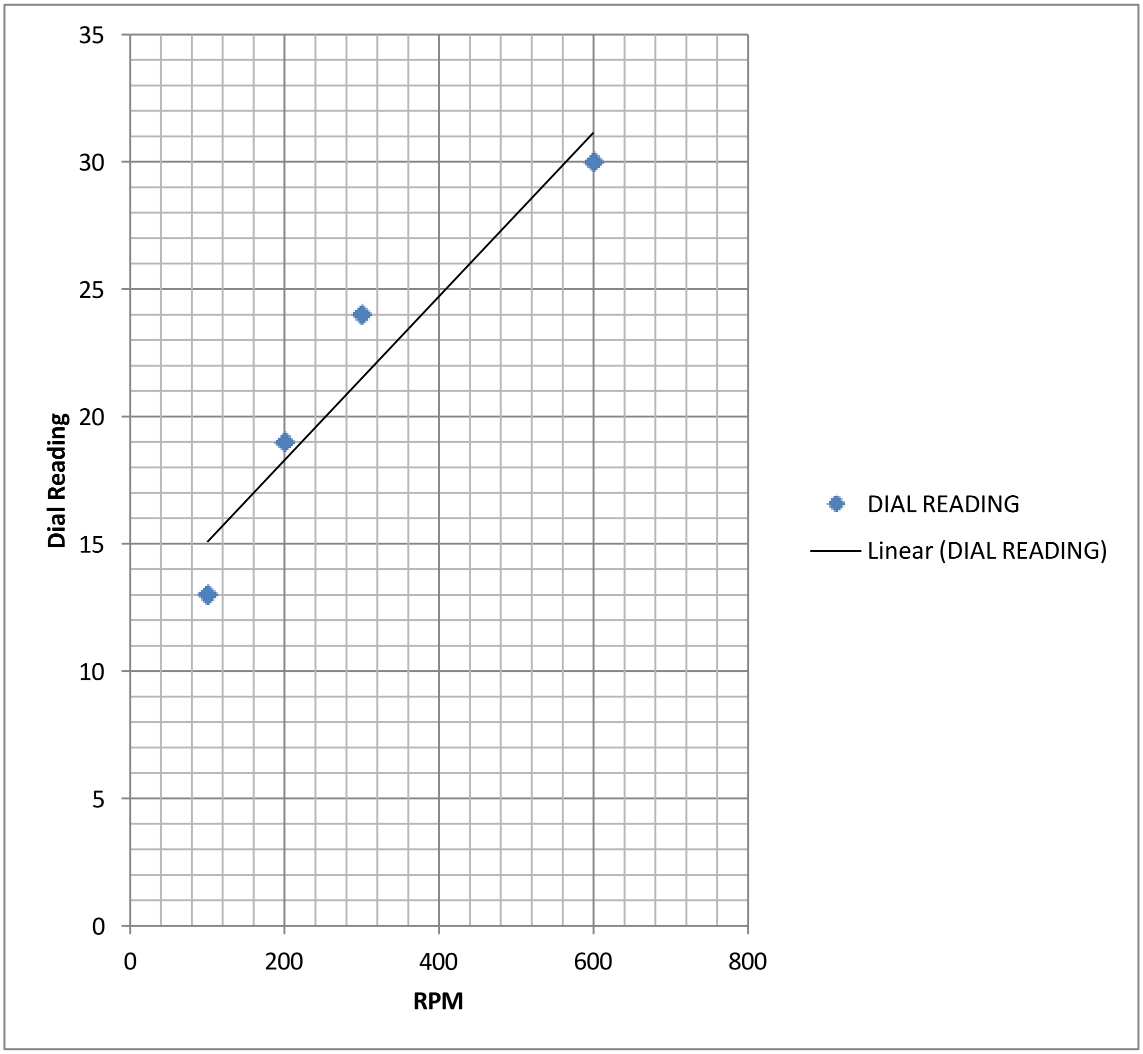

Fig 3.4.1.b Plot of Dial reading versus RPM on 37.5g of gum arabic + 12.5g of cocoyam

TABLE 3.5.1: RESULT OF MUD WITH GUM ARABIC AND GINGER

RPM	**25g of Gum Arabic +25g of Ginger**	**37.5g of Gum Arabic + 12.5g of Ginger**
600	48.0	44.5
300	30.0	28.0
200	24.0	21.5
100	21.0	15.5
GEL		
10 SECONDS	20.0	19.0
10 MINUTES	24.0	18.0
PV	18.0	16.5
YP	12.0	11.5
DENSITY	8.0g/cc	8.1g/cc

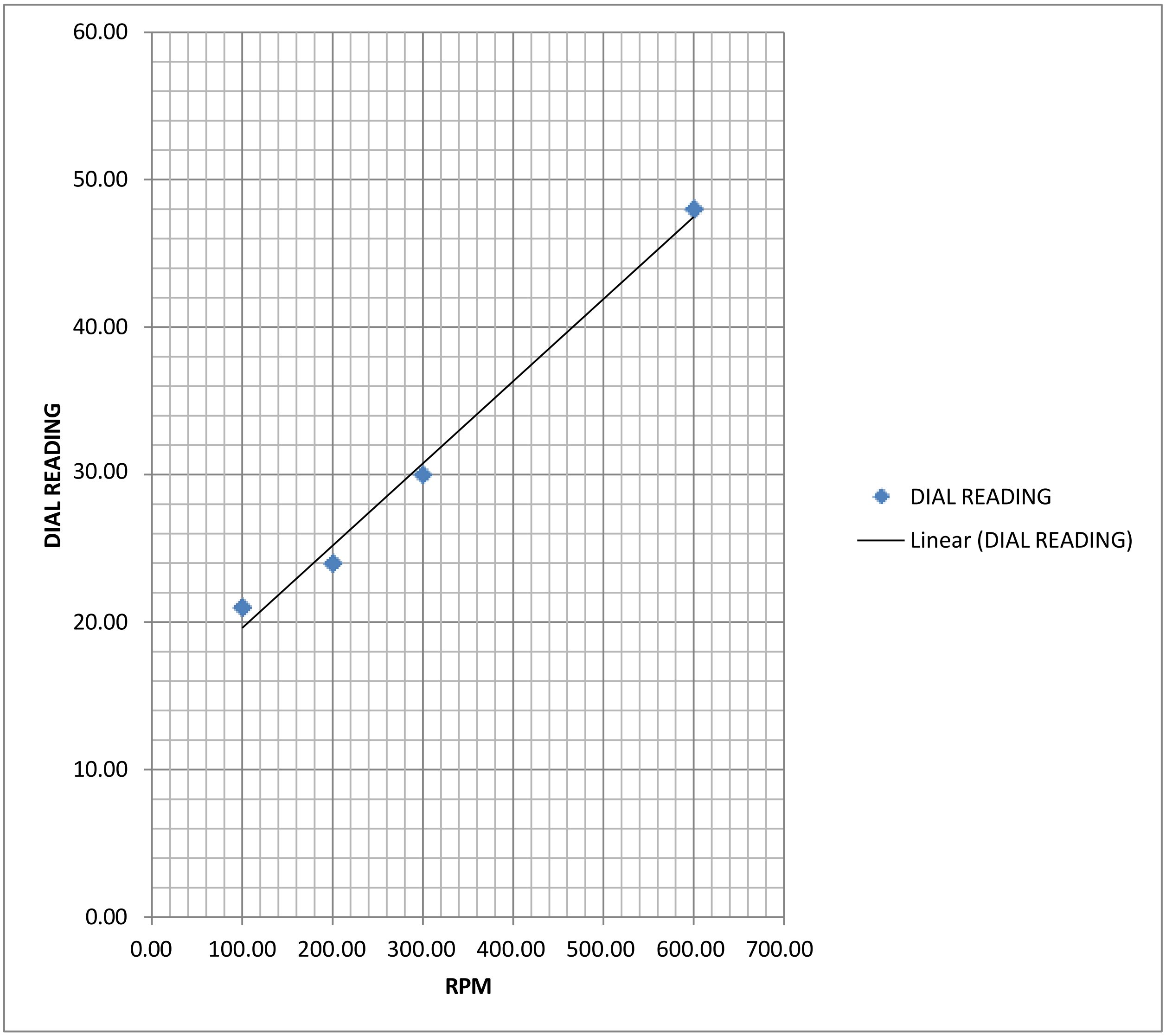

Fig 3.5.1 Plot of Dial reading versus RPM on 25g of Gum Arabic + 25g of Ginger and 37.5g of Gum Arabic + 12.5g of Ginger and

EXPERIMENT TWO

RESULTS:

TABLE 3.2.2: EFFECT OF SALT ON 1g OF XANTHAN GUM MUD SYSTEM

RPM	**7.5g of $CaCl_2$**	**15g of $CaCl_2$**
600	40.5	36.0
300	21.0	19.0
200	19.0	14.0
100	15.0	10.0
GEL		
10 SECONDS	39.0	31.0
10 MINUTES	45.0	35.0
PV	19.5	17.0
YP	1.5	2.0
N	0.948	0.922
K	0.290	0.309
DENSITY	8.1g/cc	8.6g/cc

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 1g OF XANTHAN GUM

TABLE 3.2.2b

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	44	270	207	251
511	23	151	107	130
341	20	108	73	93
170	16	76	38	54

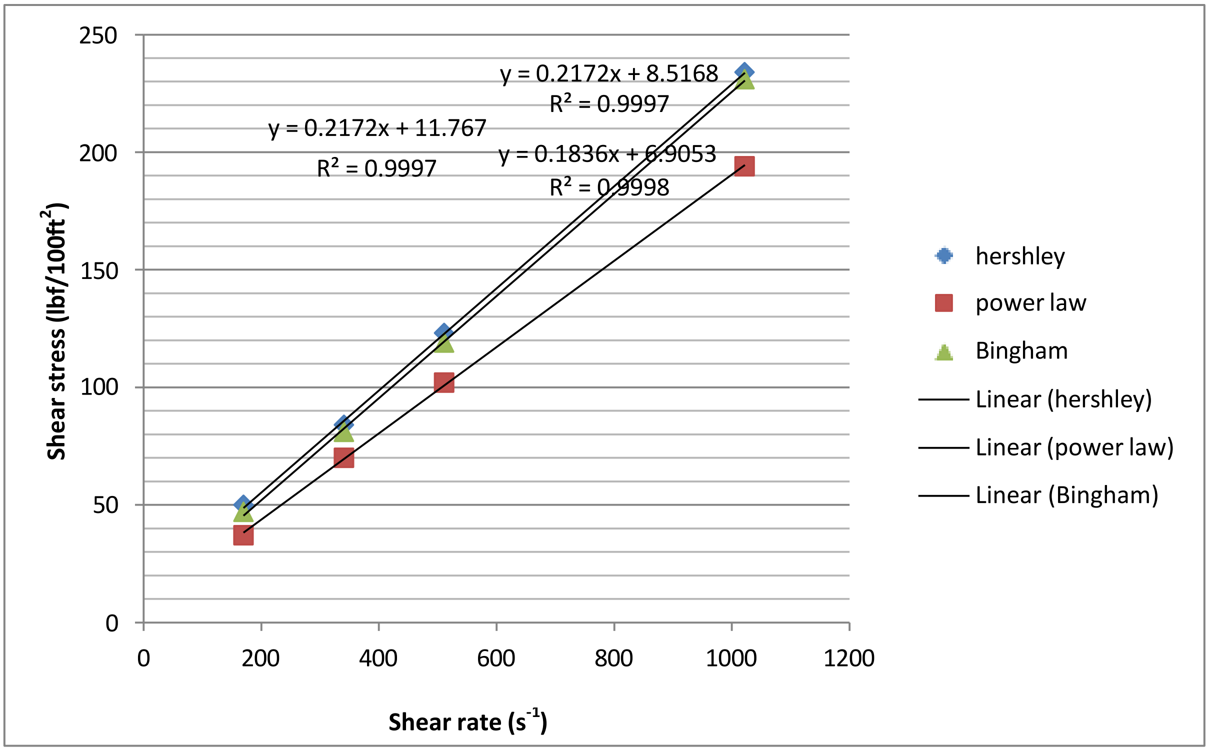

Fig 3.1.2b Plot of Shear stress versus shear rate of the effect of 7.5g of CaCl2 on 1g of xanthan gum mud system

MODEL DATA TO DETERMINE THE EFFECT OF 15g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 1g OF XANTHAN GUM

TABLE 3.1.2c

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	**38**	**250**	**184**	**222**
511	**20**	**150**	**97**	**117**
341	**15**	**108**	**67**	**82**
170	**11**	**94**	**35**	**46**

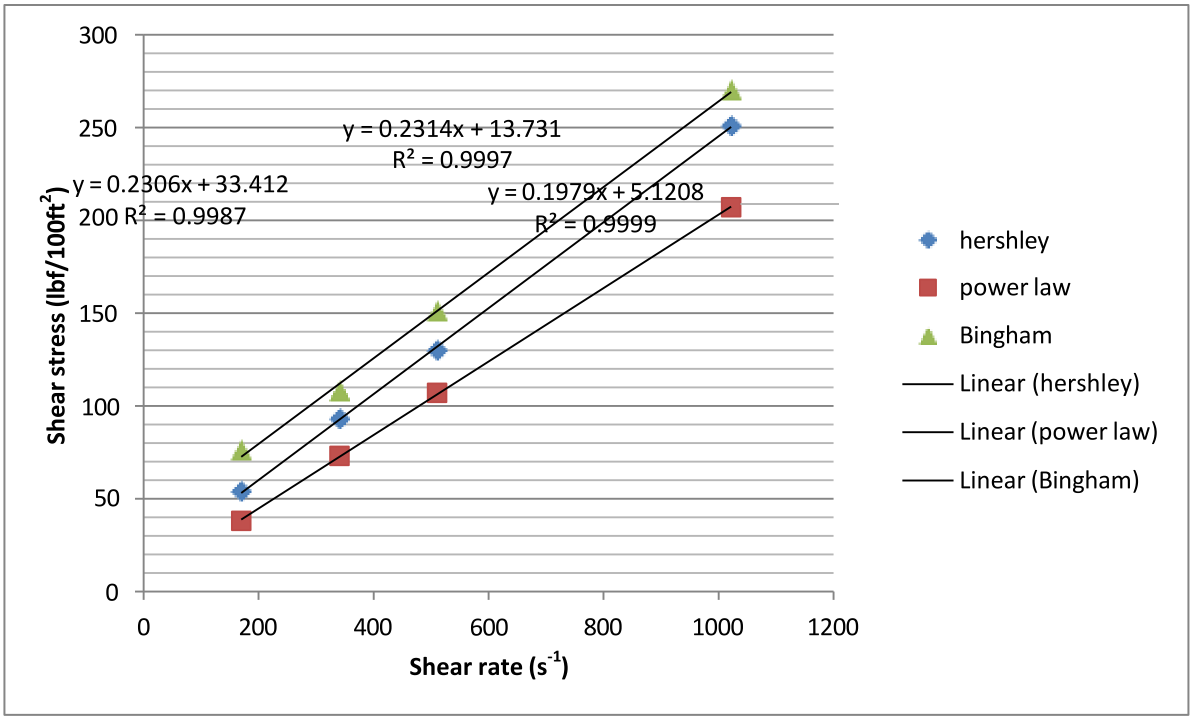

Fig 3.1.2c Plot of Shear stress versus shear rate of the effect of 15g of CaCl2 on 1g of xanthan gum mud system

TABLE 3.2.2: EFFECT OF SALT ON 50g OF GUM ARABIC MUD SYSTEM

RPM	**7.5g of $CaCl_2$**	**15g of $CaCl_2$**
600	31.0	28.0
300	17.0	15.0
200	15.0	12.0
100	11.0	10.0
GEL		
10 SECONDS	20.0	20.0
10 MINUTES	25.0	25.0
PV	14.0	13.0
YP	3.0	2.0
N	0.840	0.873
K	0.461	0.331
DENSITY	8.4g/cc	8.3g/cc

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 50g OF GUM ARABIC

TABLE 3.2.2b

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	33	160	155	188
511	18	74	87	105
341	16	70	62	78
170	12	45	35	47

