EFFECTS OF DRILLING FLUIDS, OIL OR WATER BASE MUD ON DRILL CUTTINGS

BY

EWA JANET CHIAMAKA
ENG1604318

DEPARTMENT OF PETROLEUM ENGINEERING
FACULTY OF ENGINEERING
UNIVERSITY OF BENIN
BENIN CITY

DECEMBER, 2022

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A PROJECT THESIS SUBMITTED TO THE DEPARTMENT OF PETROLEUM ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF ENGINEERING IN PETROLEUM DEPARTMENT IN UNIVERSITY OF BENIN, BENIN CITY

DECEMBER, 2022.

CERTIFICATION

This is to certify that this research work was carried out by EWA JANET CHIAMAKA with matriculation number ENG1604318, in partial fulfillment of the requirement for the award of Bachelor of Engineering in Petroleum Engineering.

Engr. Dr. Onaiwu Oduwa **Date**

Project Supervisor

Engr. O.A. Taiwo **Date**

Project Coordinator

Engr. Dr. Ikpomwonsa Ohenhen **Date**

Head of Department

Date

External Supervisor

DECLARATION

I hereby declare that this project "***Effect(s) of drilling fluids, oil or water base mud on drill cuttings***" was carried out by me, supervised by Engr. Dr. Oduwa Onaiwu of Department of Petroleum Engineering, University of Benin, Benin City, Edo State, Nigeria.

DEDICATION

This research work is dedicated to God Almighty whose favor and grace sustained me throughout this work and my stay in the University of Benin, to Him alone I gave all the glory.

ACKNOWLEDGEMENT

I want to extend my profound gratitude to God Almighty for his guidance, direction and grace throughout my stay in uniben.

I want to express my gratitude to my project supervisor Engr. Dr. D.O. Onaiwu for his support offered during my course of study may God bless you and bring to perfection all that concerns you. Amen. To all my lecturers in the department for their positive impact on me throughout my stay in the department, I am grateful.

My regards to my amazing parents, Mr. and Mrs. Benjamin Eaw Okoro, who have been there for me financially and spiritually both also for their generous love, care, affection, encouragement, moral support and rendering the best advice, I pray God keeps you both in good health to enjoy the fruits of your labor, Amen. To my loving husband Mr. David Chinedu Orah thanks for always being there for me may God continue to bless you, Amen and to my beloved siblings, I love you all, you’re the best.

I won’t fail to appreciate my wonderful friends who gave me moral support during my research work may the Lord bless you all. Amen.

ABSTRACT

This chapter deals with compositions for drilling muds and special chemical used for drilling muds. Drilling fluids are mixtures of natural and synthetic chemical compounds used to cool and lubricate the drill but, clean the hole bottom, carry cuttings to the surface, control formation pressures, and improve the function of the drill string and tools in the hole. Drilling muds are divided into two general types: water-based drilling muds and oil-base drilling muds. Each type needs special additives which are discussed in this chapter.

The type of fluid base used depends on drilling and formation needs, as well as the requirements for disposition of the fluids after it is no longer needed. Drilling muds are special class of drilling fluids used to drill most deep wells.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Contamination of drilling fluids with drilled cuttings is an unavoidable consequence of successful drilling operations. If the drilling fluid does not carry cuttings and cavings to the surface, the rig either is not “making hole” or soon will be stuck in the hole it is making. The drill cuttings that are separated from the drilling fluid on the surface by the soldis control equipment and some quantity of unrecoverable or economically unwanted drilling fluid are a major source of drilling waste. Drilled and formation solids that are sized smaller than can be removed by the solids control equipment are often reported as drill solids. Some quantitiy of drill solids will accumulate in the drilling fluid and must be removed by the solids control equipment or reduced in concentration by dilution.Exploration and production operations generate chemicals such as crude oil, condensate, natural gas, hydrogen sulphide, carbon dioxide, heavy metals, brine salts and solid cuttings Waste components include the following

a) **Waste lubricants:** lube oil, grease.

b) **Spacers and completion fluids:** Mineral oil, detergents, surfactants.

c) **Water based muds and cuttings:** Formation solids, water based muds and mineral oil.

