DEVELOPMENT OF AN ENVIRONMENT-FRIENDLY OIL-BASED MUD USING CANOLA OIL

BY

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ABSTRACT

The conventional practice of petroleum industry is to formulate oil-based mud system using No. 2 diesel as the base oil. However, their high toxicity level made them unsustainable for using in many environmentally sensitive offshore and onshore locations globally. The recent environmental legislation and control restriction of the usages of oil-based mud become more stringent in many parts of the world in general, and the Kingdom of Saudi Arabia in particular. For instance, a set of regulations called the Corporate Regulations for Offshore Drilling Operations in Saudi Arabia established by the Royal Decree No. M/9 of November 18, 1987, stipulates that all oil-based drilling fluids that are designated as toxic fluids, and cuttings must be hauled back to an approved onshore disposal site, and that cuttings from oil-based mud should be cleaned using the best practical technology and then be discharged as close as possible to the sea floor. In addition, a recent study shows that the cost to haul a barrel of drilling waste is USD 40, and cost of cleaning one pound of oil-soaked cuttings is USD 25. Therefore, implementation of these regulations will make the overall drilling cost skyrocket. As a result synthetic solvent-based mud systems are being used in the oil industry for drilling. However, these mud systems are not only toxic, but also very expensive too. Hence, the development of a sustainable drilling fluid from natural, biodegradable, environmentally friendly oils which satisfies both technical and environmental criteria becomes inevitable. This study is an account of the development of two mud systems: An oil-based mud system and a synthetic solvent-based mud system. Complete mud check conducted on them and a comparison between their properties made. Results of measured parameters such as dial readings, plastic viscosity (PV), yield point (YP), Gel strength, high temperature and high pressure (HTHP) filtration loss, electrical stability, and base oil ASTM specification tests show that the developed non-toxic OBM meets the requirement and compares favorably with the synthetic-based mud currently being used in offshore location in Saudi Arabian waters. This research will have a positive environmental impact on the petroleum industry’s current practices which will eventually make a strong position of Saudi Arabia globally. The development of an oil-based mud from canola oil had been carried out using standard additives. Canola oil was chosen for use because it is environmentally friendly, non-toxic (belonging to a group of oils collectively called GRAS), and meets the standard specifications required of any oil to be used as a base oil for the formulation of an oil based mud. Laboratory results indicate that canola oil can be used as base oil for OBM formulation. Formulated canola oil based OBM also compared favorably with a synthetic OBM system in terms of rheology, stability, quantity of additives used, and level of toxicity.

خلاصة الرسال

اسم الطالب : سانمي أديلي أبيليكيه

عنوان الرسالة : تطوير مائع حفر ذو قاعدة زيتية غير مضرة للبيئة باستخدام زيت الكانولا

التخصص : هندسة البترول

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يعتبر استخدام زيت الديزل رقم 2 في تحضير موائع الحفر ممارسة عادية في مجال صناعة النفط . ولكن درجة السمية العالية لهذه الموائع تمنع استخدامها في مواقع حساسة بيئياً في اليابسة أو الشواطئ عالمياً. وأن التشريعات البيئية الأخيرة والقيود المطلوبة في استخدام موائع الحفر الزيتية أصبح أكثر صرامة في أجزاء كثيرة في العالم على العموم وفي المملكة العربية السعودية على الخصوص . فمثلاً أصدرت المملكة العربية السعودية لوائح الشركات في عمليات الحفر في الشواطئ بالمرسوم الملكي رقم م /9 بتاريخ 18 نوفمبر 1987م وينص على نقل الموائع السامة المستخدمة وتصريفها في مواقع مصدقة عليها مسبقاً في اليابسة وأن المخلفات الصخرية الملوثة بالموائع السامة يجب معالجتها وتنظيفها باتباع أفضل التقنيات قبيل التخلص منها برميها في أعماق البحر . وعلاوة على ذلك ، أظهرت دراسة حديثة أن نقل برميل واحد من مخلفات موائع الحفريكلف 40 دولاراً أمريكياً ، وأن تنظيف رطل واحد من مخلفات الصخرية الملوثة يكلف 25 دولاراً ، مما يعني أن تطبيق هذه اللائحة يجعل التكاليف الكلية لعمليات الحفر عالية جداً . فعليه فإن تطوير موائع حفر مستدامة من الزيوت الطبيعية والقابلة للتحلل البيولوجي والغير مضرة للبيئة وتلبي المتطلبات التقنية والبيئية تعد أمراً حتمياً.

وتقوم هذه الدراسة بتطوير نظامين من موائع الحفر : نظام مائع ذي قاعدة زيتية ونظام مائع ذي قاعدة زيت اصطناعي. وقامت الدرساة باجراء فحص شامل للنظامين واجراء تجارب لمقارنة خواصهما . وأظهرت نتائج التجارب مثل اللزوجة البلاستيكية ، والقوة الهلامية ، ونقطة الخضوع ، والرشح عند الضغط ودرجة الحرارة العاليتين ، والاستقرار الكهربائي أن المائع الزيتي المطور يلبي جميع المتطلبات ويماثل المائع الاصطناعي المستخدم حالياً في شواظي المملكة العربية السعودية.

وسيكون لهذا البحث تأثير بيئي ايجابي على الممارسات الحالية للصناعة النفطية مما يجعل موقف المملكة العربية السعودية قوياً في العالم . ولقد تم تطوير المائع الزيتي باستخدام زيت الك انولا مع الاضافات القياسية. و تم اختيار زيت الكانولا لأنه غير سام ، وغير مضر للبيئة ويلبي المواصفات القياسية المطلوبة لأي زيت يراد استخدامه كقاعدة لموائع الحفر . ولقد أظهرات النتائج المخبرية أن زيت الكانولا يمكن استخدامه كقاعدة لمائع حفر زيتي ويمكن مقارنته مع موا ئع الحفر الاصطناعية في المواصفات والاستقرار وكمية المطافات المستخدمة ومدى السمية.

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CHAPTER 1

Introduction and Knowledge Gap

1.1 Introduction

Drilling fluid or mud is an essential part in the rotary drilling system. Drilling fluid can be defined as a mixture of clays, water, and chemicals used to drill a borehole into the earth and whose basic functions are to lubricate and cool the drill bit, carry drill cuttings to the surface, and to strengthen the sides of the hole. Drilling fluid can also be defined as a fluid compositions used to assist the generation and removal of cuttings from a borehole in the ground (Hossain and Al-Majed, 2012). Most of the problems encountered during the drilling of a well are directly or indirectly related to the mud. The successful completions of a hydrocarbon well and its cost depend on the properties of the drilling fluid up to some extent**.**

Water was the first drilling fluid used by the drillers for rotary drilling operations (Brantly, 1961). The Egyptians, far back in the third millennium used water to remove cuttings from holes drilled using hand-driven rotary bits (Brantly, 1971)**.** Water-based drilling fluids or muds (WBMs) use water or brine as the continuous or external phase with the vital functions of the muds achieved by the addition of various materials (Dosunmu and Ogunrinde, 2010). According to the Amoco Production Company Drilling

Fluid Manual, 1994, three major sub-classifications of water-based drilling fluid include: non-inhibitive fluids (muds that do not suppress clay swelling); inhibitive muds (muds that considerably retard clay swelling and, achieve inhibition in the presence of cations); polymer muds (fluids mainly consisting of macromolecules). Water based muds are the most extensively used, environmentally friendly, easy to build and cheap to maintain. However, major short comings of water-based mud include: difficulty in drilling through shale and clay-rich geological formations, hole enlargement, bit balling, accretion, low rates of penetrations, and inadequate hole cleaning (Montilva et al, 2007).

Oil-based muds (OBMs) were developed to solve some of the unwanted characteristics of water-based muds. Oil base drilling fluid originated with the use of crude oil in well completions, but the date of first usage is unknown. Oil- based muds provide excellent borehole stability, reduce borehole washout, remain stable at high temperatures, effective in drilling highly deviated wells which require low torque and drag on the drill string, and their non-polar nature make them perfect for drilling through troublesome shale, gypsum, and anhydrite (Peresich et al., 1991). Oil-based muds are also non-damaging to the formation due to their negligible or no aqueous filtrate invasion, and also because oil is native to the reservoir (Amanullah, 2005). However, the high toxicity of the diesel based conventional oil-based mud made them unsuitable for use in many environmentally sensitive offshore and onshore locations. Because the disposal of used oil-based muds and contaminated drill cuttings cause severe environmental hazards while still raising serious challenges to the health of drilling crew, environmental legislation and control become more stringent in many parts of the world such as USA, United Kingdom, Denmark, Norway, Australia, Nigeria, most Gulf Countries, to mention but a few (Dosunmu and Ogunrinde, 2010). A typical well may generate between 1000-1500 tonnes of cuttings. Cuttings have about oil retention of 15%, which means that 150-225tonnes of toxic oil from a single well is introduced into the environment. The cuttings generated using diesel oil-based muds need special treatment before discharging them, and often times, they are transported to onshore locations for disposal and this increases the total drilling cost significantly. On the average, to dispose a barrel of oil-based muds/cuttings requires 10 to 40USD (Veil, 1998).

The industry has been replacing diesel oil with low aromatic mineral oils as well as synthetic oils in the formulation of oil-based mud. But because these oils, though less toxic are non-biodegradable, they may be adjudge unsuitable. Hence, the development of fluids that satisfies both technical and environmental criteria from natural, biodegradable, environmentally friendly oils such as canola oil, become inevitable. The first trial of ester based drilling fluid derived from palm oil took place in the Norwegian waters in 1990 (Dosunmu and Ogunrinde, 2010). The trial was technically and economically successful. Even, in Nigeria, over 300 hundred well have been drilled using vegetable oil-based muds (Nigerian National Petroleum Corporation, 1997). Therefore, it is a challenge and responsibility of the Petroleum Industry to green its environment for the sake of other living entities. This study is an attempt toward this step.

1.2 Impacts of Unsustainable Mud Systems on the Environment and Associated Living Entities

The oil and gas industry has made tremendous progress in developing techniques, procedures, and less toxic materials for the protection of human health and the environment. In literature, it is well documented that diesel-based/mineral-based fluids have high toxicity levels (Hossain, 2011; Hossain et al. (2010); Amanullah, 2010; Dosunmu et al. (2010); Duchemin et al. (2008); Rana, 2008; Melton et al. (2004)). Toxicity of drilling fluids to a large extent also depends on the type of additive, which means that even water based drilling fluid systems can also be environmentally unfriendly if the right additives are not used for its formulation. Toxicity levels of additives is influenced directly by the quantity of the drilling fluid used, concentration of the additive in the drilling fluid, and the rate at which the sump drilling fluid disperses when discharged into the environment. Almost every day toxic materials are disposed to the environment. There is no specific worldwide statistical data for this.

However, nowadays the toxicity of drilling fluids and their disposal are tightly controlled to minimize the effects on the subsurface and environment by the government and non-government Environmental Protection Agencies (EPAs). Yet, it is a challenge to tackle and reduce the level of health hazard and environmental disaster coming from drilling fluid. The following section pointed out in brief about the challenges needed to be addressed by the researchers. It is also a challenge to find out the solution of these challenges. Moreover, the existence of current drilling fluids depends on the greening process of the mud. Different government and non-government environmental agencies are also active in this regard which also the future challenges for the drilling fluid industry.