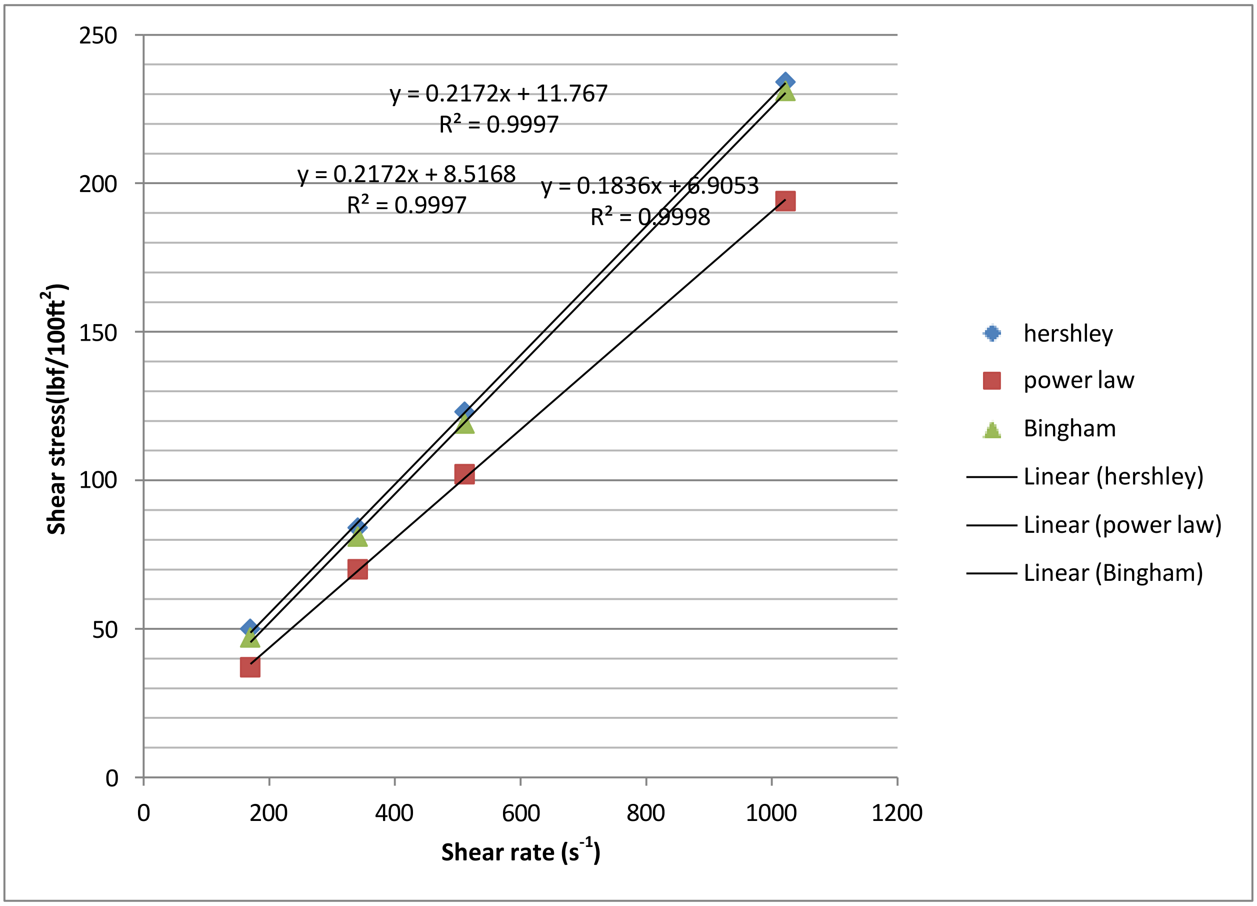

Fig 3.2.2b Plot of Shear stress versus shear rate of the effect of 7.5g of CaCl2 on 50g of Gum Arabic mud system

MODEL DATA TO DETERMINE THE EFFECT OF 15g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 50 g OF GUM ARABIC

TABLE 3.2.2c

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	30	187	140	170
511	16	98	78	94
341	13	75	54	67
170	11	47	29	40

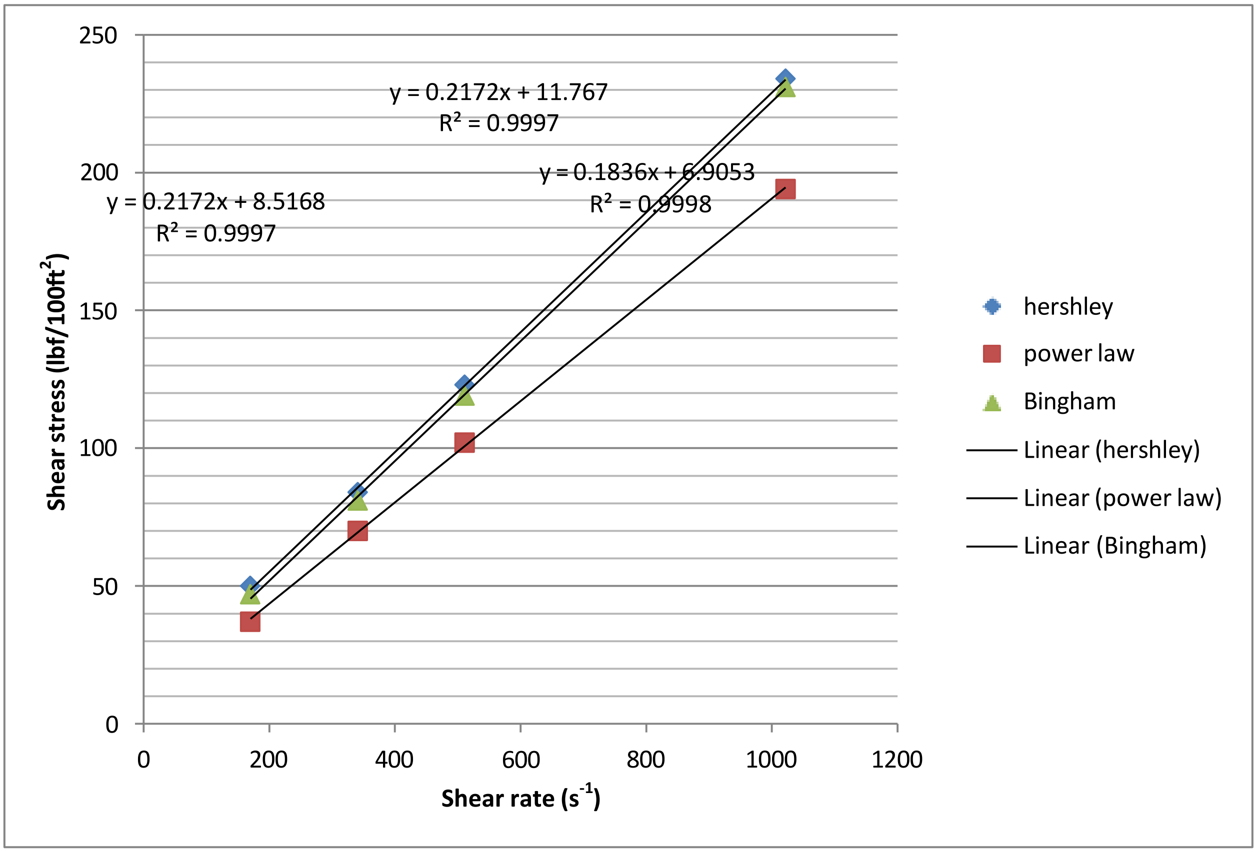

Fig 3.2.2c Plot of Shear stress versus shear rate of the effect of 7.5g of CaCl2 on 50g of Gum Arabic mud system

3.3.2 : EFFECT OF SALT ON 25 g OF GUM ARABIC AND 25g OF COCOYAM MUD SYSTEM

RPM	**7.5g of $CaCl_2$**	**15g of $CaCl_2$**
600	40.0	38.0
300	21.0	20.0
200	17.0	14.0
100	15.0	12.0
GEL		
10 SECONDS	24.0	25.0
10 MINUTES	26.0	35.0
PV	19.0	18.0
YP	2.0	2.0
N	0.929	0.926
K	0.327	0.317
DENSITY	8.1g/cc	8.2g/cc

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC + 25g OF COCOYAM

TABLE 3.3.2b

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	43	242	204	247
511	23	126	107	130
341	18	86	74	92
170	16	48	39	55