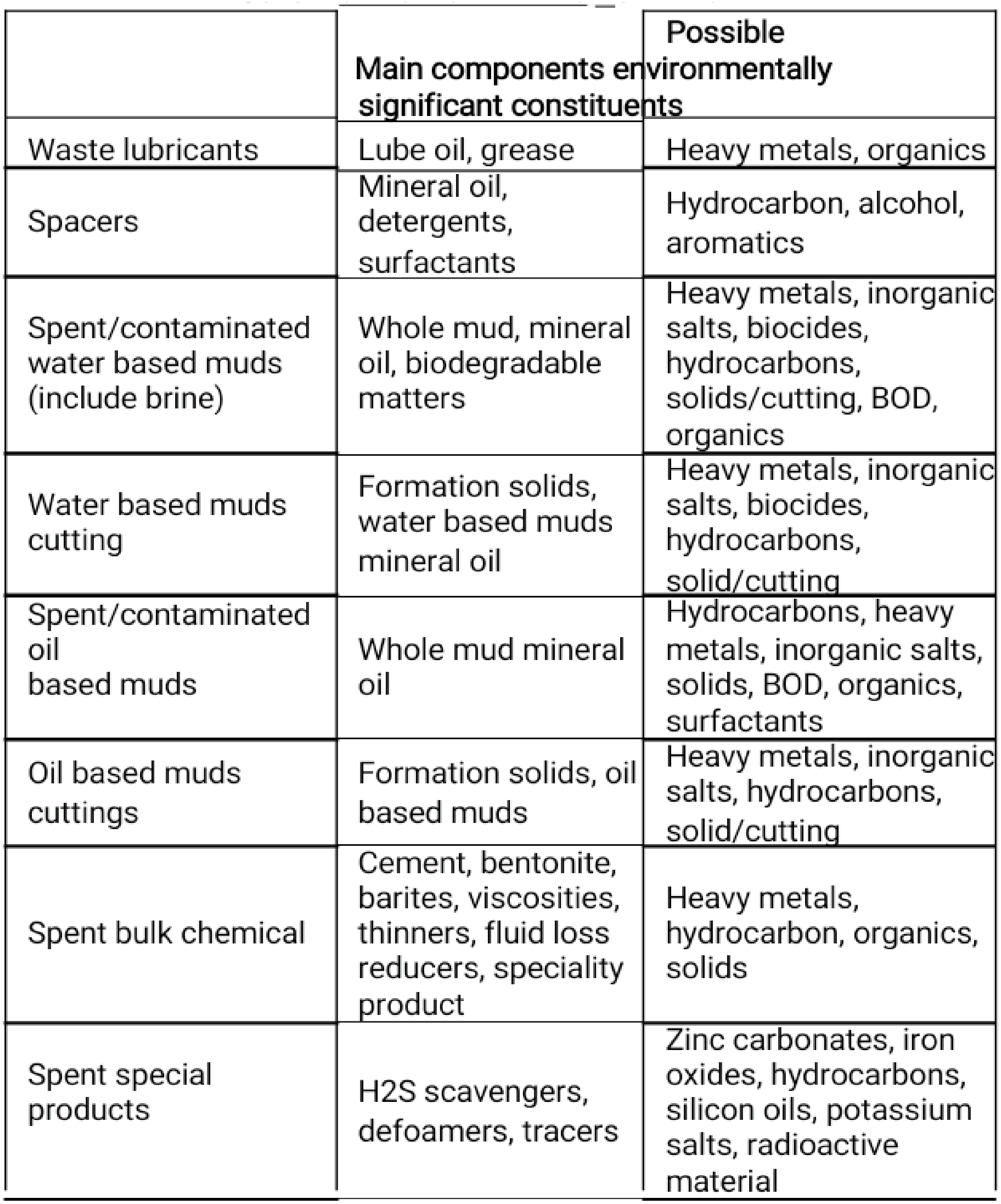
d) **Oil based and synthetic based muds cuttings:** Formation solids, oil based muds.