Becket et al. (1976) conducted the acute toxicity test carried out on 34 drilling fluid components using Rainbow Trout. They observed that the organic polymer additives are extremely viscous, and at high viscosities, fish could not circulate the materials past the gills resulting in their deaths due to suffocation. Table 1.1 shows the different types of additives used for the formulation of drilling fluids. Miller et al.'s (1980) experimental observation shows that additives such as asbestos, asphalt, vinyl acetate, and a host of others caused slight reduction in plant yield at low concentrations, increased reduction in plant yield at higher concentrations. Finally, they concluded that diesel oil, and potassium chloride (KCL) causes the most severe damage to plant yield. Younkin et al. (1980) reported that waste drilling fluid and/or sump fluid discharged into the terrestrial environment cause green plants to become variegated (loose chlorophyll) which results stunted in growth, and finally leads to the death of the plants. Murphy et al. (1984) studied the contamination of shallow ground water by oil and gas well drilling fluids in Western Dakota, U.S.A. Candler et al. (1992) reported that drilling fluid's heavy metals such as cadium (Cd), and mercury (Hg) discharged into the environment through sump/drain may be picked up by fishes and other living entities in the sea. Ultimately, these discharged heavy metals are being consumed by human beings through those living entities. The toxic heavy metals then get passed on to humans via consumption of such contaminated seafood resulting in food poisoning and a number of other health problems. Table 1.2 shows the various types of toxic additives and their associated toxic effects.

According to Ameille et al. (1995) and Greaves et al. (1997), the most observed symptoms in workers exposed to not-environment friendly drilling fluid additive such as aerosols are cough and phlegm. They also reported that workers exposed to mist and vapor from mineral oils (major continuous phase of oil based drilling fluids) showed increased prevalence of pulmonary fibrosis. Jonathan et al. (2002) also reported the toxic effects of drilling fluid additives on the physiology, fertility, and growth of fish egg and fry. They concluded that at high concentrations of additives, fish fry, and even mature fish will die. The authors of this article also gathered that drillers became chronically asthmatic due to prolonged exposure to toxic, and not-user friendly drilling fluids particularly the oil-based (diesel and mineral oil based) drilling fluids. The medical report shows that they were not asthmatic before joining to the company as a driller (from unpublished and undisclosed documents).

TABLE 1.1: DIFFERENT TYPES OF ADDITIVES FOR MUD FORMULATION

Weighting materials	Thickening materials (viscosifiers)	Filtration control materials	Thinners (conditioning material)	Loss circulatio n materials
Galena	Bentonite	Starch	Tannins	Cellophan e

Hematite	Attapulgite	Modified starch	Quebracho	Cotton seed hulls
Magnetite	Sepiolite	Guar gum	Modified tannins	Vermiculite
Iron Oxide	Organophilic clays	Xanthan gum	Polyphosphates	Mica
Illmenite	Palygorskite	Sodium Carboxymethlycellulo-se	Organic phosphates	Surfactants
Barite	Asbestos	Hydroxyethylcellulos-e	Phosphonates	Diatomaceous earth
Siderite		Acrylic polymer	Lignite	Olive pits
Celestite		Alkylene Oxide polymer	Lignosulfonates	Gilsonite
Dolomite				Bagasse
Calcite				Perlite

TABLE 1.2: TOXIC ADDITIVES AND HEALTH/ENVIRONMENTAL EFFECTS

Components of SOLTEX	Conc. (mg/kg)	Effects on human body/environment
Antimony (weighting)	6.0	Cough, dizziness, headache, nausea, vomiting, stomach cramps, insomnia, and anorexia.
Arsenic (weighting)	0.4	Includes all inorganic arsenic in form of copper acetoarsenite and all compounds containing arsenic except arsine. Causes: dermatitis, gastrointestinal disturbances, hyperpigmentation of skin, peripheral neuropathy, and respiratory irritation.
Barium (weighting)	16.0	As salts of nitric acid. Causes: eye and skin irritation, muscle spasm, gastroenteritis, extrasystoles, hypokalemia.
Cadium (weighting)	0.6	Highly carcinogenic, also causes eyes and skin irritations.
Cobalt (weighting)	2.0	As cobalt metal dust or fumes. Causes: wheezing, dyspnea, asthma, nodular fibrosis.
Copper (weighting)	1.3	As dust, mist, fume CuO. Causes: muscle ache, fever, lassitude/weakness, skin and hair discoloration, respiratory problem.
Fluoride (weighting)	200.0	Causes: cyanosis, lassitude/weakness, dizziness, pulmonary edema, anoxia, and pneumonitis.
Lead (weighting)	3.0	Causes: insomnia, facial pallor, constipation, anemia, tremor, hypertension, renal problems.
Mercury (weighting)	0.2	Causes: bronchitis, chest pain, insomnia, anorexia, dyspnea, headache, and lassitude.
Nickel (weighting)	11.0	Highly carcinogenic, asthma, pneumonitis, and dermatitis.
Vanadium (weighting)	16.0	Causes: skin and throat irritation, bronchitis, wheezing and dyspnea.
Zinc	2.1	As dibasic zinc stearate. Causes: irritation to eyes and skin,

(weighting)		cough, and bronchitis.
Calcite (weighting)	-	The synthetic form is toxic. Causes: skin problems, cough, and breathing difficulty.
Iron Oxide (weighting)	-	Causes: pneumocomosis, and fibrotic pneumocomosis (siderosis).
Starch (filtration cont.)	-	The synthetic form is toxic. Causes: chest pain, dermatitis, and rhinorrhea (discharge of nasal mucus).
Asbestos	-	As Actinolite, Amorite, and Tremolite. Causes: dyspnea, intestinal fibrosis, finger clubbing, and cancer,
Acrylic Polymers (viscosifier)	-	Lung, liver, and kidney injuries.

1.3 Knowledge Gap

Saving our planet in a sustainable fashion is one of the major challenges for the researchers, industries, government, and non-governmental agencies. As mentioned earlier, Petroleum Industry is one of the hazardous and unsustainable industries. Therefore, it is a very important and timely initiative to find out a gateway for greening the Petroleum Industry. This study is aimed toward this destiny.

CHAPTER 2

History of Canola Oil

2.1 Canola Oil

The term "canola" is used as the name for rapeseed with substantially reduced quantities of erucic acid and glucosinolates. "Canola" is used mainly in American continent, and Australia. Rapeseed is used commonly is Europe and other countries, (Bailey's Industrial Oil and Fat Products). Economically, it is cheaper compared with other edible oils such as olive, sunflower and castor costing which are available in literature. The cost of canola oil is about USD0.11 per pound.

2.2 Origin of Canola Oil

Canola refers to a cultivar of either Rapeseed (*Brassica napus L.*) or field mustard (*Brassica campestris L.* or *Brassica Rapa var.*) (Mag et al., 1990). Oilseed rape species is the origin of canola oil. It is produced from the Brassica genus in the Cruciferae family. Rapeseeds were first cultivated in India about 4000 years ago. Rapeseed (*Brassica napus*), is known as rape, oilseed rape, rapa, rappi, rapaseed. It is a bright yellow flowering member of the family Brassicaceae (mustard or cabbage family). The name derives from the Latin for turnip, *rāpa* or *rāpum*. According to the Wikipedia, rapeseed was first recorded in English at the end of the 14th century. However, In Europe, large-scale cultivation was first reported in the thirteenth century. The Brassica species probably evolved from the same common ancestor as wild mustard (Sinapsis), radish (Raphanus), and arrugula (Eruca), (R. Przybyliski et al, 2005).

Originally, Canola was produced naturally from rapeseed in Canada in the early 1970s but it has a very different nutritional profile in addition to much less erucic acid. The name "canola" was derived from "**Can**adian **o**il, **l**ow **a**cid" in 1978 (Ackman et al., 1990)). Genetically modified rapeseed is sometimes referred to as Rapeseed 00. A product known as LEAR (for *low erucic acid rapeseed*) was derived from cross-breeding of multiple lines of *Brassica juncea* which may also be referred to as canola oil. Canola seeds are used to produce edible oil. This oil is considered safe for human consumption. The oil is also suitable for use as biodiesel.

2.3 Development of Canola

Early rapeseed cultivars had high levels of erucic acid in the oil and glucosinolates in the meal. The presence of erucic and glucosinolates in high levels in canola caused fatty deposition in the heart, skeletal muscles, and adrenals of experimental rodents. Cases of growth impairment were also recorded. Due to this, initiated plant breeding programs resulted in the identification in 1959 of Liho, a rapeseed line having low levels of erucic acid. A program of backcrossing and selection was conducted to transfer the low erucic acid trait into agronomically adapted cultivars. This led to the first low erucic acid cultivar of B. napus, Oro, in 1968. In 1950, Dr. Krzymanski, identified a Polish line with low-glucosinolate trait. Dr. Baldur Stefansson at the University of Manitoba introduced the Polish line trait into the low erucic cultivars to produce the first low-glucosinolate, low-erucic acid cultivar of B. rapa in 1977. The name canola was registered by the Western Canadian Oilseed Crushers in 1978 and subsequently transferred to the Canola Council of Canada in 1980, (R. Przybyliski et al, 2005). In 1986, the definition of canola was amended to B. napus and B. rapa lines with less than 2% erucic acid in the oil and less than 30 μmol/g glucosinolates in the air-dried, oil-free meal. The oil was added to the Generally Recognized as Safe (GRAS) list of food products in the United States.

2.4 Composition of Canola Oil

According to Ying et al, (1989) and T. Mag et al, (1990), TAGs constitute 94.4% to 99.1% of the total lipid in canola oil. The typical composition of canola is presented in Table 2.1

TABLE 2.1: COMPOSITION OF CANOLA

Component	Canola
Triacylglycerols (%)	94.4-99.1
Crude Oil (%)	up to 2.5
Water-degummed (%)	up to 0.6
Acid-degummed (%)	Up to 0.1
Free Fatty Acids (%)	0.4-1.2
Unsaponifiables (%)	0.5-1.2
Tocopherols (mg/Kg)	700-1200

Chlorophylls (mg/Kg)	5-50
Sulfur (mg/Kg)	3-25
Iron (mg/Kg)	Less than 2

CHAPTER 3

Research Challenges and Objectives

3.1 States-of-the-Art Literature Review

Currently, research efforts towards the development of environmentally friendly drilling fluid that will rival the conventional diesel-based oil mud in terms of performance, sustainability, and cost are from two main stand points:(1) using environmentally friendly oils to formulate oil-based muds; (2) development of water based drilling fluids which simulates the performance of the oil-based drilling fluid, and which are referred to as high performance water-based drilling fluids (HPWBF). In this literature review, a number of previous research works based on the two approaches stated are presented.

Hille et al. (1985) developed a HPHT water base fluid system composed of vinlysulfonate and vinlyamide copolymers for improved and sustained good rheological properties even when the electrolytic concentration of the mud increases. The problem with this system is that it rapidly disperses in water and poses minimal degree of environmental effects. E Van Dort et al. (1996) formulated an improved water based drilling fluid based on soluble silicates capable of drilling through heaving shale which is environment friendly. However, this is not recommended because silicate has the potential to damage the formation. Brady et al. (1998) came up with a polyglycol enriched water based drilling fluid that will provide high level of shale inhibition in fresh water and low salinity water based drilling fluid. However, this formulation has defects on it which are to perform optimally, and electrolytes must be presented. Nicora et al. (1998) developed a new generation dispersant for environmentally friendly drilling fluids based on zirconium citrate. The functions of zirconium citrate are to improve the rheological stability of conventional water based fluids at high temperature. However, this formulation has a limitation that the concentration of zirconium citrate may be depleted in the drilling fluid due to solids absorption. Hayet et al. (1999**)** developed an additive from the modification of natural polymers hydrophobically for the formulation of non-damaging drilling fluids which are of great importance when drilling through un-cased sections of horizontal wells. Increased hydrophobicity improves viscosity, yield point, and also prevented the sedimentation of suspended solids. However, there is the risk of reduced production induced by reservoir damage when this formulation is used for drilling and well completion. Skalle et al. (1999) suggested the use of microsized spherical monosized polymer beads as a blend to WBDF to improve lubrication. Thaemlitz et al. (1999) formulated a new environmentally friendly and chromium-free drilling fluid for HPHT drilling based on only two polymeric components which make it simple, easy to handle, environmentally friendly, and hence suitable for use in remote areas as compared with traditional HT systems which normally composed of a large number of additives. Nicora et al. (2001) formulated a new low solids oil-base drilling fluid system for HPHT application using cesium formate as the internal phase, and ilmenite as the weighting agent so as to address the problem of stability and rheology reduction due to high solid content of drilling fluids especially, when drilling inclined holes. The limitation of this formulation however, is its environmental unfriendliness. Sharm et al. (2001) developed an environmentally friendly drilling fluid which can effectively replace oil based drilling fluid by using eco-friendly polymers derived from tamarind gum and tragacanth gum. Tamarind gum is derived from tamarin seed while tragacanth gum is from astragalus gummifier. This formulation is also cheaper and has less damaging effect on the formation. Hector et al. (2002) developed a formulation with a void toxicity based on a potassium-silicate system. The advantage of this formulation apart from being environmentally friendly is that cuttings from the use of this drilling fluid can be used as fertilizers. Durrieu et al. (2003) formulated an additive called "booster fluid" which is a mixture of organic nitrogen, phosphorus compounds, and fatty acids that can be added to synthetic oil base fluid system in order to enhance the rate of biodegradation. They observed that synthetic oil based drilling fluid treated with "booster fluid" still demonstrated some level of environmental impact to marine life and hence not totally environmentally friendly.