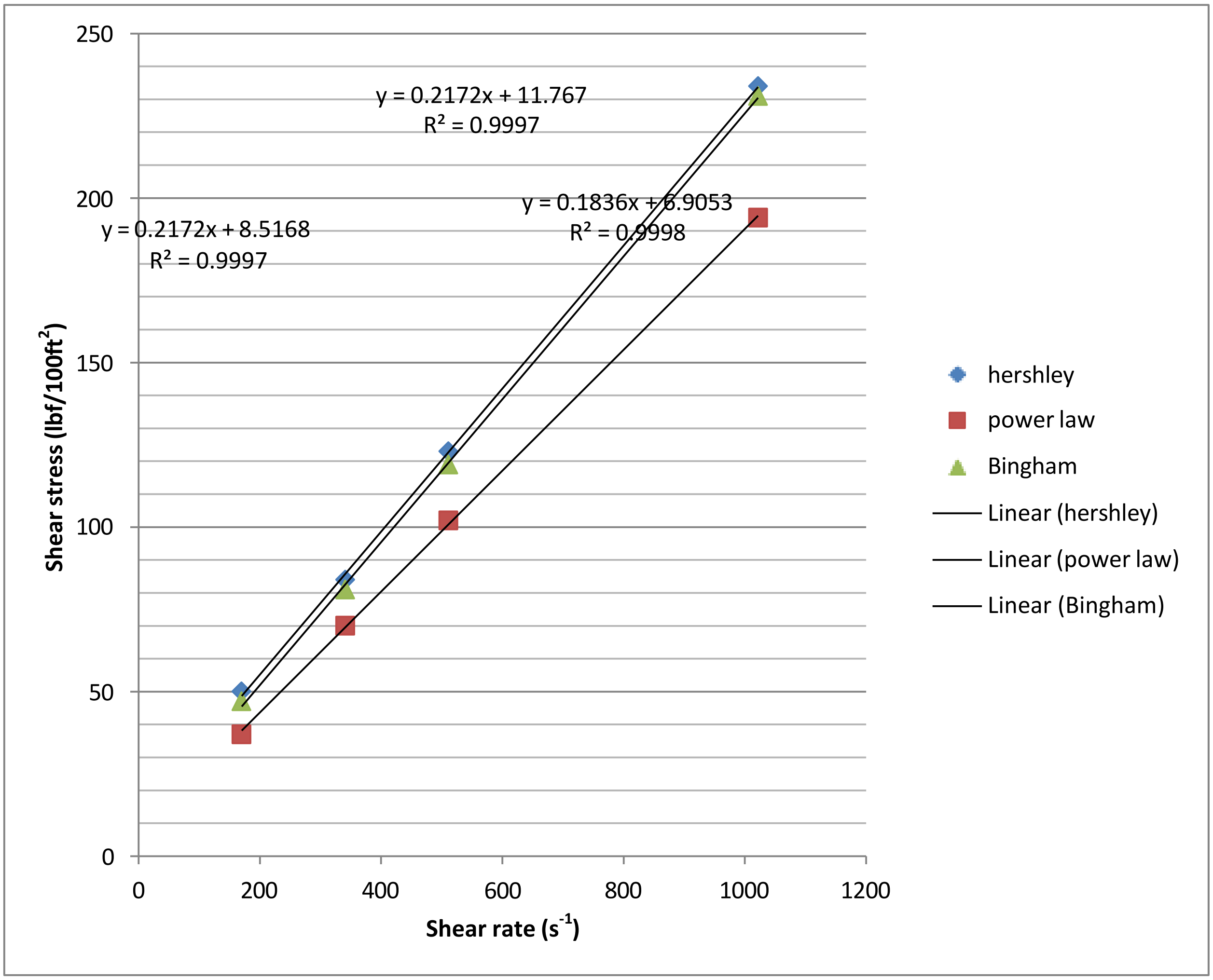

Fig 3.3.2b Plot of Shear stress versus shear rate of the effect of 7.5g of CaCl2 on 25g Gum Arabic + 25g of cocoyam mud system

MODEL DATA TO DETERMINE THE EFFECT OF 15g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC + 25g OF COCOYAM

TABLE 3.3.2c

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	41	231	194	235
511	21	119	102	123
341	15	81	70	84
170	13	47	37	50

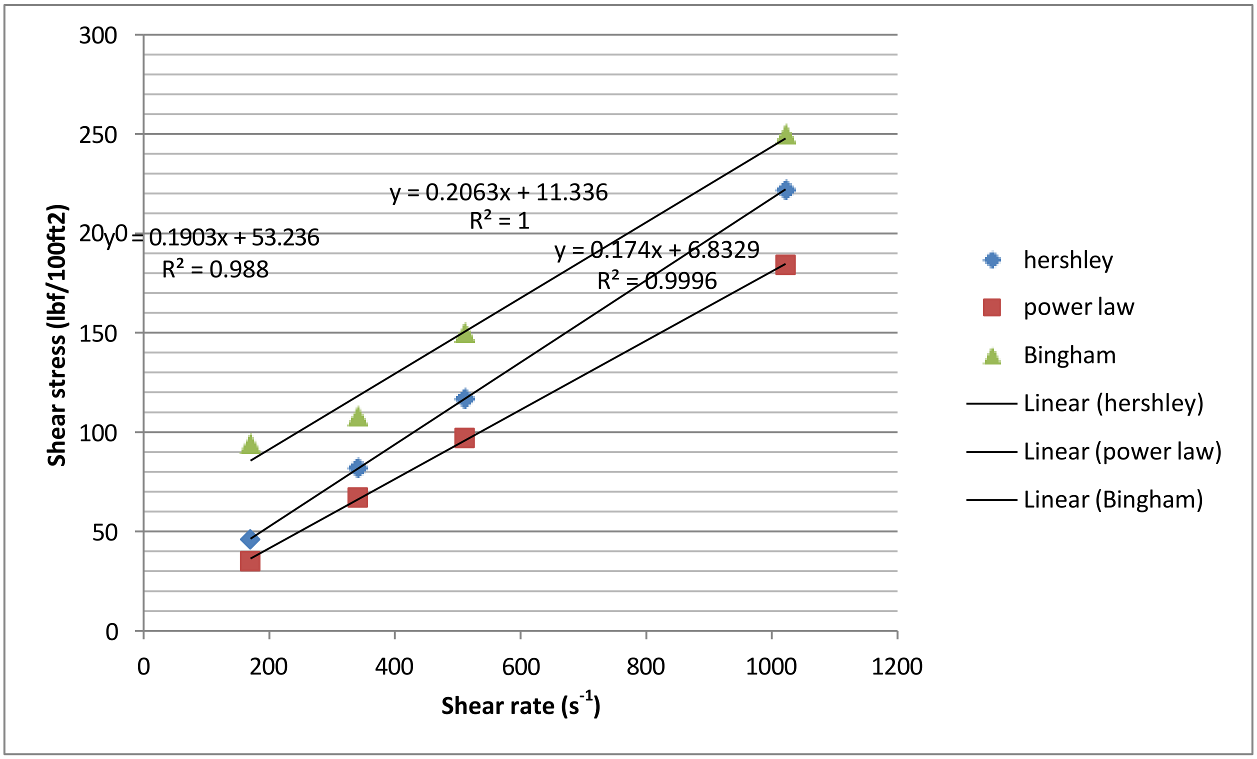

Fig 3.3.2c Plot of Shear stress versus shear rate of the effect of 15g of CaCl2 on 25g Gum Arabic + 25g of cocoyam mud system

3.4.2 : EFFECT OF SALT ON GUM ARABIC AND GINGER MUD SYSTEM

RPM	**7.5g of $CaCl_2$**	**15g of $CaCl_2$**
600	42.0	35.0
300	22.0	19.0
200	19.0	15.0
100	17.0	13.0
GEL		
10 SECONDS	25.0	25.0
10 MINUTES	30.0	35.0
PV	20.0	16.0
YP	2.0	3.0
N	0.933	0.912
K	0.334	0.329
DENSITY	8.0g/cc	7.8g/cc

MODEL DATA TO DETERMINE THE EFFECT OF 7.5g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC + 25g GINGER

TABLE 3.4.2b

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	45	248	215	260
511	24	123	112	136
341	20	83	77	97
170	18	49	40	58