e) **Spent bulk chemical/additives:** Cement, Bentonite, barites, viscosities, thinners, fluid loss reducers, specialty product.

f) **Spent special products:** H_2S scavengers, defoamers, tracers.

g) **Produced Water:** Deck drainage is water that reaches the deck of offshore installations through precipitation, sea spray, rainwater or from routine operations such as wash down and fire drills.57 It may be contaminated with oil and grease that lands on the deck of offshore installations. It is also known as platform drainage or machinery space drainage.

Table 1.1: Wastes Components and Environmentally Significant Constituents from Drilling Activities



	Main components	Possible environmentally significant constituents
Waste lubricants	Lube oil, grease	Heavy metals, organics
Spacers	Mineral oil, detergents, surfactants	Hydrocarbon, alcohol, aromatics
Spent/contaminated water based muds (include brine)	Whole mud, mineral oil, biodegradable matters	Heavy metals, inorganic salts, biocides, hydrocarbons, solids/cutting, BOD, organics
Water based muds cutting	Formation solids, water based muds mineral oil	Heavy metals, inorganic salts, biocides, hydrocarbons, solid/cutting
Spent/contaminated oil based muds	Whole mud mineral oil	Hydrocarbons, heavy metals, inorganic salts, solids, BOD, organics, surfactants
Oil based muds cuttings	Formation solids, oil based muds	Heavy metals, inorganic salts, hydrocarbons, solid/cutting
Spent bulk chemical	Cement, bentonite, barites, viscosities, thinners, fluid loss reducers, speciality product	Heavy metals, hydrocarbon, organics, solids
Spent special products	H2S scavengers, defoamers, tracers	Zinc carbonates, iron oxides, hydrocarbons, silicon oils, potassium salts, radioactive material

Some of the waste treatment and disposal practices in the exploration and production operations such as offshore discharge, Landfill/land farming, waste-soil mixtures, Thermal desorption, injection, solidification and bioreactors are not meeting the existing effluent limitations set by the the Nigerian government.

However, drilling wastes are expected to undergo further treatment in order to meet the more stringent regulations that are currently being developed worldwide.

An environmental permit from DPR is required before any drilling operation can commence in Nigeria.32 Accordingly, an environmental permit is required for the use and discharge of drilling fluids/mud. The application for an environmental permit must include the treatment and disposal programmes for drilling fluid/mud and drill cuttings as well as detailed information and an approval letter for the mud system to be used.33 A formal application for the use of OBMs must also be made to DPR and must be justified on geological, safety and/or economic grounds.34 The permitting requirement reflects the practice in many countries and is essential for controlling the discharge of drill cuttings and drilling fluid/mud into the offshore environment. It is helpful because the discharge of drill cuttings and fluids/mud without a permit is prohibited and is an offence.35 So, it serves as a deterrent because operators will not want to be held liable for the discharge of drilling fluid/mud and risk revocation of their drilling licences. However, the transfer of drill cuttings to another field for treatment and re-injection is not covered by a permit under EGASPIN and needs to be addressed by DPR.The discharge of spent oil based drilling mud/fluids and whole fluids/mud into offshore waters is prohibited. However, the discharge of whole drilling mud/fluids, spent drilling mud/fluids, OBMs or SBMs and drill cuttings is permitted in offshore areas 12 nautical miles away from the shoreline and of depth not less than 200 feet provided the specified effluent limitations are satisfied.

1.2 PROBLEM STATEMENT

Waste management is one of the problems facing the oil and gas industry. This has often thrown the industry into numerous challenges ranging from technological development to ensuring a clean and safe environment. Oil and gas well drilling processes generate large volume of drill cuttings and spent mud. Onshore and offshore operators have used a variety of methods to manage these drilling wastes. This paper discusses the basic concepts for managing waste generated during drilling operations and provides systematic approach for pro-active waste management practices. It addresses the various stages in drilling waste management, and emphasizes the phases of waste identification, minimization, treatment and disposal as integral parts of waste management process.