Warren et al. (2003) developed a formulation based on a water-soluble polymer amphoteric cellulose ether, (ACE) which is cheaper, low in solids content, environmentally friendly but with some potential to damage the formation. Jayne et al. (2004) developed a potassium silicate based drilling fluid system which is cheaper, re-useable, can eliminate background gas breakthrough, and eco-friendly as an alternative to sodium silicate based drilling fluid system which can be problematic due to the high sodium loading associated with cuttings generated when it is used to drill. Davidson et al. (2004) developed a drilling fluid system that is environmentally friendly and which will also remove free hydrogen sulphide. It may be encountered while drilling based on ferrous iron complex with a carbohydrate derivative (ferrous gluconate). Ramirez et al.

(2005) formulated a biodegradable drilling fluid that will maintain hole stability. This mud also enables to drilling through sensitive shale possible based on aluminum hydroxide complex (AHC). This formulation contains some blown asphalt and hence posses some environmental problem. Amanullah et al. (2006) developed an environmentally friendly thermal degradation inhibitive additive for water-based bentonite mud using raw material from natural sources. This additive which is also able to prevent thickening and flocculation of bentonite, however, becomes ineffective at elevated temperature. Malloy et al. (2007) suggested drilling with compressed air as an alternative to other drilling fluid system. Because compressed air as stressed is very effective in drilling through very hard and dry rock which is very cheap, and environmentally friendly. However, drilling with compressed air has some short comings. It can only be used to drill through hard, non hydrocarbon, and non water producing formation. This compressed air fluid is associated with high risk of fire accidents that could occur when air mixes with hydrocarbon during drilling operation. Dosunmu et al. (2010) developed an oil based drilling fluid based on vegetable oil derived from palm oil and ground nut oil. The fluid did not only satisfy environmental standards, it also improved crop growth when discharged into farm lands. Generally, all these formulation do not have zero environmental impact.

Amanullah et al. (2010) proposed the use of waste vegetable oil as an alternative to the use of mineral and diesel oil as the continuous phase in the formulation of high performance drilling fluids for HPHT applications. This formulation is not only eco-friendly, it is also cheap, and will be vastly available because large volumes of waste vegetable oil are generated annually worldwide. Amin et al. (2010) developed an environmentally friendly drilling fluid system based on esters sourced from the Malaysian palm oil bio-diesel production plant which include methyl ester and ethylexyl ester. The short coming of this formulation is that the palm oil bio-diesel market determines the availability of the identified esters (the esters are by-product from the bio-diesel plant which means that increase in demand for bio-diesel, means increase in availability of esters, and vice-versa). The path to the future direction of research is paved by a question posed by Hall et al. (2005), and this question is “Designing the perfect environmentally friendly drilling fluid and additives: can it be done?”

3.2 Problem Statement

Though, oil-based drilling fluids perform better technically relative to other types of drilling fluids, their high toxicity made them unsuitable for use in many environmentally sensitive offshore and onshore locations. Because the disposal of used oil-based muds and contaminated drill cuttings cause severe environmental hazards while posing serious challenges to the health of drilling crew, environmental legislation and control restricting the use of diesel oil-based mud become more stringent in many parts of the world such as USA, United Kingdom, Denmark, Norway, Australia, Nigeria, most Gulf Countries, to mention but a few. A typical well may generate between 1000-1500 tonnes of cuttings. Cuttings have about oil retention of 15%, which means that 150-225 tonnes of toxic oil from a single well are disposed into the environment. The cuttings generated using diesel oil-based mud need special treatment before discharging them, and often times, they are transported to onshore locations for disposal and this increases the total drilling cost significantly. On the average, to dispose a barrel of oil-based mud/cuttings requires 10 to

40USD (Veil, 1998). Hence, the development of fluids that satisfies both technical and environmental criteria from natural, biodegradable, environmentally friendly oils such as canola oil, as potential alternative to diesel oil-based mud is inevitable. It has been recognized that canola oil, a non-toxic vegetable oil can be used to formulate the environment-friendly OBM.

3.3 Objectives

1. To develop an environment-friendly OBM using canola oil that can serve as a potential alternative to the conventional diesel oil-based mud.

2. To use commercially available chemical additives that would be carefully selected, and be petro-free components for the development the environment friendly OBM system.

CHAPTER 4

Research Methodology

4.1 Equipment used for Experiment

This study is an applied research where series of experiment have been conducted. The following equipments were used while conducting the experiment.

Mud Balance – it is used to determine the mud density after mixing all the drilling fluid composition. Normally, the required mud weight is calculated before mixing as determined by so many factors such as bottom-hole pressure, the section of the hole you are drilling, etc. Figure 4.1 shows a conventional mud balance equipment.

Figure 4.1: Mud Balance

Rotational Viscometers – Two different viscometers were used. These are; the OFITE 900 digital viscometer, and the FANN viscometer, (Figures 4.2 and 4.3). OFITE 900 Digital Viscometer is used for carrying out a complete rheology check on the mud sample. Mud sample is placed in a thermo-cup set at 49^0C. Equipment is calibrated without the bob in the mud, and after this, mud check starts. Figure 4.2 shows an OFITE 900 Digital viscometer.

Figure 4.2: OFITE 900 Digital Viscometer for measuring viscosity

Fann Model 34 Viscometer: The Fann Model 34 Viscometer also used for carrying out a complete rheology check on the mud sample. Mud sample is placed in a thermo-cup set at 49^0C. Equipment is calibrated without the bob in the mud, and after this, mud check starts. Figure 4.3 shows a Fann Model 34 Viscometer.

Figure 4.3: Fann Model 34 Viscometer

OFITE electrical stability tester: OFITE Electrical Stability Tester is used for measuring the stability of mud sample. The equipment is first calibrated. Then, mud sample is heated to 49^0C. The conductive cable of the equipment is then dipped into the mud sample. The higher the value it reads in Volts, the more stable the mud. Figure 4.4 shows an OFITE Electrical Stability Tester.

Figure 4.4: OFITE Electrical Stability Tester

Weigh balance: This equipment is used for measuring the amount of additives to be added into the mud. It must be ensured that the surface of the balance is wiped clean otherwise, measured weights will be inaccurate. Figure 4.5 shows a digital weighing balance.

Figure 4.5: Weighing Balance

HTHP filtration loss tester: This is used for measuring the HTHP Spurt loss in 10 second, and HTHP fluid loss in 30 minutes. If the bottom-hole temperature is know, test is conducted at that temperature. If not, test is run at 250^0F.

Figure 4.6: HTHP Single Cell Filtration.

Multicell API filtration loss tester: This is used basically for testing water based mud filtration loss. Testing pressure is at 100 PSI and at room temperature. Figure 4.7 shows a Multicell API filtration loss tester.

Figure 4.7: Multicell API filtration loss tester

Hot-rolling oven: This is used for heating mud sample at a particular temperature in a process called hot-rolling which is to simulated down-hole condition. Sample is placed in a hot-rolling cell and then kept in the oven for 16hrs, a process called ageing. Figure 4.8 shows a hot-rolling oven.

Figure 4.8: Hot-rolling oven.

Hamilton Beach Mixer: This is used for mixing the mud. It has three speeds: high, medium and low. The mud should be sheared long enough for each additive to be dispersed in the fluid phase of the mud system. Figure 4.9 shows a Hamilton Beach Mixer.

Figure 4.9: Hamilton Beach Mixer.

High Speed Mixer: This is for mixing the mud by applying a high rate of shear to the mixture placed in a mixing cup. The temperature of the mixing cup should not be too high so that water does not evaporate from the mixture. Figure 4.10 shows a High Speed Mixer.

Figure 4.10: High Speed Mixer.

4.2 Base Oil Selection and Specification

Before the formulation of an oil-based mud, the oil to be used must be analyzed in order to determine its physical properties which must fall within the range of particular standard values for maximum safety and reliability of mud properties. The properties of canola oil meet these standards, hence its suitability for use as the base oil. Table 4.1 shows the results of the specification tests carried out on canola oil with those of the base oil used for the formulation of the SBM system called safra oil or Saudi sol.

TABLE 4.1: SPECIFICATION OF BASE OIL

PROPERTIES	STANDARD	DIESEL	CANOLA OIL	SAFRA OIL
API Gravity	25-37^0	26-30^0	24.4^0	49.9^0
Flash Point	180^{0}F	126-204^{0}F	442^{0}F	185^{0}F
Fire Point	200^{0}F	410^{0}F	514^{0}F	*
Aniline Point	140^{0}F	201.2^{0}F	250^{0}F	167^{0}F

Note: “*” not available in literature

4.3 Mechanism behind Oil/Water Ratio

The developed canola OBM system is an "oil emulsion mud". It is a mud system in which some water is uniformly dispersed in a continuous canola oil phase. Canola oil is the external or continuous phase and the water is the internal or the discontinuous phase. The more the water present in an emulsion, the greater the chances of the water droplets coming together and coalescing and the greater the chances of the emulsion being unstable. Therefore, the selection of Oil/Water ratio must be carefully selected during the preparation of mud formulation.

4.4 Oil/Water Ratio

The Oil/Water ratio relates both the oil and water fractions of the mud as a percent of the liquid fraction. In newly constructed mud systems, this ratio is extremely important in that the initial viscosities, emulsion stability and HTHP fluid loss values depend upon it. The addition of solids results in the reduction of the percent by volume of the liquid fraction (i.e., some of the oil and water are displaced by solids). If the original percentage by volume of water is maintained throughout the formulation, the solids increase. It would be possible to experience higher rheological values than normal due solely to the increasing amount of solids. This may be due to the solids displacing only the oil rather than water and oil. This decreases the Oil/Water ratio giving higher percentage of emulsified water content in the liquid phase. The use of the Oil/Water ratio value gives the engineer a method for controlling the viscosity of the liquid phase by keeping it relatively constant. In newly formulated mud, it is advisable to keep the O/W ratio high. This is important because as the disperse water phase increases, thus decreasing the O/W ratio, the mean distance between the water droplets decreases bringing them closer together. This apparently allows for easier circuit completion through coalescence, hence a lowered electrical/emulsion stability.