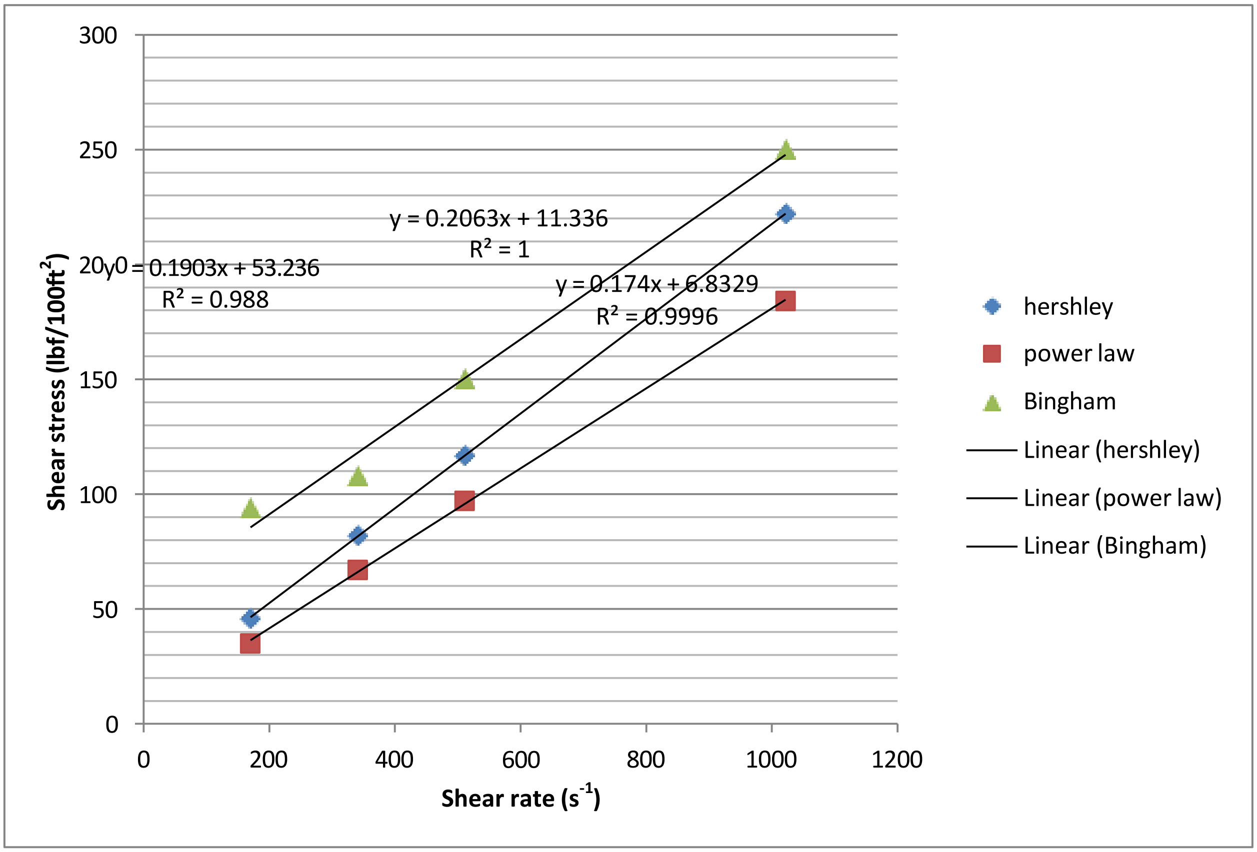

Fig 3.4.2b Plot of Shear stress versus shear rate of the effect of 7.5g of CaCl2 on 25g of Gum Arabic + 25g of ginger mud system

MODEL DATA TO DETERMINE THE EFFECT OF 15g OF CACL2 ON THE RHEOLOGICAL PROPERTIES OF 25g OF GUM ARABIC + 25g GINGER

TABLE 3.4.2c

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	37	254	183	220
511	20	128	97	117
341	16	94	67	83
170	14	58	36	50

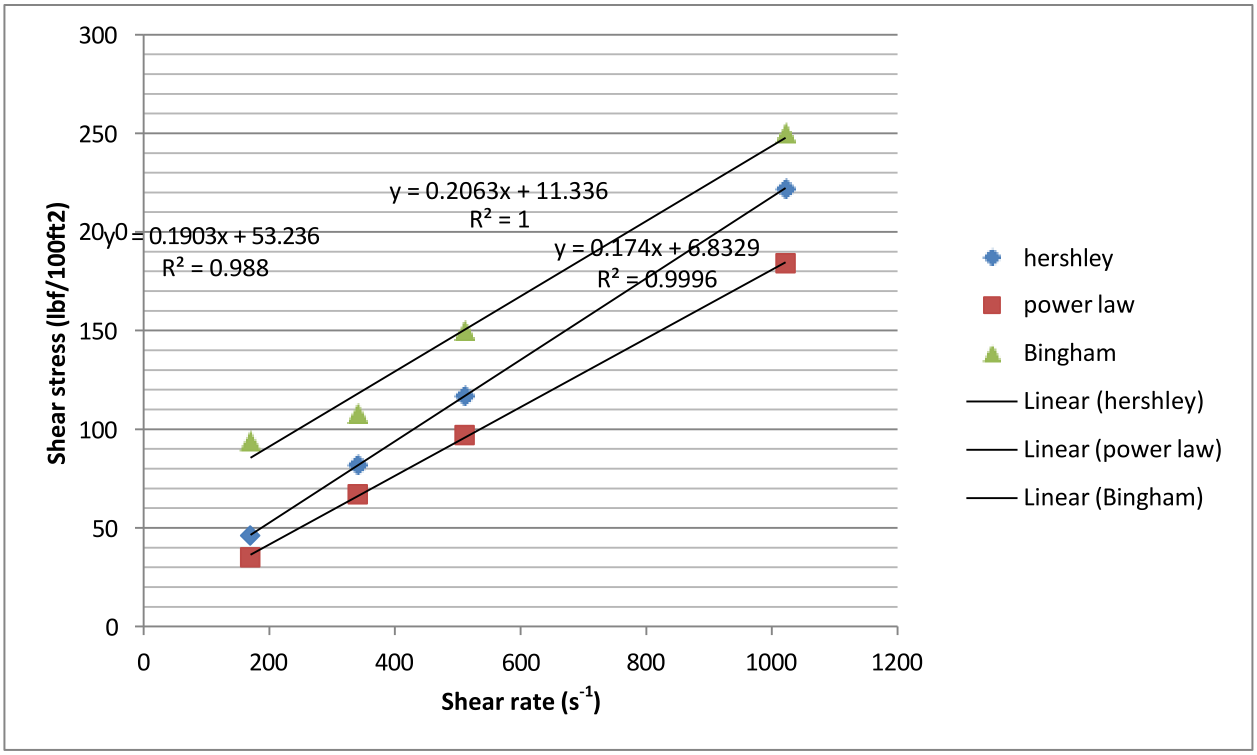

Fig 3.4.2c Plot of Shear stress versus shear rate of the effect of 15g of CaCl2 on 25g of Gum Arabic + 25g of ginger mud system

3.5.2 PROCEDURE FOR VISCOSITY DETERMINATION

The rheometer is a special equipment use for determining mud viscosity. In determining the mud viscosity, a sample of mud was poured in to the rheometer beaker and the beaker was then raised up with the aid of a plate-like base on the viscometer until the rotor sleeve is immersed in the mud at the scribed line and held in position by tightening the lock screw on the right leg of the instrument. The gear was switched on to a speed of 600RPM, 300RPM, 200RPM and 100RPM respectively, the calibrated viscometer reading was allowed to stabilize and the reading was taken and recorded.

3.6.2 PROCEDURE FOR MUD WEIGHT DETERMINATION

The following steps were taken to determine the mud weight:

1. The lid was removed from the cup, and the cup was completely filled with the mud to be tested.
2. The lid was replaced and rotated until firmly seated making sure some mud is expelled through the hole in the cup.
3. The outside of the cup was cleaned with tissue paper to remove the mud on the outside of the cup.
4. The balance arm was placed on the base, with the knife-edge resting on the fulcrum.
5. The rider was moved until the graduated arm level, as indicated by the level vial on the beam.
6. The mud weight was read at the left-hand edge of the rider and its value was recorded.
7. The above procedure was repeated for each addition of the processed peels to the mud and the corresponding values of the mud weight were recorded down.

3.7.2 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.

3.8.2 CALCULATIONS

PLASTIC VISCOSITY (PV)

$PV = \theta\ 600 - \theta 300$

YIELD POINT (YP)

$YP = \theta\ 300 - PV$

n $= 3.32 \text{ Log } \theta 600 / \theta 300$

K $= 5.11 * \theta 300 / (511)^{n}$

(Shear stress) $\tau = 1.067 * \text{dial reading } (\text{lbf}/100\text{ft}^{2})$

(Shear rate) $\gamma = 1.703 * \text{rpm } (\text{sec}^{-1})$

Bingham Plastic Model

$\tau = PV * \gamma + YP$

Power Law Model

$\tau = K (\gamma)^{n}$

Hershely Buckley Model

$\tau = \tau_{o} + K (\gamma)^{n}$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Result Analysis

The result of this study demonstrates that the presence of divalent salts significantly alters the rheological properties of drilling mud solutions. In comparison to the control without salt, calcium chloride ($CaCl_2$) produced systematic changes in flow behavior, yield stress and viscoelastic characteristics, these effects where concentration dependent.

Steady shear measurements revealed that drilling mud solutions exhibit non-Newtonian shear thinning behavior, consistent with previous findings for polysaccharide hydrocolloids.