1.3 OBJECTIVE OF THE STUDY

The central objective of this study is the comparative analysis of drilling waste disposal methods, while the specific objectives are as follows:

1) To identify and compare the various methods of managing drilling wastes and adopt the technique which is more effective and efficient.

2) To ascertain the impact of drilling waste on the environment.

3) To identify the nature of drilling wastes or fluids.

4) To highlight the benefits, as well as the limitations of the various waste disposal options.

5) To keep detailed records of drilling wastes disposals to ensure that all drilling wastes are properly handled, stored and treated before disposal

1.4 SCOPE AND LIMITATION OF STUDY

This study will clearly outline the effects of drilling fluids on drill cuttings and also review four methods of drilling waste disposal technique, namely: the re-injection method, offshore discharge method, stabilization method, and incineration waste disposal methods. An attempt will be made at highlighting the benefits of these different methods mentioned above with respect to cost and efficiency.

This study will be limited to the Niger-Delta Area of Nigeria because it possesses one out of six sedimentary bases in Nigeria that is still being exploited for oil and gas.

1.5 SIGNIFICANCE OF THE STUDY

In any oil company, profit maximization is paramount in the management plan of action. Hence, the significance of this study is to bring to the fore the benefits, as well as the most effective and efficient method of drilling waste disposal, which serves as a tool in analysing drilling wastes before decisions can be taken in the management or handling of drilling wastes. It is intended to summarize the technical knowledge about the discharges and management of drilling wastes cuttings. It should aid in environmental assessment process for new projects as it provides a comprehensive synopsis of what is known about the environmental impacts resulting from drilling wastes discharge.Where this information needed by management is lacking, the grave consequence can better be imaged due to the huge financial involvements.

CHAPTER TWO

LITERATURE REVIEW

2.1 THE NATURE OF DRILLING FLUIDS

In geotechnical engineering, drilling fluid, also called drilling mud, is used to aid the drilling of boreholes into the earth. Often used while drilling oil and natural gas wells and on exploration drilling rigs, drilling fluids are also used for much simpler boreholes, such as water wells. One of the functions of drilling mud is to carry cuttings out of the hole. The three main categories of drilling fluids are: water-based muds (WBs), which can be dispersed and non-dispersed; non-aqueous muds, usually called oil-based muds (OBs); and gaseous drilling fluid, in which a wide range of gases can be used. Along with their formatives, these are used along with appropriate polymer and clay additives for drilling various oil and gas formations.

The main functions of drilling fluids include providing hydrostatic pressure to prevent formation fluids from entering into the well bore, keeping the drill bit cool and clean during drilling, carrying out drill cuttings, and suspending the drill cuttings while drilling is paused and when the drilling assembly is brought in and out of the hole. The drilling fluid used for a particular job is selected to avoid formation damage and to limit corrosion.

2.1.1 TYPES OF DRILLING FLUIDS

Many types of drilling fluids are used on a day-to-day basis. Some wells require different types to be used at different parts in the hole, or for some types to be used in combination with others(Heriot Watt University 2010).The various types of fluid generally fall into a few broad categories:

- Air/polymer: A specially formulated chemical, most often referred to as a type of polymer, is added to the water and air mixture to create specific conditions. A foaming agent is a good example of a polymer.
- Water: Water by itself is sometimes used. In offshore drilling, seawater is typically used while drilling the top section of the hole.
- Water-based mud (WBM): Most basic water-based mud systems begin with water, then clays and other chemicals are incorporated into the water to create a homogeneous blend resembling something between chocolate milk and a malt (depending on viscosity). The clay is usually a combination of native clays that are suspended in the fluid while drilling, or specific types of clay that are processed and sold as additives for the WBM system. The most common of these is bentonite, frequently referred to in the oilfield as "gel." Gel likely makes reference to the fact that while the fluid is being pumped, it can be very thin and free-flowing (like chocolate milk), though when pumping is stopped, the static fluid builds a "gel" structure that resists flow. When an adequate pumping force is applied to "break the gel," flow resumes and the fluid returns to its previously free-flowing state. Many other chemicals (e.g. potassium formate) are added to a WBM system to achieve various effects, including: viscosity control, shale stability, enhance drilling rate of penetration, and cooling and lubricating of equipment.
- Oil-based mud (OBM): Oil-based mud is a mud where the base fluid is a petroleum product such as diesel fuel. Oil-based muds are used for many reasons, including increased lubricity, enhanced shale inhibition, and greater cleaning abilities with less viscosity. Oil-based muds also withstand greater heat without breaking down. The use of oil-based muds has special considerations, including cost, environmental considerations such as disposal of cuttings in an appropriate place, and the exploratory disadvantages of using

oil-based mud, especially in wildcat wells. Using an oil-based mud interferes with the geochemical analysis of cuttings and cores and with the determination of API gravity because the base fluid cannot be distinguished from oil that is returned from the formation.

- Synthetic-based fluid (SBM) (Otherwise known as Low Toxicity Oil Based Mud or LTOBM): Synthetic-based fluid is a mud in which the base fluid is a synthetic oil. This is most often used on offshore rigs because it has the properties of an oil-based mud, but the toxicity of the fluid fumes are much less than an oil-based fluid. This is important when the drilling crew works with the fluid in an enclosed space such as an offshore drilling rig. Synthetic-based fluid poses the same environmental and analysis problems as oil-based fluid.

2.1.1 WATER-BASED MUD

Most basic water-based mud systems begin with water, then clays and other chemicals are incorporated into the water to create a homogeneous blend resembling something between chocolate milk and a malt (depending on viscosity)(M. S.Nwakaudu,2018).The clay is usually a combination of native clays that are suspended in the fluid while drilling, or specific types of clay that are processed and sold as additives for the WBM system. The most common of these is bentonite, frequently referred to in the oilfield as "gel." Gel likely makes reference to the fact that while the fluid is being pumped, it can be very thin and free-flowing (like chocolate milk), though when pumping is stopped, the static fluid builds a "gel" structure that resists flow. When an adequate pumping force is applied to "break the gel," flow resumes and the fluid returns to its previously free-flowing state. Many other chemicals (e.g. potassium formate) are added to a WBM system to achieve various effects, including: viscosity control, shale stability, enhance drilling rate of penetration, and cooling and lubricating of equipment.

2.1.2 OIL-BASED MUD

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Table 2.1: The Advantages and Disadvantages of Water Based Mud (WBM)

S/N	ADVANTAGES	DISADVANTAGES
1	Provides the highest probability of drilling holes in area(s) of known instability including the minimization of: (i) Shale hydration and associated problems i.e. stuck pipe, out-of-gauge hole etc., (ii) Repeated washing and reaming to keep the hole open, (iii) Abnormal viscosity and solids accumulation due to dispersion of clays.	Water-based mud can swell shale formation, a brittle mineral, collapse boreholes and impact drilling outcome in the drilling operations.
2	Addition of electrolytes to the mud results in dehydration of water-wet shale cuttings. This dehydration gives firm undispersed cuttings that reach the surface as particles large enough to be removed effectively by the shale shaker.	Gases produced among shale cracks whose non-organic part is possbly aqueous wetting phase can be easily displaced by water, offsetting the well loggings.
3	Less damaging to the permeability of producing oil formation.	Excessive massive solids will increase pressure more than formation pressure, and drilling mud will permeate into strata while fine particles will enter into oil channel which results in

		blockage causing damage of oil reservoir
4	Easy to formulate and less expensive.	
5	Does not require stringent disposal conditions as the oil-based mud.	
6	Does not require special laundry facilities for the personnel.	