The Oil/Water ratio calculation of previously formulated mud requires only direct retort readings and is calculated as follows (Magcober Drilling Fluid Engineering Manual, 1995):

$$\%\ \text{Oil in Liquid Phase} = \frac{\%\ \text{by Volume of Oil}}{\%\ \text{by Vol. Oil} + \%\ \text{by Vol. Water}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\%\text{Water in Liquid Phase} = \frac{\%\ \text{by Volume of Water}}{\%\ \text{by Vol. Oil} + \%\ \text{by Vol. Water}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

4.5 Selection of Additives

The development of an oil emulsion mud requires special products/additives. These additives ensure that the emulsion is extremely stable and can withstand conditions of HT/HP and contaminants. Additives to be used must be compatible with the selected base oil, and they must be dispersible in the external/continuous oil phase. The most important of these additives (MI-SWACO Drilling Fluid Manual, 2010) include:

Emulsifying Systems- Calcium soaps are the primary emulsifiers in OBMs. They are made in the mud by reaction of lime and long-chain fatty acids. Soap emulsions are strong emulsifying agents, but a long reaction time is needed for emulsion to be properly formed. To make up for this shortcoming of primary emulsifying agents, secondary emulsifiers are used. Secondary emulsifiers consist in powerful oil-wetting chemicals which generally do not form emulsions but wet solids before the emulsion is formed. They are also used to prevent any water intrusion.

Lime- Lime is extremely important in OBMs. It neutralizes fatty acids in the fluid, stabilizes the emulsion, affects viscosity, gel and controls alkalinity. In the field, it is also used to neutralize acid gases (H_2S and CO_2). However, great care must be taken when adding lime because lime is very sensitive at elevated temperatures leading to a total change in the properties of the OBM. Hence, the optimum amount of it to be used must be determined carefully.

Fluid Loss Reduction Additives- These are usually organophilic lignites (amine-treated lignites, Gilsonites, Asphalt derivatives or special polymers (polyacrylates). The impact of filtration control additives however, depend on their nature. While lignites do not affect mud viscosity even high concentrations are used, asphalt derivatives even at moderate concentrations can cause excessive viscosity and/or gelation.

Wetting Agents- These are supplemental additives to quickly and effectively oil-wet solids that became water-wet. Emulsifying agents perform their functions in most of the times and hence may not be included in the OBM formulation.

Viscosifiers- These are additives that build mud viscosity. Bentonite, hectorite or attapulgite that has been amine treated to make them dispersible in oil are the commonly used organophilic gellants. For special applications especially SBM formulations, a large number of these viscosifiers are available from different vendors.

Weighting Agents- Used to increase the mud density. Most commonly used weighting agents are Calcite, Barite, and Hematite. The usability of materials such as manganese oxide and volcanic ash is currently being investigated. However, the choice of a suitable weighting material is a function of pressure requirements as well as the section of the hole being drilled.

Calcium chloride- Calcium Chloride is an electrolyte used in OBM systems to control the activity (Aw) of the mud. Calcium chloride is generally available as tech grade which is 77- 80% in purity or as pure grade which is 95 - 98% in purity. For most field applications, the 77 - 80% tech grade is used and the concentration added is determined by the Aw of the formation water of the zone to be drilled.

CHAPTER 5

Formulation and Testing of Canola Oil-Based Mud System

5.1 Mud Formulations

When developing a new mud system in the laboratory, the units of measure most commonly used are grams for weight and cubic centimeters for volume. 1barrel of mud in the field is equivalent to 350 millimeters (also called 1 lab. Barrel), in the laboratory. Thus, adding 1 gram of material to 350 mL of fluid in the laboratory is equivalent to adding 1 lbm of material to 1 bbl of mud in the field (Bourgoyne jr. et al, 1986). In the field, volumes of all materials must add up to 1 bbl, while in the lab, volumes of all materials must add up to 350 ml. Note worthy is the fact that the volume of the fluid phase of mud is the total volume of all additives less 1 lab barrel. The amount of the internal phase or discontinuous phase in invert emulsion/ indirect emulsion mud system affects its stability. As a matter of fact, the higher the amount of water in oil, the lower the stability of the invert mud system. Hence, the amount of water should be kept as low as possible in newly developed formulations. Consequent upon this, in all formulations, an oil/ water ratio of 90:10 was used. If stability is achieved, coupled with good rheological results, the oil/water ratio may be varied.

The concentrations of the different additives in the initial formulations were determined using the concentrations or what are called the "recipes" of Amanullah, (2005) and Yassin, et al., (1991) as a guide (Table 5.1). Barite was kept out of all formulations since it is needed to increase mud weight in response to down hole pressure changes and also because in new formulations, the amount of suspended materials should be kept as low as possible. All formulations were low-salinity muds (i.e. 17 ppb of 78% pure $CaCl_2$ added to all formulations).

TABLE 5.1: AMANULLAH AND YASSIN'S FORMULATIONS

Amanullah (Refined vegetable oil mud) O/W Ratio:	Yassin et al., (Methylester CPO mud) O/W Ratio: 85/15
Refined vegetable oil	Methylester of crude palm oil (me.CPO)
Primary emulsifier	Primary emulsifier
Secondary emulsifier	Secondary emulsifier
Filtration control additive	Filtration control additive
Nacl	$Cacl_2$
Water	water
Gelant	Gelant
*	Lime

*	Wetting agent
*	Barite

Note: “*” not available in literature

The concentration of lime was varied in the initial formulations so as to determine the optimum concentration of lime needed for the formulation of the new OBM system. This is a very important strategy to kick-start the development of the new OBM system because lime is important in maintaining a stable mud system in extreme environments to which the fluid may be exposed. Its addition, although necessary, tends to have the effect of promoting water wetting. Lime over treatment which will result in excessive alkalinity, and consequently increased values of rheological values is not desirable. Hence, it is of paramount importance that the amount of lime in a new formulation be determined. Lime is consumed with circulating time and temperature. This consumption is very rapid in a new and unstable mud system, but tends to slow down as the mud attains stability. Hence, in the field, alkalinity titration should be run daily to maintain lime concentration and mud alkalinity in the appropriate range.

5.2 Order of Adding Additives

The most important step in the formation of any emulsion is to ensure that ample energy in the form of shear is applied to the fluid. This is to make sure emulsifiers and other additives are completely dispersed into the external or oil-continuous phase. The definite order of mixing outlined below should be strictly followed:

1. Base oil
2. Primary emulsifier
3. Lime
4. Filtration control additive
5. Water
6. Viscosifier
7. Secondary emulsifier
8. Brine/Salt
9. Weighting material.

The addition of components in their proper sequence when mixing a fresh OBM system will optimize the performance of each product. A time interval of 10-30 minutes should separate the addition of additives and the mixing cup must be watched closely so that it does not become too hot. The introduction of water into the base oil marks the beginning of emulsion formation. This step, require energy in form of shear. The amount of shear energy required is proportional to the amount of water being added and the rate at which it is being added. Water should be added slowly while shearing it into the mud system. During mixing, the mud engineer must ascertain that air is not emulsified into the mud system because air can cause emulsion instability and a graining appearance. After emulsifying all the water into the mud system, the system should have a smooth, glossy, shiny appearance.

After the emulsion has been formed, a complete check of the mud should be made before adding barite.

5.3 Measurement of Mud Properties

A complete and comprehensive check on the newly formulated mud system is completed during this research. The following tests were performed:

Density determination- the density of the mud was measured using a mud balance as shown in in Figure 4.1 where it was in accordance with M.I. SWACO Drilling Fluid Manual guidelines. The selection of mud weight is based on the wellbore pressure required to control the formation pressures encountered in the open hole without causing loss circulation.

Viscometer readings- Also performed after M.I. SWACO guidelines and at rotational speeds of 600, 300, 200, 100, 6, and 3-rpm respectively. Both the OFITE (Figure 4.2) and Fann (Figure 4.3) were used. Gel strengths were taken at 10 seconds and 10 minutes respectively while the plastic viscosities values were determined from 600 and 300 rpm dial readings. Plastic viscosity (PV) relates to the portion of flow resistance caused by mechanical friction. For a good mud system, PV value before hot rolling (BHR) and after hot rolling (AHR) should not be excessive. An excessive PV will result in an excessive equivalent circulating density (ECD). This ultimately results in an increased risk of lost loss circulation. Low PV will result in poor suspension of additive and weighting material in the mud system. Yield point (YP) and Gel strengths (Gels) are also properties that should not be too high for good mud system. If these properties are too high, the consequences will be the same as for high PV. If they are too low, the results with poor cutting transport and an increased potential for barite settling or sag.

Emulsion stability (ES)- Performed as described my M.I. SWACO drilling fluid manual using OFITE ESM-30A. This measurement gives an indication of how well water phase is held in the overall emulsion with base oil. A high reading in Volts is an indication of a stable mud with strong water-in-oil emulsion or invert emulsion. Mud systems with poor ES tend to separate and stratify, especially during static conditions and at ambience or room temperature.

High-Temperature High-Pressure (HTHP) Filtration- Carried after M.I. SWACO guidelines, at 250^0F (if the bottom hole temperature is unknown) and 500 psig with an OFITE 175 ml HTHPT filter press (Figure 4.6). Filtrate loss is important because excessive filtrate loss can contribute to formation damage and differentially stuck pipe. For a good mud HTHP loss should be between 4-10 ml over 30 minutes.

CHAPTER 6

Results and Discussion

6.1 Preparation of Experimental Results

In developing the canola oil-based mud system, a total of 15 (fifteen) formulations were mixed. Thirty (30) BHR and AHR complete rheology check conducted, five (5) HTHP filtration tests performed, five (5) electrical stability of mud measured, making a total of 40 (forty) tests executed. For clarity and ease of understanding of experimental results, experimental results have been divided into four (4) stages. The first stage is to determine the optimum amount or concentration of lime required for the formulation of a stable canola oil-based mud system. The second stage is tagged the optimization stage in the sense that the formulation that is stable at a particular lime concentration after aging both at room temperature and simulated down hole conditions was repeatedly formulated and checked . All aging were carried out only at HT in order to independently verify the effect of HT on the new mud system. The third stage involved the application of HTHP to aging to verify the effect of the combined action of HTHP the mud system. Finally, stage four shows results of additives modification to correct for the effects due to HTHP on mud system and hence to arrive at the final formulation.

6.2 Results and Discussions

The developed canola oil-based mud system is formulated based on the recipe or components depicted by Table 6.1. All other formulations were based on the modification of Table 6.1.

TABLE 6.1: CANOLA-OBM MUD SYSTEM COMPOSITION

Material	Amount
Base-oil(Canola-oil)	90%
Primary emulsifier	12ml
Lime	Varies
Filtration control additive	10ppb
Water	10%
Gelant(Viscosifier)	6ppb
Secondary Emulsifier	8ml
$Cacl_2$ (78%)	17ppb
Barite	#
Density	8ppg

The first five formulations to determine the amount or concentration of lime needed for the formulation of a stable mud system contained lime in 0 ppb, 3 ppb, 5 ppb, 7 ppb and 10 ppb keeping the amount of all other additive and components the same. On each of the formulations, a complete rheology measurement was conducted. Table 6.2 shows the detailed results of measured properties. The rheological properties are based on at different lime concentration and at a temperature of 120^0F.

TABLE 6.2: MUD RHEOLOGY AT DIFFERENT LIME CONCENTRATION BHR

Lime conc. (ppb)	600 rpm	300 rpm	200 rpm	100 rpm	6 rpm	3 rpm	10 sec lb/ft^2	10 min lb/ft^2	PV cp	YP lb/ft^2
0	86.6	49	32.9	22	1.9	1.7	3.4	4.2	79	19.9
3	100.8	50.1	35.3	18.7	2.6	2.0	1.7	2.7	44.6	0
5	139	62.7	42.9	24.7	4.1	3.3	3.5	4.3	53.6	7.4
7	139.4	57.3	42.8	23.4	3.0	2.4	1.7	3.6	47.5	10.6
10	113.6	50.4	34.7	19.8	3.9	3.5	2.9	4.1	40.7	10.9

Mud system containing 0 ppb lime has the highest PV and YP, mud system containing 10 ppb lime has the lowest PV and the 3 ppb lime mud the lowest YP. Mud system containing 5 ppb lime has the highest value of 10 minutes and 10 seconds gel strengths and the 3 ppb lime mud the lowest 10 minutes and 10 seconds gel strengths respectively. All mud systems show good dial readings with values increasing progressively from 3 rpm dial speed to 600 rpm.