4.1 LINKING OF XANTHAN GUM AND DIVALENT SALT($CaCl_2$) AS DRILLING FLUID ADDITIVES.

(1) EFFECT OF CONCENTRATION

Increase in the concentration of $CaCl_2$ with a constant mass of xanthan gum showed decrease in viscosity for all shear rate values. When lower viscosity is needed around the bit, this combination is suitable. The plastic viscosity is moderate and can allow easy rate of penetration, also pipe sticking can be mitigated, there is increase in the value of yield point as concentration increases. Higher concentration of calcium chloride causes flocculation that promotes settling rather than structure build up.

(2) EFFECT OF STATIC AGEING

The solution showed increase in gel strength from 10 seconds to 10 minutes, meaning the fluid builds structure over time when static, this could enable well bore stability. Lower gel build up with high $CaCl_2$ means poorer suspension ability during static conditions (risk of bentonite sag or cuttings settlement in drilling). Ageing improves gel strength but this effect is suppressed at higher concentrations of $CaCl_{2.}$

(3) SALINITY

Increment in the value of $CaCl_2$ in the formulation resulted in reduction in viscosity for all constant shear rates. Gel strength values were also reduced by addition of the salt. Variation was also experienced in both initial and final gel strength, when the concentration of the salt was increased from 7.5g to 15g, final gel strength moved from 45cp to 35cp, which indicated 10cp difference. Results are shown in table 3.1.2

4.2 LINKING OF GUM ARABIC AND DIVALENT SALT (CaCl$_2$) AS DRILLING FLUID ADDITIVES.

(1) EFFECT OF CONCENTRATION

Readings obtained by increasing the concentration of $CaCl_2$ with a constant mass of gum Arabic indicated a decrease in the viscosity of the drilling fluid for constant shear rate across the condition imposed. The gel strength value was good, plastic viscosity was moderate for the formulation. This formulation shows reduced ability to carry cuttings and suspend solids, high $CaCl_2$ concentration may reduce carrying capacity and suspension ability, although it may improve filtration control by tightening the filter cake. Low to moderate $CaCl_2$ improves fluid stability and salt tolerance but has poor hole cleaning ability. Results shown in table 3.2.2

(2) EFFECT OF STATIC AGEING

With further settling or rest of the drilling mud, the gel strength increases, the gel strength is relatively stable but could weaken over long-term ageing. The presence of Ca^{2+} causes flocculation over time, this leads to changes in gel strength and sometimes a slight drop in viscosity due to polymer degradation or precipitation. The effect on static ageing has minimal effect on gel build up in $CaCl_2$ contaminated systems because calcium ions stiffens or collapse polymer chains, preventing further network formation over time. Results shown in table 3.2.2

(3) SALINITY

With more $CaCl_{2,}$ viscosity, yield point and k value all decreased. Salinity compresses the electric double layer around the gum Arabic molecules, reducing repulsion and promoting coil shrinkage. High salinity can adversely affect gum Arabic performance, making the fluid less viscous, less stable, and less efficient as a viscosifier or filtration control agent. Results shown in table 3.2.2

4.3 LINKING OF GUM ARABIC, COCOYAM AND DIVALENT SALT ($CaCl_2$) AS DRILLING FLUID ADDITIVES.

(1) EFFECT OF CONCENTRATION

At the higher concentration of calcium chloride, the fluid becomes slightly less viscous under shear (reduced PV and rpm readings). That is consistent with polymer coil contraction / reduced hydration and partial flocculation which lower viscous resistance at shear. However, net effect of increasing $CaCl_2$ results in lower flow viscosity under shear but stronger low shear/longer-time gel structure. The addition of $CaCl_2$ to cocoyam and gum Arabic drilling fluid produces competing effects. Divalent calcium ions form ionic bridges between polysaccharide chains, promoting a stronger lower shear gel with time. Simultaneously, increased ionic strength screens electrostatic repulsion and reduces polymer hydration, causing a modest fall in high-shear viscosities and plastic viscosity. Consequently, raising $CaCl_2$ from 7.5g to 15g slightly lowered apparent and plastic viscosity but increased longtime gel strength, indicating more rapid network formation at rest even though the fluid flows more readily under shear. Result is shown in table 3.3.2

(2) EFFECT OF STATIC AGEING

Higher $CaCl_2$ speeds or enhances this rebuilding, so ageing leads to more pronounced gelation at higher salt. Practically, the fluid becomes more stronger (at rest) after a few minutes in the hole when $CaCl_2$ is present. During ageing, water molecules gradually redistribute within the polymer network, in low-salinity fluids, water hydrates polymer chains, making the gel softer and more flexible, while in saline systems, water activity decreases, polymer chains lose some hydration and draw closer together. Static ageing in the gum Arabic – cocoyam- $CaCl_2$ mud sytem reflects the time dependent structural rebuilding that occrs when the fluid is left undisturbed. The 10 seconds and 10 minutes gel values show that ageing time increases, the ionic cross linking between gum Arabic and cocoyam polymers, mediated by calcium ions strengthens the three dimensional gel network. This leads to higher gel strength, particularly at higher $CaCl_2$ concentrations (15g), indicating enhanced inter polymer bridging. The process improves the mud’s ability to suspend cuttings when static, but excessive gelation may cause high restart pressures after shutdowns. Result is shown in table 3.3.2

(3) SALINITY

Higher salinity causes polymer to shrink, decreases hydration and inter chain repulsion; this reduces high shear viscosity and can eventually cause flocculation o precipitation of the polymer if excessive. Reduced high shear viscosity may reduce the fluid’s ability to suspend and transport cuttings while circulating. But stronger gel at rest helps suspend cuttings when circulation stops. Ionic cross linking can improve filter cake strength, but excessive salt that collapses polymer may reduce filtration control (less colloidal stabilization). Result is shown in table 3.3.2

4.4 LINKING OF GUM ARABIC, GINGER AND DIVALENT SALT ($CaCl_2$) AS DRILLING FLUID ADDITIVES.

(1) EFFECT OF CONCENTRATION

When the concentration of $CaCl_2$ increases from 7.5 g to 15 g, the readings at 600, 300, and 200 rpm all decrease (from 42 to 35, 22 to 19, and 19 to 15, respectively). The plastic viscosity (PV) decreases from 20 to 16 CP, while yield point (YP) slightly increases from 2 to 3 lb/100 ft^2. This indicates that higher Ca^{2+} concentration reduces the overall flow viscosity but promotes some degree of structure formation. The decrease in viscosity occurs because excessive Ca^{2+} ions neutralize the negative sites on the gum arabic and ginger molecules, reducing their hydration and flexibility. However, some Ca^{2+} ions act as ionic bridges, linking polymer chains (cross-linking), which accounts for the slightly higher YP at 15 g $CaCl_2$. Thus, increasing concentration initially enhances cross-linking but at higher levels, viscosity reduction dominates due to polymer contraction and reduced solubility. Result is shown in table 3.4.2.

(2) EFFECT OF STATIC AGEING

From the data, the 10-second gel strength remains constant at 25 lb/100ft^2 for both concentrations, while the 10-minute gel increases markedly from 30 to 35 lb/100ft^2 as $CaCl_2$ increases. This shows that static ageing (the resting period after agitation) allows more time for ionic cross-linking and network consolidation between gum arabic and ginger polysaccharides through Ca^{2+} bridging. During rest, the divalent Ca^{2+} ions enhance intermolecular attractions, causing polymer chains to aggregate and form a more rigid three-dimensional gel structure. The longer the ageing time, the more complete the formation of these bridges. The 10-minute gel increase shows that the fluid strengthens with time, improving its ability to suspend cuttings when static. However, excessive gelation could make restarting circulation more difficult. Overall, static ageing demonstrates the thixotropic recovery and time-dependent network formation enhanced by Ca^{2+} ions in the gum arabic–ginger system. Result is shown in table 3.4.2.

(3) SALINITY

Salinity, contributed by $CaCl_2$, significantly influences polymer interaction and rheology. As salinity increases (more $CaCl_2$), the ionic strength of the system rises, leading to electrostatic shielding around polymer chains. This reduces repulsive forces between negatively charged sites, causing the polymers to coil and the overall viscosity to drop (PV from 20 to 16). However, divalent Ca^{2+} ions also promote localized cross-linking through coordination with hydroxyl and carboxyl groups in gum arabic and ginger polysaccharides. Hence, while high salinity compresses the polymer network and reduces high-shear viscosity, it simultaneously enhances low-shear gelation and structure building. This dual effect makes the fluid more gel-like at rest but thinner under circulation. Therefore, salinity from $CaCl_2$ must be carefully optimized — too low gives poor gel strength, while too high leads to over-flocculation, reduced hydration, and potential instability. Result is shown in table 3.4.2.