Source: Heriot Watt University,2009

Table 2.2. THE ADVANTAGES AND DISADVANTAGES OF OIL-BASED MUD (OBM)

S/N	**ADVANTAGES**	**DISADVANTAGES**
1	Lower well friction is one of the advantages with oil-based drilling fluids. They are therefore often used in long-reach wells where friction is a critical parameter	High initial cost.
2	More inhibitive than inhibitive water based mud	Requires more stringent pollution control procedures.
3	Effective against all types of corrosion	Remedial treatment for lost circulation.
4	Superior lubricating characteristics	Reduces effectiveness of some logging tools.

Source: Piopetro (2017)

2.1.3 CLASSIFICATION OF MUD

Drilling fluids (mud) are classified according to the principal constituents gas, water, and oil. Table 2.3 shows the mud classification.

TABLE 2.3: CLASSIFICATION OF DRILLING FLUIDS ACCORDING TO PRINCIPAL CONSTITUENTS

GAS	WATER	OIL
Dry gas: air natural gas, exhaust gas, combustion gas	Fresh water	Oil: Diesel or crude
Mist droplets of water or mud carried in the air stream	Solution: true and colloidal i.e. solid do not separate from water on prolonged standing	Oil mud: a stable oil based drilling fluids contains: -coemulsifying agents -suspending agents -filtration control agents.
Foam: air bubbles surrounded by a film of water containing a foam stabilising surfactant	Solids in solution with water include: Salts e.g. NaCl, calcium Surfactants e.g. detergent, flocculent Organic colloids e.g. cellulosic and acrylic polymer	Contains cuttings from the formation drilled.
Table foam containing film-strengthening materials, such as organic polymers and bendorite.	Emulsion: on oily liquid maintained in small droplets in water by an emulsifying	

	agents e.g. Diesel oil and a film stabilizing surfactant. Mud: a suspension of soild on any of the above liquids, with chemical additives as required to modify the properties.	

Source: Piopetro (2016)

2.1.3 MUD RAW MATERIAL COMPOSITIONS

The mud slurry to be used for any drilling location must meet certain properties consistent with the geology of the location (Baker Hughes 2013).Such properties, which are usually determined and specified, include, the mud weight, the lithology (i.e. plastic, viscosity, yield point, gel strength, and the funnel viscosity); the filtrate (quantity and quality); and others, such as lubricity, corrosivity and osmotic effects, (R.Bland 2011)

Usually, most of these properties are determined for various depth intervals in a mud programme, prepared for each well. The above mud properties are manipulated to attain a desired effect by the addition, subtraction or otherwise of certain chemicals. Lee et al. (2009) reported that, some of these chemicals constitute a major source of environmental concern if spilled (blowout) or improperly disposed.

The mud materials used in Nigeria are detailed in table 2.4. Available significant data on each product are included, such as the physical and chemical characteristics, the concentration normally used in drilling mud, the toxicity data for aquatic organisms, water solubility, the threshold limit value and finally comments on the usage, handling and disposal precautions.

TABLE 2.4 MUD MATERIALS USED IN NIGERIA

Physical and chemical - characteristics	Cone, normally used in drilling mud (ppm)	96 hr. Tim or Ld50 (ppm)	Water solubility	Tlv dust only (mg/m)	Uses/hazards
Dry powder, barium sulfate	Depend on mud weight desired	Fresh & salt- 100,000	insoluble	10	Increase specific gravity/inert natural, mineral core.
A montmorillonite clay mineral, dry powder	15,000...15,000	Fresh- 14,000	Insoluble	10	Adds colloids and viscosity, natural mineral core
Sodium salt of 'carboxlmethyl cellulose, white granular polymer	750-6,000	N/A	Appreciable	10	Adjust viscosity and filtration / biodegradable
Chrome .lignosulfonate, dark brown powder	12,000	Fresh & salt- 25,000	Complete	10	Disperse colloids, reduce conglomeration
Sodium hydroxide,	750-6000	Toxicity well	-do-	2	Adjust pH between 9.5&10..5/ corrosive