6.2.1 Rheology of Mud System in Response to Lime Concentration

Figure 6.1 shows the combined plot of dial speeds versus dial readings for all formulations. From Figure 6.1, it can be seen that for each of the mud system, dial readings increased progressively from 3 rpm to 600 rpm which is an indication of good rheological behavior. PV is the difference between the 600 rpm dial reading and the 300 rpm dial reading, YP is the difference between the 300 rpm dial reading and PV, and the apparent viscosity, AP is 600 rpm divided by 2. The 6 rpm is also a performance indicator especially in the field. For field applications, the value of the 6 rpm should be approximately 1.2 X the wellbore diameter where it is narrowest.

Figure 6.2 shows PV versus lime concentrations on the formulation of mud system. Considering Figure 6.2, PV is highest in the mud system containing no lime because of the high original PV of canola which is around 25 cp without any additive. In other concentrations of lime such as 3 ppb, 5 ppb, 7 ppb, and 10 ppb on the formulated mud systems, two processes are in action – i) Flocculation tends to improve PV being an optimal liming, and ii) aggregation tends to reduce PV being either a case of under liming, or over-liming. Adding 3 ppb lime is under liming, resulting in aggregation, and hence reduced PV. On the other hand, same trend appears for 7 ppb, and 10 ppb of lime in the mud system. PV is optimal at 5 ppb lime mud because the mud is optimally flocculated.

Figure 6.3 shows gel strength verses lime concentration for 10 seconds and 10 minutes at 49^0C for all the formulations. It reflects the direct effect of PV. PV ensures that materials in mud system are kept suspended when mud is static. The values of the Gels (10 sec and 10 min) are highest in the optimally flocculated mud (5 ppb) due to good suspension of added materials. The value of gels declined in the under limed 3 ppb mud, and over limed 7 ppb and 10 ppb muds due to poor suspension of added materials. However, these values are not indicators of stability.

Figure 6.4 shows YP versus lime concentrations. The yield point is a measure of how cohesive particles of added materials are in the mud system. The YP value BHR is not as important as the AHR value. A mud may have a good YP BHR and yet be unstable. For a good mud, the AHR value of YP should increase which will be an indication of the fact that the mud is removing debris from the hole.

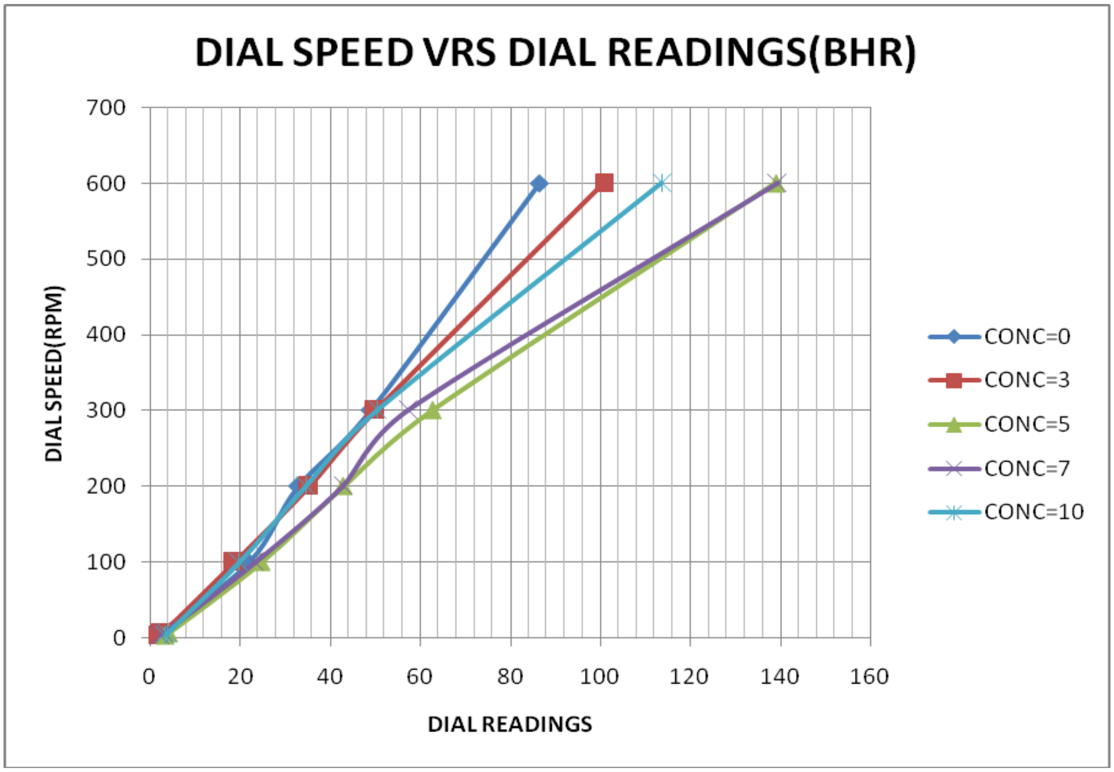

Figure 6.1: Dial Speed versus Dial Readings BHR @ 120^{0}F.

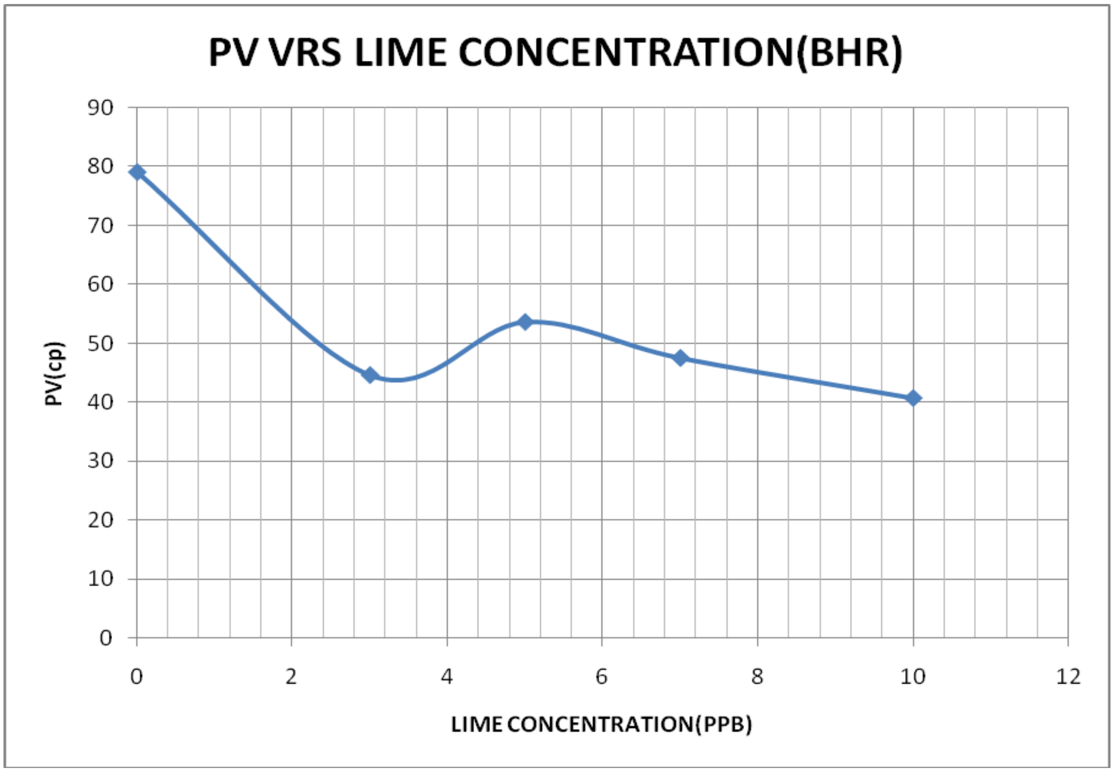

Figure 6.2: PV versus Lime Concentrations BHR @ 120^0F.

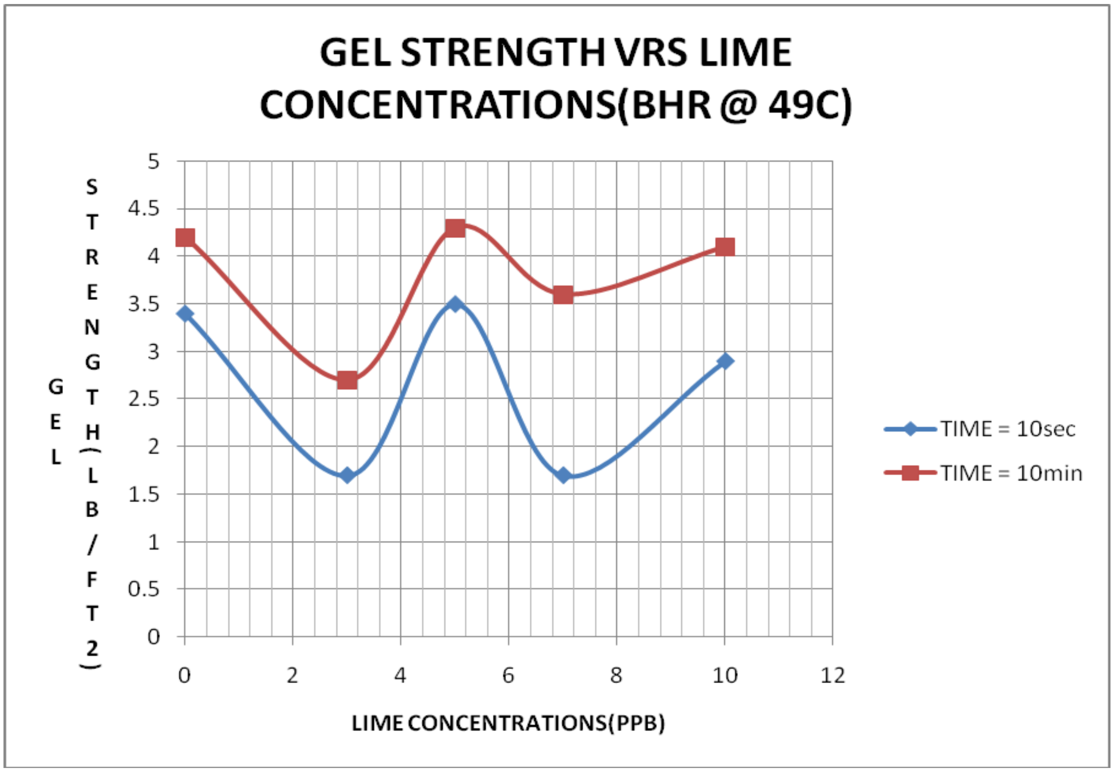

Figure 6.3: Gels versus Lime Concentrations BHR @ 120^0F.