CLASSIFICATION OF MUD SYSTEMS UNDER RHEOLOGICAL MODELS:

Drilling muds are classified based on their flow behavior or rheological response to applied shear stress, which determines how they perform under downhole conditions. These behaviors are described using rheological (logical) models, which relate shear stress and shear rate to characterize the fluid type. The main classifications include:

- **BINGHAM PLASTIC MODEL**: These require a certain yield stress to initiate flow and then behave linearly afterward. Many clay-based muds fit this model due to their internal particle structure.
- **PLASTIC OR PSEUDO-PLASTIC (POWER LAW) MODEL**: These show a non-linear relationship where viscosity decreases with increasing shear rate (shear-thinning

behavior). Polymer-based muds such as those containing xanthan gum or gum arabic are typical examples.

- **HERSHELY–BUCKLEY MODEL**: A more general model combining yield stress and non-linear shear behavior. It represents most real drilling fluids that show both yield and shear-thinning characteristics.

These classifications help in predicting mud performance, optimizing hydraulics, and controlling cuttings transport and suspension during drilling.

Drilling muds, also known as drilling fluids, are complex mixtures designed to perform several vital functions during drilling operations, such as removing cuttings, cooling and lubricating the drill bit, maintaining hydrostatic pressure, and stabilizing the wellbore.

The flow behavior of these muds determines how effectively they perform these functions under various shear conditions in the wellbore and annulus.

To describe this flow behavior, rheological models are used. These models express the relationship between shear stress (τ) and shear rate ($\dot{\gamma}$) and help determine how the mud will behave under laminar and turbulent flow regimes.

Drilling muds exhibit different flow behaviors depending on their composition, solid content, and additives. To understand and predict their flow under various shear conditions, rheological models such as Newtonian, Bingham Plastic, Power Law, Hershely–Buckley models are used.

These models help in classifying mud systems into categories based on n (flow behavior index), k (consistency index), and correlation (R^2) between shear stress and shear rate. The n value indicates the type of flow (Newtonian, pseudo-plastic, or dilatant), while k reflects the viscosity or consistency of the fluid. High R^2 values (close to 1) show a good fit to that rheological model.

IMPORTANCE OF RHEOLOGICAL CLASSIFICATION

Classifying drilling muds based on rheological models is important because it:

(1) Helps in predicting pressure losses in the drill pipe and annulus.

(2) Guides the design of hydraulic programs for optimal hole cleaning.

(3) Aids in the selection of mud additives and formulation adjustments.

(4) Determines flow type (plastic, pseudo-plastic, or dilatant) and stability under temperature, salinity, and ageing conditions.

TABLE 4.5 : MODEL DATA RESULTS

S/N	**Drilling Mud Form**	**Rheological Model**	**N**	**K**	**R^2**
1.	7.5g $CaCl_2$ + 1g of xanthan gum	Power law	0.948	0.290	0.9998
2.	15g $CaCl_2$ + 1g of xanthan gum	Power law	0.922	0.309	0.9999
3.	7.5g $CaCl_2$ + 50g of Gum Arabic	Power law	0.840	0.461	0.9998
4.	15g $CaCl_2$ + 50g of Gum Arabic	Power law	0.873	0.331	0.9998
5.	7.5g of $CaCl_2$ + 25g of Gum Arabic + 25g of Cocoyam	Power law	0.929	0.327	0.9998
6.	15g of $CaCl_2$ + 25g of Gum Arabic + 25g of Cocoyam	Hershely Buckley	0.926	0.317	1
7.	7.5g of $CaCl_2$ + 25g of Gum Arabic + 25g of Ginger	Hershely Buckley	0.933	0.334	1
8.	15g of $CaCl_2$ + 25g of Gum Arabic + 25g of Ginger	Hershely Buckley	0.912	0.329	1

CHAPTER FIVE

CONCLUSION(S)

The study on the effect of divalent salt on rheological properties of beneficiated gum arabic has provided valuable insights into its potential as ecofriendly drilling fluid additive. The experimental results demonstrated that the presence and concentration of divalent salts ($CaCl2$) significantly influence the viscosity, yield stress, and flow behavior of gum arabic solution. Moderate concentrations of $CaCl2$ enhanced cross-linking between gum molecules, leading to improved gel strength and better suspension stability, which are desirable for drilling fluid performance. However, excessive salt concentration caused structural breakdown of polymer network, reducing viscosity and flow consistency. The rheological characterization indicated that the fluid exhibits non-Newtonian, shear-thinning behavior, conforming largely to the power law and Bingham plastic models depending on salt concentration. This behavior is beneficial for drilling operations as it promotes efficient cutting transport at low shear rates while maintaining manageable pump ability at high shear rates. It is also observed that:

1. Ginger is a good stabilizer and also a good viscosifier in the formulation of drilling fluids.

2. With the increase in salt concentration ($CaCl2$) the viscosity of ginger with gum Arabic decreases this means that the drilling fluid cannot be used in a salty formation (if encountered during drilling operation)

3. With the addition of Arabic cocoyam, viscosity reduces with more concentration of Arabic cocoyam this proves that the Arabic cocoyam is not exactly a good viscosifier compared with ginger.

4. With the increase in the alkalinity the viscosity of ginger with gum Arabic increases exponentially this means that it can be used successfully in alkaline formation.

5.1 RECOMMENDATION(S)

On achieving the objectives of this research work in the laboratory under normal room temperature, the following recommendations are made:

- Optimization of salt concentration: moderate concentrations of divalent salts such as calcium chloride should be optimized during formulation to enhance the viscosity and gel strength of gum arabic-based drilling fluids without causing excessive flocculation or degradation of the polymer structure.
- Use in drilling fluid formulation: beneficiated gum arabic has shown promising rheological behavior suitable for use as a vicosifying and filtration control agent in water-based drilling muds. It is recommended for application in low-to-medium salinity environments where its stability and performance are maximized.
- Further research on Temperature and ageing effects: future studies should examine the combined effects of temperature, ageing time, and salinity on the rheological stability of gum arabic to simulate real downhole conditions. This provide more accurate predictions of its field performance.
- Comparative studies with other natural polymer: it is advisable to compare beneficiated gum arabic with other bio-based polymers under similar conditions to evaluate cost-effectiveness and performance advantages.
- Industrial application and scale-up: since beneficiated Gum arabic is biodegradable and locally available, industries should consider its large-scale production and incorporation into eco-friendly drilling fluid systems, reducing dependence on expensive imported additives.

5.2 CONTRIBUTION OF KNOWLEDGE

This research has made several important contributions to both scientific knowledge and practical applications I petroleum engineering and drilling fluid technology.

- Scientific contribution: the research provides a deeper understanding of how divalent salts, particularly calcium chloride ($CaCl_2$), influence the behavior of natural polymers like gum arabic. It establishes the relationship between salt concentration and key rheological properties such as viscosity, yield stress, plastic viscosity and gel strength, thereby contributing to the broader knowledge of polymer-electrolyte interactions.
- Development of eco-friendly drilling fluid additive: the study demonstrates that beneficiated gum arabic can serve as an effective and biodegradable vicosifying and filtration control agent in drilling fluid formulations. This promotes the use of environmentally friendly and renewable materials as alternatives to synthetic polymers
- Practical application in drilling operations: the study offers valuable data that can guide the formulation of water-based drilling muds under varying salinity conditions. Understanding the behavior of gum arabic in the presence of divalent salts aids in optimizing mud performance in saline formations or offshore drilling environments

REFERENCES

Abdou, M. I., Al-Sabagh, A. M., & Ahmed, H. E. (2013). Impact of barite and ilmenite mixture on enhancing the drilling mud weight. Egyptian Journal of Petroleum, 22(4), 573-580.

Agarwal, S., Tran, P., Soong, Y., Martello, D., & Gupta, R. K. (2012). Flow behavior of nanoparticle stabilized drilling fluids and effect of high temperature aging. Proceedings of the AADE National Technical Conference and Exhibition, Houston, Texas.

Ahmed, S., Elraies, K. A., Forooozesh, J., Shafian, S. R., Hashmet, M. R., & Hanafy, A. (2023). Experimental investigation of immiscible supercritical CO_2 water-alternating-gas injection performance in carbonate reservoirs. Journal of Natural Gas Science and Engineering, 107, 104794.

Al-Azani, K., Elkatatny, S., Ali, A., Ramadan, E., & Abdulraheem, A. (2019). Cutting concentration prediction in horizontal and deviated wells using artificial intelligence techniques. Journal of Petroleum Exploration and Production Technology, 9(4), 2769-2779.