white solid flakes					
Lignite, white granular polymer	6,000- 15,000	Fresh- 24,500 Salt - 20,000	negligible	10	Colloids dispersion at high temperature
Paraffinic hydrocarbon	1,500- 6000	Fresh- 5,400 Salt- 6,000	complete	None	Biodegradable
Potassium/sodium chloride	-	N/A	N/A	None	N/A
Sodium carbonate white powder	7,500- 6,000	-do-	Moderate	10	Hardness remover, basically non-toxic
Chrome lignite, dark brown powder	9,000- 12,000	Fresh- 3,000 Salt- 9,600	Appreciable	0.5	Avoid prolonged exposure in dust
Calcium hydroxide, white powder	1,500- 6,000	N/A	Forms solution	5	Irritating eyes and skin
Reacted and neutral ind phenols, light brown, high	9,000- 18,000	Fresh-97 Salt-80	-	None	Avoid prolonged exposure to vapour

pressure lubricant					
Liquid hydroxide	0.5% by vol.	N/A	N/A	N/A	N/A
Organic polymer, dark brown Jowder	6,000-15,000	Fresh-5,400 Salt 6,800	Complete	None	High temp, fluid, loss control agent& sec. defflocculant, avoid contact with eyes
Surfactant in a naptha base, dark .brown liquid	3,000-4,500	Fresh-2,800 Salt-6,800	Insoluble	400 for naptha	Emulsifies readily in sea water
Blended clay&asphalt, dark grey powder	15,000-30,000	Fresh-25,000 Salt-25,000	-do-	5	Dust response and water dispersible asphalt
Aluminum Stearate, white Powder	30-300	N/A	Negligible	None	Allowed in the manufacture of food container
Asbestos	15,000-30,000	-do-	Insoluble	2 fibres cc	Toxicity well documented for inhalation, handle with caution. Do not breath dust

Anhydride copolymer	150	Salt water 690	Appreciable	10	Avoid prolonged exposure to dust
Formulated polymers	9,000-18,000	Fresh-7.4 Salt-	Insoluble	10	Dry inert materials
'Formulated petroleum sulfate	1,500-6,000	Fresh- 5,400 Salt- 6,000	Insoluble	None	Almost totally non dispersible in water.
Polysaccharide	up 36,000	Fresh- 31,500	Appreciable	10	Easily biodegrade with time
Paraffin hydrocarbon	1,500-6,000	Fresh- 5,400 Salt- 6,000	Complete	None	Biodegradable
Cellulose etherpolymer	750-15,000	N/A	Complete	10	Drilling fluid with Drispac added has a toxicity of 4,600-7,400
Mica flakes	6,000-90,000	N/A	Insoluble	10	Toxicity should be nil as this flake are insoluble

Source: EIA (2012)

Table 2.5 shows the composition of a typical water-based mud system used in Nigeria. The varied components of the drilling mud are a focal point when analyzing the impact of mud and cuttings disposal into the environment (American Petroleum Institute, “Summary and Analysis of API Onshore Drilling Mud and Produced Water Environmental Studies,” API Bulletin D19, Washington DC,Nov.2007). On the average, the components that are used occasionally may have high level of toxicity and are normally used in smaller concentrations than those components that are used routinely.

TABLE 2.5 COMPOSITION OF TYPICAL WATER-BASED MUD (WBM)

Component	**Description**	**Cone .lb/Bbl**	**Application**	**Hazard/ Symptoms**	**Precautions**
Component	**Montomorillonite clay**	**15-25**	**1**	Inhalation causes accumulation of dust in the lungs and coughing	Breathing protections are won **during handling**
Component	**Barium sulphate**	**Up to 600**	**1**	Inhalation of dust causes **coughing**	**-do-**
Component	**Sodium carboxymethyl**	**2-6**	**1**	Coughing, shortness of	**-do-**