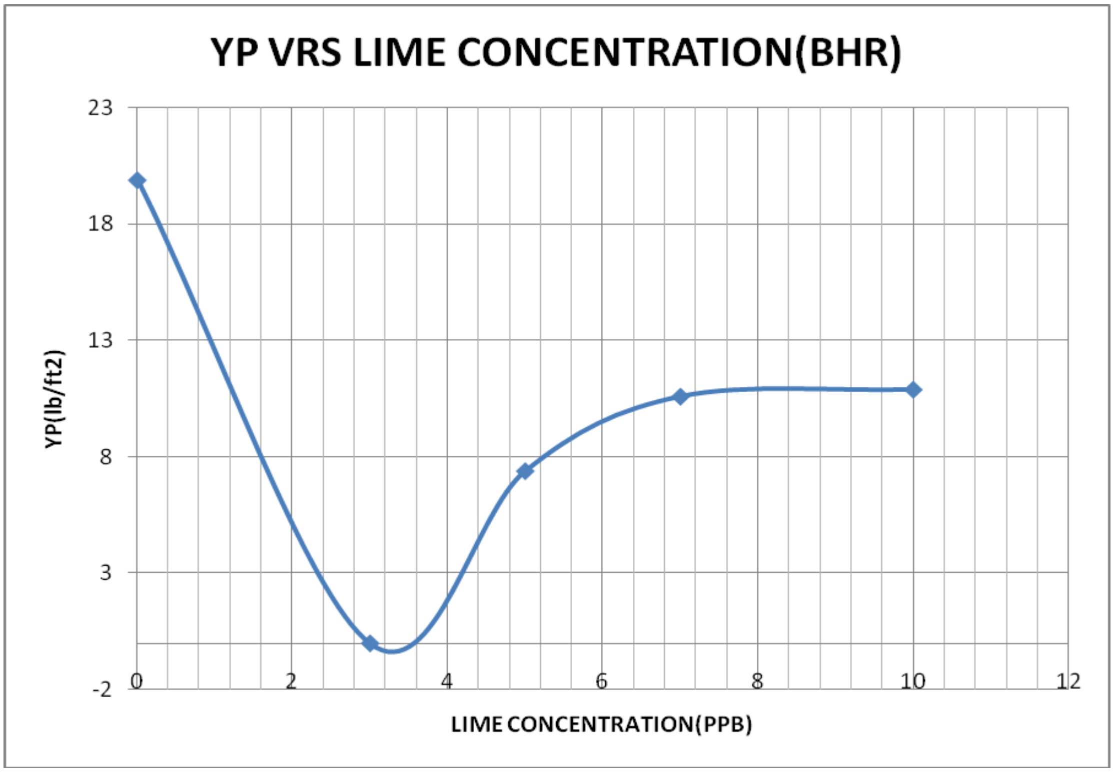

Figure 6.4: YP versus Lime Concentrations BHR @ 120^{0}F

Referring to Table 6.2, it seems that results are reasonably good and makes all formulations look good. This is because individually, each mud system has good dial readings, PV, YP and Gels. A mud sample with too low or too high dial readings, PV, YP, and Gels at room temperature may be considered as bad mud. These values for the mud samples may be considered as reasonable based on experience, and hence the mud may be considered to be good.

6.2.2. Rheological Behavior of Mud at Different Lime Concentration BHR and AHR

However, not all lime concentrations are optimum for the formulation of a stable mud system. To determine the mud system with the optimum lime concentrations, two approaches were employed. The first approach involved ageing each mud at room temperature for 72 hrs. It is expected that a stable mud will remain intact, while an unstable mud will have the liquid phase and the suspended solids clearly separated. Mud systems containing 0 ppb lime and 3 ppb lime were proven to be unstable after 72 hrs because the liquid phase and suspended materials in these muds clearly separated as shown in Figure 6.5 and Figure 6.6 respectively.

The second approach employed to determine the mud system containing the optimum amount of lime among the stable systems after 72 hrs. This is called hot-rolling and the experiment was conducted with the 5 ppb, 7 ppb and 10 ppb lime concentration. After ageing the mud systems with 5 ppb, 7 ppb, and 10 ppb lime concentration for 16 hours at 250^0F, mud system containing 7 ppb and 10 ppb lime respectively became thickened, congealed and lost all rheology properties. These phenomena are shown in Figures 6.7 and 6.8 respectively. On the other hand, while the mud system containing 5 ppb lime remained stable with very high values of measured rheological property as shown in Figure 6.9.

Figure 6.5: Mud system containing 0 ppb lime after ageing for 72hrs at room temperature

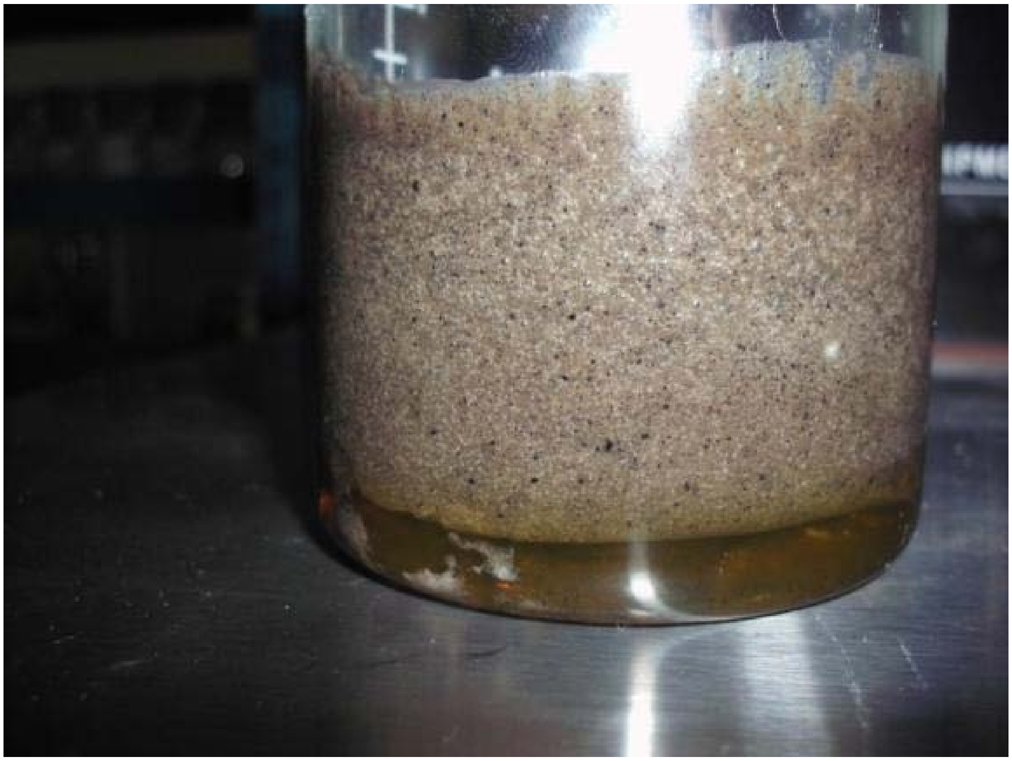

Figure 6.6: Mud system containing 3ppb lime after ageing for 72hrs at room temperature.

Figure 6.7: Mud system containing 7 ppb lime after ageing for 16 hrs at 250^0F.

Figure 6.8: Mud system containing 10 ppb lime after ageing for 16 hrs at 250^0F

Figu

Figure 6.9: Mud system containing 5 ppb lime after ageing for 16 hrs at 250^0F

To confirm the consistency and stability of the mud system containing 5 ppb lime, the mud system was formulated four times with complete mud check conducted on each formulation (Table 6.3). HTHP Filtration loss and electrical stability tests were performed for each formulation. Ageing for 16 hrs was done at 250^0F without pressurizing the hot-rolling cell so that the effect of temperature on the new mud system can be independently observed. Table 6.4 shows the average values of measured properties BHR and AHR using Table 6.3. The table is created so that data can be brought into a sharp focus and errors can be measured to reduce it.

TABLE 6.3: VALUES OF PARAMETERS MEASURED FOR 4 DIFFERENT MIXES OF 5PPB LIME MUD BHR & AHR

Parameters	**MIX 1**		**MIX 2**		**MIX 3**		**MIX 4**	
Dial Speed	BHR	AHR	BHR	AHR	BHR	AHR	BHR	AHR
600 rpm	139	229.5	119.2	261.2	122.7	270	128	250
300 rpm	62.7	110.5	56.5	133.2	66.7	198.2	59.1	175.5
200 rpm	42.9	68.3	55.8	104.1	43.7	204.7	44.8	145.4
100 rpm	24.7	40.2	21.0	84.3	25.4	149.7	26.5	102.5
6 rpm	4.1	10.4	4.2	28.4	5.7	67.1	4.6	44.5
3 rpm	3.3	7.3	3.8	20.2	4.3	55	3.5	30.2
10 sec, lb/ft^2	3.5	5.3	1.2	19.6	4.1	62.6	3.8	58.7
10 min, lb/ft^2	4.3	10.7	2.9	31.3	4.8	80.8	5.1	76.6
PV, cp	53.6	54.8	45.4	131.9	56.6	42.0	53.3	33.7
YP, lb/ft^2	7.4	13.9	3.4	37.7	7.9	21.9	7.7	23.6

TABLE 6.4: AVERAGE VALUES OF BHR AND AHR CALCULATED FROM TABLE 6.3

Parameters	BHR (Averages)	AHR (Averages)
600 rpm	127	252.7
300 rpm	61.3	154.4
200 rpm	46.8	130.6
100 rpm	24.3	94.2
6 rpm	4.7	37.6
3 rpm	3.7	28.2
10 sec, lb/ft^2	3.2	36.5
10 min, lb/ft^2	4.3	49.7
PV, cp	52.2	65.6
YP, lb/ft^2	6.6	24.3
HTHP Spurt loss, mm	*	2 ml (2x1)@250^{0}F
HTHP filt. loss, mm	*	10 ml (2x5)@250^{0}F
Cake thickness, mm	*	3.1mm
Emulsion stability,Volt	*	990

Note: “*” not available in literature

Figure 6.10 presents the dial readings with dial speed at the rate of 5 ppb lime concentration in the form of bar chart. For each dial speed, it is observed that the AHR dial readings were approximately four times than the BHR readings. This is an indication of the fact that the 5 ppb lime concentration mud at the elevated temperatures is unstable. This is a challenge that must be corrected in the mud system.

Figure 6.11 shows the average Gels BHR and AHR for 10 sec and 10 minutes in the form of bar chart. The data has been generated from the Table 6.4. From the figure, it can be inferred that AHR Gel values go up to approximately nine times higher than that of the BHR values. This indicates that the 5 ppb mud system is sensitive to elevated temperatures which will results very high rheological behavior changes during the development of mud system. This is a challenge for the formulation of new mud which needs to be considered seriously at the time of formulation.

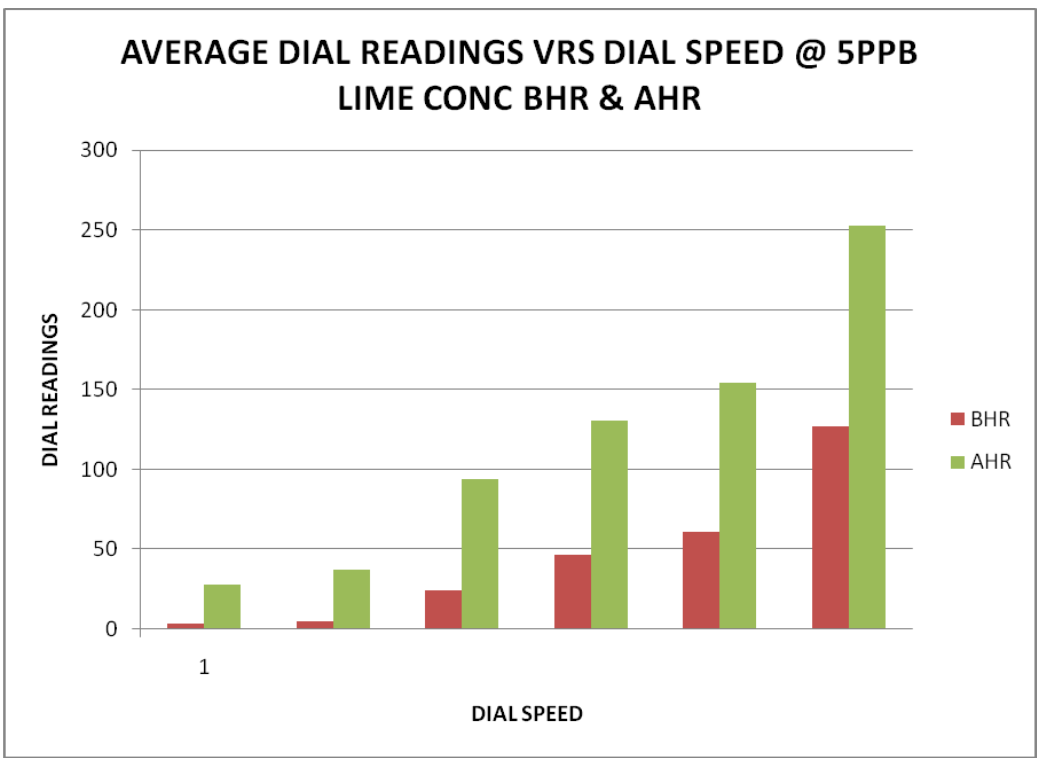

Figure 6.10: Average Dial Readings versus Dial Speed @ 5 ppb Lime.