Ali, M., Jarni, H. H., Aftab, A., Ismail, A. R., Saady, N. M. C., Sahito, M. F., ... & Shuker, M. T. (2017). Nanomaterial-based drilling fluids for exploitation of unconventional reservoirs: A review. Energies, 10(9), 1292.

Al-Muntasheri, G. A., Nasr-El-Din, H. A., & Hussein, I. A. (2017). A rheological investigation of a high temperature organic gel used for water shut-off treatments. Journal of Petroleum Science and Engineering, 159, 937-950.

Alohaly, A., Alqasemi, K., Omran, M., Al-Yami, A., & Al-Arfaj, M. (2021). Environmentally friendly drilling fluid additives: A review of recent advances. SPE Middle East Oil & Gas Show and Conference, Manama, Bahrain.

Amanullah, M., & Yu, L. (2005). Environment friendly fluid loss additives to protect the marine environment from the detrimental effect of mud additives. Journal of Petroleum Science and Engineering, 48(3-4), 199-208.

Amanullah, M., Al-Tahini, A. M., & Yu, L. (2007). New approach to evaluate the filtration characteristics of waterbased drilling fluids. IADC/SPE Drilling Conference, Amsterdam, Netherlands.

Anderson, D. M. W., & Weiping, W. (1990). The characterization of Acacia gum quality and evaluation for food use. Food Additives & Contaminants, 7(3), 303-321.

API RP 13B-1. (2019). Recommended practice for field testing water-based drilling fluids (5th ed.). American Petroleum Institute.

Bak, J., Lee, T., Lim, J., Yoon, H., Lee, J., Park, M., ... & Choi, S. (2025). Salt effects on the rheological properties of gum Arabic solutions: Implications for drilling fluid applications. Carbohydrate Polymers, 324, 121058.

Barnes, H. A. (1997). Thixotropy—a review. Journal of Non-Newtonian Fluid Mechanics, 70(1-2), 1-33.

Barry, M. M., Jung, Y., Lee, J. K., Phuoc, T. X., & Chyu, M. K. (2015). Fluid filtration and rheological properties of nanoparticle additive and intercalated clay hybrid bentonite drilling fluids. Journal of Petroleum Science and Engineering, 127, 338-346.

Ben-Ali, S., Khodja, M., Canselier, J. P., & Bergaya, F. (2006). Brownian dynamics simulation of colloidal hard spheres. Applied Clay Science, 31(1-2), 142-148.

Bera, A., Kumar, T., Ojha, K., & Mandal, A. (2013). Adsorption of surfactants on sand surface in enhanced oil recovery: Isotherms, kinetics and thermodynamic studies. Applied Surface Science, 284, 87-99. Bingham, E. C. (1916). An investigation of the laws of plastic flow. US Bureau of Standards Bulletin, 13, 309-353.

Bourgoyne Jr, A. T., Millheim, K. K., Chenevert, M. E., & Young Jr, F. S. (1991). Applied drilling engineering. Society of Petroleum Engineers.

Caenn, R., Darley, H. C., & Gray, G. R. (2017). Composition and properties of drilling and completion fluids (7th ed.). Gulf Professional Publishing.

Chenevert, M. E. (1970). Shale alteration by water adsorption. Journal of Petroleum Technology, 22(9), 1141-1148.

Darley, H. C., & Gray, G. R. (1988). Composition and properties of drilling and completion fluids (5th ed.). Gulf Professional Publishing. Elsharkawy, A. M., & Nasr-El-Din, H. A. (2018).

Drilling Fluid Processing Handbook. Gulf Professional Publishing (2005)

Effect of pH on the rheological properties of aqueous polyacrylamide solutions. Journal of Applied Polymer Science, 135(28), 46421.

Fakoya, M. F., & Ahmed, R. M. (2018). A generalized model for apparent viscosity of oil-based muds. Journal of Petroleum Science and Engineering, 165, 777-785.

Ferraz, S., Lopes, L., Teixeira, G., & Lomba, R. (2014). Influence of pre-hydrated bentonite on the properties of water-based drilling fluids. Applied Clay Science, 95, 25-31.

Gamal, H., Elkatatny, S., Basfar, S., & Al-Majed, A. (2019). Effect of pH on rheological and filtration properties of water-based drilling fluid based on bentonite. Sustainability, 11(23), 6714.

Herschel, W. H., & Bulkley, R. (1926). Konsistenzmessungen von Gummi-Benzollösungen. Kolloid-Zeitschrift, 39(4), 291-300.

Hossain, M. E., & Rahman, S. S. (2008). A comprehensive drilling engineering course for final year petroleum engineering students. European Journal of Engineering Education, 33(2), 235-250.

Howard, G. C., & Fast, C. R. (1970). Hydraulic fracturing (Vol. 2). Society of Petroleum Engineers. Ibrahim, A. F., Nasr-El-Din, H. A., & Al-Bagoury, M. (2022). A comprehensive review of nanoparticles applications in the oil and gas industry from enhanced oil recovery to drilling and completion fluids. Advances in Colloid and Interface Science, 299, 102555.

Jiao, D., & Sharma, M. M. (1994). Mechanism of cake buildup in crossflow filtration of colloidal suspensions. Journal of Colloid and Interface Science, 162(2), 454-462.

Kelessidis, V. C., & Maglione, R. (2006). Modeling rheological behavior of bentonite suspensions as Casson and Robertson–Stiff fluids using Newtonian and true shear rates in Couette viscometry. Powder Technology, 168(3), 134-147.

Kelessidis, V. C., & Maglione, R. (2008). Shear rate corrections for Herschel-Bulkley fluids in Couette geometry. Applied Rheology, 18(3), 34482.

Kelessidis, V. C., Maglione, R., Tsamantaki, C., & Aspirtakis, Y. (2006). Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity and ECD calculations. SPE Drilling & Completion, 21(3), 203-213.

Khodja, M., Canselier, J. P., Bergaya, F., Fourar, K., Khodja, M., Cohaut, N., & Benmounah, A. (2010). Shale problems and water-based drilling fluid optimisation in the Hassi Messaoud Algerian oil field. Applied Clay Science, 49(4), 383-393.

Liu, Y., Wang, J., Zhang, L., & Chen, M. (2019). Effects of alkali treatment on the rheological properties of natural polymer solutions. Carbohydrate Polymers, 216, 89-96.

Livescu, S. (2012). Mathematical modeling of thixotropic drilling mud and crude oil flow in wells and pipelines- A review. Journal of Petroleum Science and Engineering, 98, 174-184.

Lomba, R. F., Chenevert, M. E., & Sharma, M. M. (2000). The role of osmotic effects in fluid loss control. SPE Drilling & Completion, 15(3), 158-164.

Mahmoud, O., Nasr-El-Din, H. A., Vryzas, Z., & Kelessidis, V. C. (2021). Effect of ferric oxide nanoparticles on the properties of filter cake formed by calcium bentonite-based drilling muds. SPE Drilling & Completion, 36(1), 135-148.

Mahto, V., & Sharma, V. P. (2004). Rheological study of a water based oil well drilling fluid. Journal of Petroleum Science and Engineering, 45(1-2), 123-128.

Mitchell, R. F., & Miska, S. Z. (2011). Fundamentals of drilling engineering. Society of Petroleum Engineers. Mullineux, G. (2008).

Navarrete, R. C., Seheult, J. M., & Coffin, G. V. (2000). Enhanced oil-based mud formulations with organophilic lignite resin. SPE Drilling & Completion, 15(1), 21-30.

NIPES Journal. (2024).

Non-linear least squares fitting of coefficients in the Herschel–Bulkley model. Applied Mathematical Modelling, 32(12), 2538-2551.

Ofei, T. N., Irawan, S., & Pao, W. (2016). CFD method for predicting annular pressure losses and cuttings concentration in eccentric horizontal wells. Journal of Petroleum Engineering, 2016, Okoro, E. E., Dosunmu, A., & Iyuke, S. E. (2018). Cost effective drilling mud formulation using locally sourced materials. Petroleum & Coal, 60(6), 1080-1090.

Ostwald, W. (1925). Über die Geschwindigkeitsfun

Phillips, G. O., & Williams, P. A. (2009). Handbook of hydrocolloids. Woodhead Publishing. Springer. (2016).

Verbeken, D., Dierckx, S., & Dewettinck, K. (2003). Exudate gums: occurrence, production, and applications. Applied Microbiology and Biotechnology, 63(1), 10-21.

Vryzas, Z., & Kelessidis, V. C. (2017). Nano-based drilling fluids: A review. Energies, 10(4), 540.

Williams, P. A., & Phillips, G. O. (2000). Gum arabic. Handbook of hydrocolloids, 155-168.