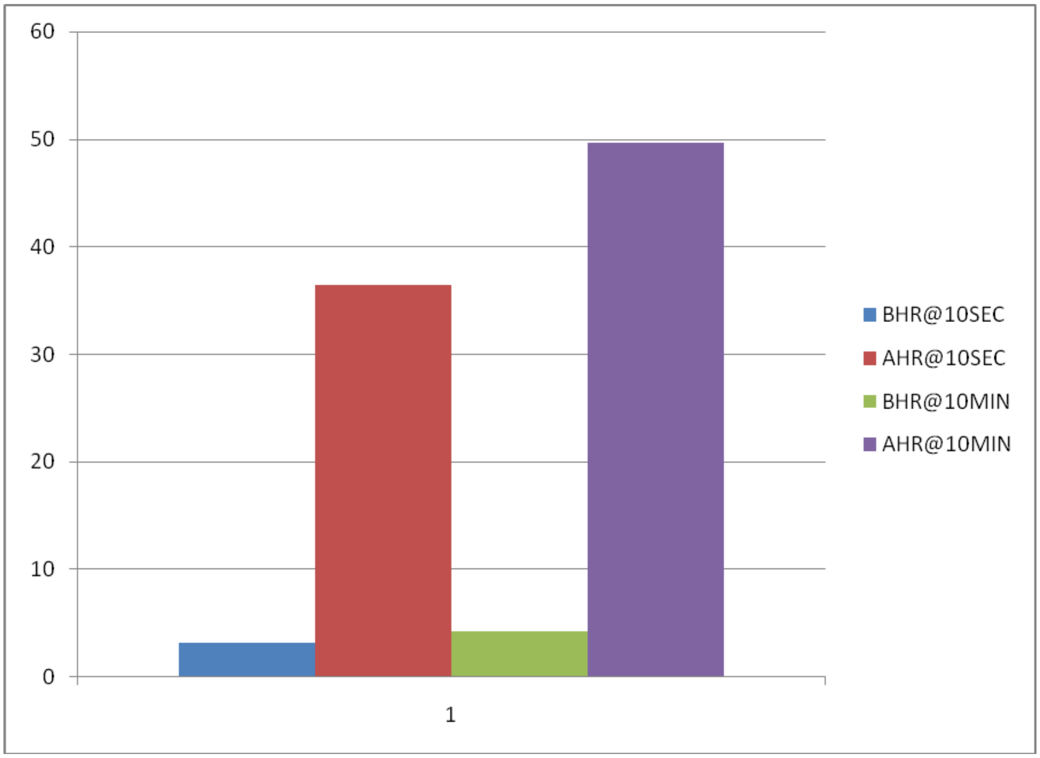

Figure 6.11: Average Gels BHR and AHR.

Figure 6.12 depicts the PV of the newly formulated mud with BHR and AHR in the form of bar chart. The figure shows a very high AHR PV value comparing with BHR. This is an unwanted behavior of the mud at elevated temperatures which is a challenge again for the formulation. It needs to be corrected before suggesting any new formulation.

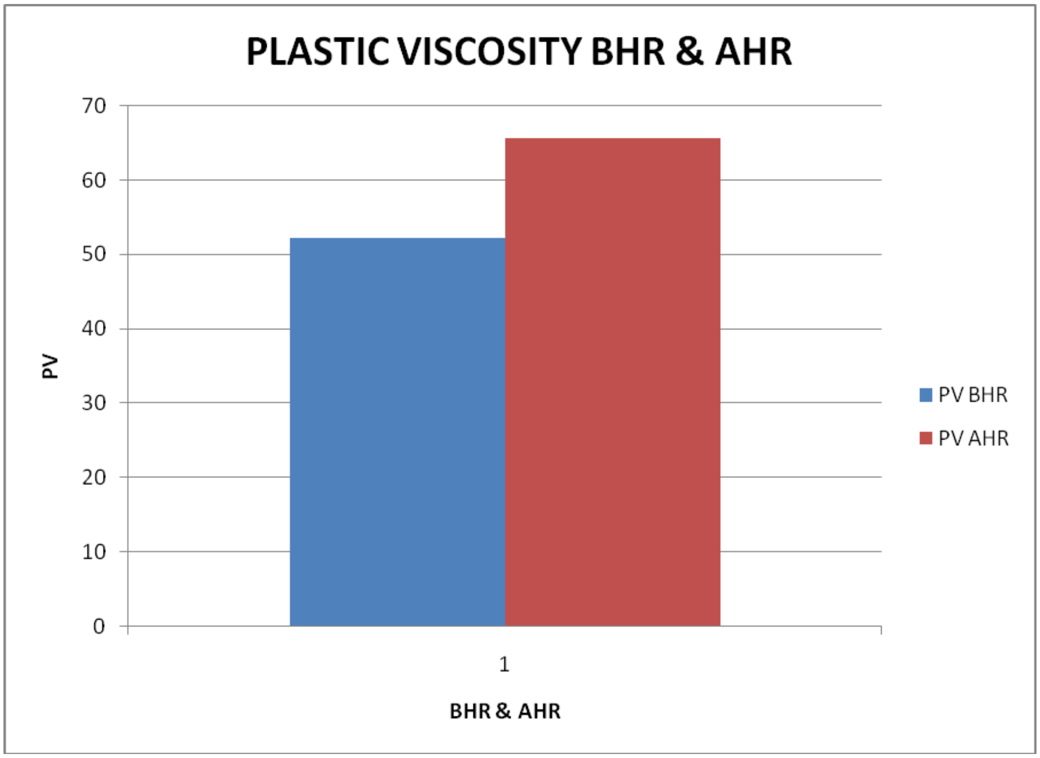

Figure 6.12: Average PV @ 5 ppb BHR and AHR

Figure 6.13 depicts the YP of the newly formulated mud with BHR and AHR in the form of bar chart. The figure shows a very high AHR YP value comparing with BHR which is similar to Figure 6.12. This is an unwanted behavior of the mud at elevated temperatures which is a challenge again for the formulation. It needs to be corrected before suggesting any new formulation.

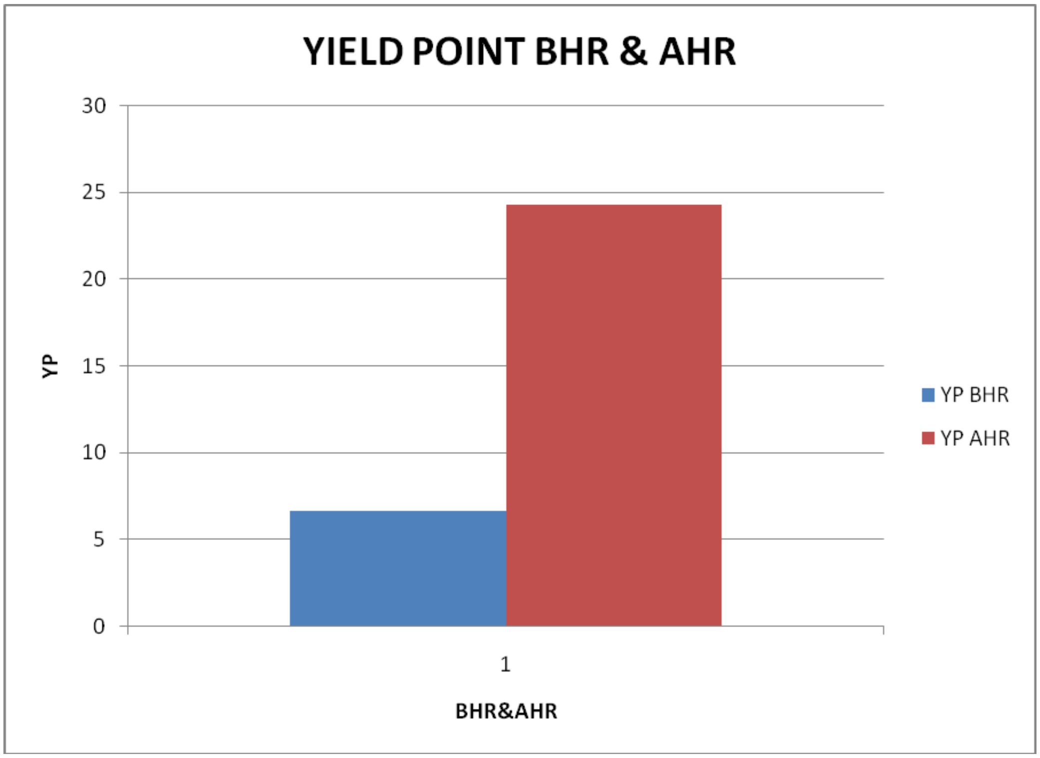

Figure 6.13: Average YP @ 5ppb BHR and AHR.

Under the applied test conditions, a strong indication of consistency is observed at this level of the development of mud system. Table 6.2 shows the values of PV, YP, and Gels measured for the 5 ppb mud system BHR at 120^0F which is in the same range with average values in Table 6.4. For example, PV in Table 6.2 is 52.2 cp, while PV_{avg} in 6.4 is 53.6 cp.

It is noted that the effect of temperature on the mud system is very clear from the above figures. Dial readings, PV, YP and Gel values AHR have been increased by a factor of nine approximately. These effects are not desirable and hence must be corrected in the mud system.

6.2.3. Rheological Behavior of Mud at Five PPB Lime Concentration at HPHT Conditions

When drilling deep wells, one of the challenges encountered is the problem due to extreme down-hole conditions of high temperature and pressure which tend to destroy the effectiveness and performance of drilling fluids leading to drilling problems such as loss returns, barite sagging and stuck pipe. As a result, a sample of the 5 ppb lime mud was aged for 16 hrs at 300 ^{0}F and 300 psi to determine the effect of the combination of HTHP effects on the developed mud system. Table 6.5 shows the properties of mud system containing five ppb lime and six ppb Gelant at 300 ^{0}F and at 300 psi. It is observed that measured properties remains consistent before hot-rolling (BHR). However, AHR dial readings became abnormal which means that 600-100 rpm dial readings went off the 300 mark on the viscometer scale. From 600 rpm to 100 rpm, AHR values of dial readings were 300 plus. And as can be seen in Table 6.5, PV, YP and Gels were not measureable.

TABLE 6.5: PROPERTIES OF MUD SYSTEM CONTAINING LIME AND GELANT

Paremeters	**6 ppb Gelant**	
Dial reading	BRH	AHR
600 rpm	135	300+
300 rpm	74	300+
200 rpm	58	300+
100 rpm	32	300+
6 rpm	10	150

3 rpm	7	*
10 sec, lb/ft^2	3	*
10 min, lb/ft^2	4	*
PV, cp	61	*
YP, lb/ft^2	13	*

Note: “*” means not measureable

High temperature and pressure generally can influence the rheology of mud systems physically by increasing the density of the liquid phase, and therefore subsequently the mud viscosity. The viscosifier used in the formulation of the new mud system is also known to be very sensitive to elevated temperatures and pressures. At HTHP, the viscosifier may impart unwanted level of viscosity on the mud system. Hence, to bring the abnormal AHR behavior of the mud system under control, the strategy employed is to reduce the amount of the viscosifier used in the mud formulation. This involved the addition of a product recommended minimum of 2 ppb and 3 ppb of viscosifier in two separate formulations. Table 6.6 shows the experimental findings of dial readings, PV, YP and Gels measured for mud system containing 2 ppb and 3 ppb of gelant respectively. These findings are similar to that obtained in Table 6.5 at 6 ppb viscosifier concentration. However, for the 2 ppb mud, BHR and AHR values of 6 rpm dial reading, 10 seconds and 10 minutes Gels were measurable (not measurable for 3 and 6 ppb). This is because of the amount of the Gelant which has been reduced resulting in a slight lowering of HTHP effect on the mud system. Hence, two ppb is considered to be the optimum amount of viscosifier to be used for the formulation of the new mud system.

TABLE 6.6: PROPERTY OF FIVE PPB LIME CONCENTRATION WITH THREE ppb AND 2 ppb GELANT RESPECTIVELY

Paremeters	**3 ppb Gelant**		**2 ppb Gelant**	
Dial reading	BHR	AHR	BHR	AHR
600 rpm	125	300+	119	300+
300 rpm	74	300+	70	300+
200 rpm	51	300+	50	300+
100 rpm	32	300+	39	249
6 rpm	9	140	9	125
3 rpm	7	*	6	110
10 sec, lb/ft^2	2	*	2	90
10 min, lb/ft^2	3	*	3	44
PV, cp	51	*	49	*
YP, lb/ft^2	23	*	21	*

Note: "*" means not measureable.

The reduction of the concentration of viscosifier in the new mud system did not do much in normalizing the effect of HTHP on its rheology. Hence, there is the need to identify the particular additives or additive that is needed to be altered in concentration. At the beginning of this research work, it was observed that the filtration control additive does not completely disperse in the liquid phase of the mud and might be contributing or imparting directly on the mud viscosity. This additive is also very sensitive to elevated temperature and pressure conditions. So, logically, it might be the target additive. However, because of the complexity of the chemistry of the additives interacting in the mud system, one cannot conclude such issue easily.

6.2.4. Rheological Behavior of Three Mud Formulations under HPHT Condition

To determine which of the additives needed to be adjusted, three different formulations were mixed and complete rheology measurement conducted on each one at 300 ^{0}F and 300 psi.

First Mix:

Table 6.7 shows the first mix containing 0 ppb gelant, 0ml secondary emulsifier and 0 ppb $Cacl_2$. Experimental findings of the measured properties of this formulation describe the preparation of this mud system as good due to an increase in the YP from 6 lb/ft^2 BHR to 24 lb/ft^2 AHR. The short coming of this formulation is that it is unstable. Additives and other suspended materials settle and sag just in few hours at ambient conditions. This is a clear reflection of the absence of a gelant in the formulation whose functions primarily to impart viscosity to the mud system but most importantly, to keep materials suspended.

The drop in values of dial readings and PV AHR may be due to the lacking of gelant and the secondary emulsifier whose functions are to make additives oil wet and also impart additional lubricity to the mud. In addition, the drop in PV reflects the direct effect of elevated temperature on the mud which is to thin or lighten the mud. The presence of a gelant in any mud system prevents this effect while also improving the PV. YP might have increased AHR due to a prolonged period of shearing which makes the additives to be strongly bonded together. This is temporary because as mentioned earlier, this mud sags only after a short period of time.

TABLE 6.7: MUD SYSTEM CONTAINING FIRST MIX BHR AND AHR

Parameters	BHR @ 120^{0}F	AHR
600 rpm	92	72
300 rpm	49	48
200 rpm	35	34
100 rpm	19	19
6 rpm	3	4
3 rpm	2	2
10sec, lb/ft^2	1	1
10min, lb/ft^2	2	1
PV, cp	43	24
YP, lb/ft^2	6	24

Second Mix

The second mix was prepared with 2 ppb gelant, 0 ml secondary emulsifier, and 0 ppb $Cacl_2$. Table 6.8 shows the different parameters BHR and AHR. It has an impressive BHR and AHR properties however it is an incomplete mud. This is because it does not contain $Cacl_2$ whose functions are to control the activity (Aw) of the mud and also the secondary emulsifier which makes suspended materials in the mud preferentially oil wet.

TABLE 6.8: MUD SYSTEM CONTAINING SECOND MIX BHR AND AHR

Parameters	BHR @ 120 ^{0}F	AHR
600 rpm	83	98
300 rpm	45	56
200 rpm	33	38

100 rpm	18	21
6 rpm	5	4
3 rpm	3	2
10sec, lb/ft^2	1	2
10min, lb/ft^2	3	5
PV, cp	38	42
YP, lb/ft^2	7	14

Third Mix

The third and final preparation was formulated with 2 ppb gelant, 8 ml secondary emulsifier, 17 ppb $Cacl_2$ and a reduced 6 ppb concentration (original concentration was 10 ppb) of the filtration control additive. The concentration of the filtration control additive is lowered down to 6 ppb based on the earlier observation. The finding was that it does not disperse uniformly even after shearing the mud for a long period of time. Based on the result of the complete mud check conducted on this mud formulation (Table 6.9), this mud can be considered to be good. This formulation is to be the desired formulation and a pointer to the fact that canola oil can be used to formulate an OBM system with zero level of toxicity.

The formulation in Table 6.9 contains all the additives vital to the development of a stable and functional mud system. The thinning effect of temperature over a small range is also good because the mud is not weighted. It is expected that when barite is added to the mud, the slight variation in BHR and AHR rheological behavior will become balanced.

TABLE 6.9: MUD SYSTEM CONTAINING THIRD MIX BHR AND AHR

Parameters	BHR @ 120 ^{0}F	AHR
600 rpm	125	95
300 rpm	66	59
200 rpm	56	42
100 rpm	28	24
6 rpm	7	6
3 rpm	5	4
10sec, lb/ft^2	2	3
10min, lb/ft^2	3	5
PV, cp	59	36
YP, lb/ft^2	7	23
Electrical Stability, Volts	*	625
HTHP filtrate, ml	*	12 (6x2) @ 250 ^{0}F
HTHP filter cake thickness, mm	*	2

Note: "*" means not available

Tables 6.10 and 6.11 are the summaries of components and the results of mud check conducted on the initial canola oil-based mud formulation and the final canola oil-based mud formulation. Table 6.10 resulted from a series of tests conducted and consequent modification of Table 2.1 which was developed using Amanullah's (2010) and Yassin et al. (1991) formulation as a guide.

TABLE 6.10: COMPOSITION OF INITIAL AND FINAL MUD SYSTEM FORMULATION

Mud Component	**Amount**	
	Initial formulation	Final formulation
Base oil	90%	90%
Primary emulsifier	12 ml	12 ml
Lime	5 ppb	5 ppb
Filtration Control additive	10 ppb	6 ppb
Water	10%	10%
Viscosifier	6 ppb	2 ppb
Secondary emulsifier	8 ml	8 ml
$Cacl_2$ (78%)	17 ppb	17 ppb

TABLE 6.11: PROPERTIES OF INITIAL AND FINAL MUD SYSTEMS BHR AND AHR

Parameters	**INITIAL FORMULATION**		**FINAL FORMULATION**	
	BHR	AHR	BHR	AHR
600rpm	127	252.7	125	95
300rpm	61.3	154.4	66	59
200rpm	46.8	130.6	56	42
100rpm	24.3	94.2	28	24
6rpm	4.7	37.6	7	6

3rpm	3.7	28.2	5	4
10sec,lb/ft^2	3.2	36.5	2	3
10min,lb/ft^2	4.3	49.7	3	5
PV,cp	52.2	65.6	59	36
YP,lb/ft^2	6.6	24.3	7	23
HTHP Spurt loss,ml	*	2ml (2x1)@250^{0}F	*	*
HTHP filt. Loss,ml	*	10ml (2x5)@250^{0}F	*	12 (6x2)@250^{0}F
Cake thickness,mm	*	3.1	*	2
Emulsion stability,Volt	*	990		625

Note: "*" means not available

6.3 Validation of Results

To validate the property of the newly formulated canola oil-based mud system, the final measured values of its properties were compared with a synthetic oil-based mud system. This synthetic based mud system is currently being used by Saudi Aramco for all of its offshore drilling operations. The formulation of this synthetic based mud is normally formulated from a synthetic solvent called Safra oil or Saudi sol which is shown in Figure 6.14.

Figure 6.14: Sample of Safra oil collected to formulate synthetic oil-based mud use for comparison.

Safra oil with the product name Safrasol D80™ is a highly de-aromatized aliphatic solvent which is commercially available and in the class of kerosene. Figure 6.15 shows a sample of synthetic oil-based mud which was formulated using Safrasol for this research.

Figure 6.15: Sample of Safra oil-based mud system prepared for comparison

To validate the result, Aramco sample result for safrasol synthetic oil-based mud system and the result of the formulation developed by Yassin et al., (1991) using methyl ester of crude palm oil are used. Table 6.12 shows the comparison of these two samples properties with the newly formulated mud system using canola oil-based mud. This table shows a complete summary of the formulation and the comparison for the validation of results.

TABLE 6.12: COMPARISONS OF DIFFERENT MUD SYSTEMS

	Canola-BMS O/W=90/10		**SAFRA-ME O/W=60/40**		**SAFRA-ARAM O/W=53/47**		**Yassin et al. O/W=85/15**	
Parameters	BHR	AHR	BHR	AHR	BHR	AHR	BHR	AHR
10sec,lb/ft^2	2	3	2	2	*	6	8	6
10min,lb/ft^2	3	4	2	3	*	8	21	28
PV,cp	59	36	20	20	*	51	28	42
YP,lb/ft^2	7	23	15	25	*	18	10	35
HTHP Spurt loss,ml	*	*	*	*	*	*	*	*
HTHP filt. Loss,ml	*	12	*	4	*	2	*	11.6
Cake thickness,mm	*	2	*	2	*	1	*	5.45
Emulsion stability,Volt	990	990	350	320	*	229	1060	770

Note: “*” means not available

From Table 6.12, Canola-BMS has a BHR PV value of 59 cp, and AHR value of PV of 36 cp meaning that HTHP has a thinning effect on the un-weighted mud which is good. When barite is added PV will become normalized. SAFRA-ME shows no change in BHR and AHR PV values reflecting a solid level of stability. Yassin’s formulation seems unstable due to a large jump in BHR and AHR values of PV. All mud show increments in

AHR YP values. Highest electrical stability is recorded for Yassin’s formulation BHR at 1060 Volts, but became reduced AHR to 770 Volts. Canola-BMS is stable BHR and AHR at 990 Volts. Lowest electrical stability is recorded for the SAFRA-ARAMCO.

CHAPTER 7

Conclusions and Recommendations

7.1 Conclusions

Based on experimental findings through this research work, the following conclusions are drawn:

1) Canola oil can be used as a base-oil for the formulation of an oil-based mud system.
2) The developed canola oil-based mud system has zero level of toxicity.
3) The reduction of concentration of the certain additives in its composition based on the oil/water ratio used will help to reduce the cost of formulation on a large scale for field applications.
4) The developed canola oil-based mud system is formulated without a wetting agent. This will also help to reduce the cost of formulation.
5) The developed canola oil-based mud system is stable at room temperature (BHR) and under simulated down-hole conditions (AHR)

7.2 Recommendations

The following recommendations were made for the future research toward the development of competitive and comprehensive sustainable mud system.

1) Efforts should be directed toward the formulation of the canola oil-based mud at a reduced oil/water ratio. An area of further research could be reducing the current oil/water ratio, 90/10 to say 80/20 or even in further reduction.
2) The effect of an alternative filtration control additive on the mud system may be investigated.
3) The effect of a suitable thinner on the mud system should also be evaluated.
4) Standard toxicity test such as the LCD50 test will be carried out on both muds.
5) Formulations to determine the level of environmental impacts.

Nomenclature

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