				breath	
Spersens	**Perrochrome lignosulfonate**	**2-6**	**1**	Harmful if taken internally, itching, coughing, shortness of breath	Hand gloves and breathing protections are won **during handling**
J Argisil	**Attapulgite clay**	**10-20**	**2**	**Inhalation causes accumulation of dust in lung, coughing**	**Breathing protection to be won**
Lime	**Calcium hydroxide**	**Up to 2**	**2**	Coughing, shortness of breath	**-do-**
Soda ash	**Sodium carbonate**	**-do-**	**2**	**Coughing**	Breathing protection, protection gloves and safety goggles are won

					during handling
Salt	**Potassium/sodium chloride**	**Up to 15**	**2**	**Coughing, shortness breath**	**-do-**
Polysal	**Cellulose polymer**	**1-3**	**2**	**Combustible**	**-do-**
Resinex	**Resin**	**2-4**	**2**	**Coughing**	Breathing equipment and gloves used. No smoking allowed on **location**

- Application:

1. Denotes components used routinely

2. Denotes components used occasionally

Source: S. I. Onwukwe 2011

2.1.4 FUNCTIONS OF DRILLING MUD

A properly designed and maintained drilling fluid performs essential functions during well construction such as transporting cuttings to the surface, preventing well-control issues and wellbore stability, minimizing formation damage, cooling and lubricating the drillstring and providing information about the wellbore.They include:

i. Remove the rock fragments, or drill cuttings, from the drilling area and transport them to the surface
ii. To cool and lubricate the drill string and drill bit.
iii. To control sub-surface pressures.
iv. To build an impermeable cake on the walls of the hole.
v. To support part of the weight of drill pipe and casing.
vi. To hold cuttings and weight materials in suspension when circulation is interrupted.
vii. To reduce to a minimum, any adverse effects upon the formation adjacent to the hole.
viii. Aids formation evaluation.
ix. Transmits hydraulic horsepower to the bit.

2.1.5 DRILLING MUD AS A WASTE

Drilling mud, drilling formation cutting, cement, spent chemicals from well completion / work- over, and acidization, as well as routine household solid and liquid wastes are some of the discharges from drilling rig platform.

Drilling mud containing several manufacture chemical additives may end up either as waste materials with the cuttings or as spent mud at the end of the drilling operations (Mbagwu, 1992). These cuttings consist mainly of clay, sand, sandstone, limestone and dolomite. The size of the cuttings may be up to 5mm, (George. 1980).

At the completion of the drilling operations, the drilling wastes whether harmful or not may go for refining or is ready for disposal.

2.2 GEOLOGICAL FORMATION OF THE NIGER DELTA

Stratigraphically, sediments and sedimentary rocks are deposited in six major basins and basement complexes in Nigeria. Onshore, these occupy about 178,000 square miles, roughly half the area of onshore Nigeria,M.Norman (2013).

These basins and basement complexes include:

(i) Abakiliki and Benue troughs;

(ii) Dahomey or Benin Basin;

(iii) Niger Delta Complex;

(iv) Sokoto base or embayment

(v) Bida or Middle Niger Embayment; and

(vi) Bornu Basin and adjacent parts of the Chad Basin.

Basically, the Niger Delta Complex (the major area under consideration), consists of three formations: ‘Benin’, ‘Agbada’ and ‘Akata’ formations, (Etim, 1994). They are believed to have been laid down under continental, transitional and marine environment.

The Agbada formation lies inter—bedded between the Benin and the Akata formation. This information is the major hydrocarbon reservoir in the Niger Delta. The Benin formation is the youngest of the three formations named above.

It is believed to contain more than 90% sand with a few shaly inter-calations. The Benin formations directly overlie the Agbada formations. Today, according to SPDC research, very little hydrocarbon has been associated with this formation. It is generally water bearing. The ‘Akata’ formation is not exposed on shore. It is Over laid by the ‘Agbada’ formation. This formation is composed mainly of marine shales, but also contains sandy and silly beds, which are thought to have been laid down by turbidities and continental slope, channel fills. The ‘Akata’ formation is believed to be the major rock for the Niger Delta Complex hydrocarbon, (M.Norman,2013). Figure2.1 is a schematic illustration showing formations.

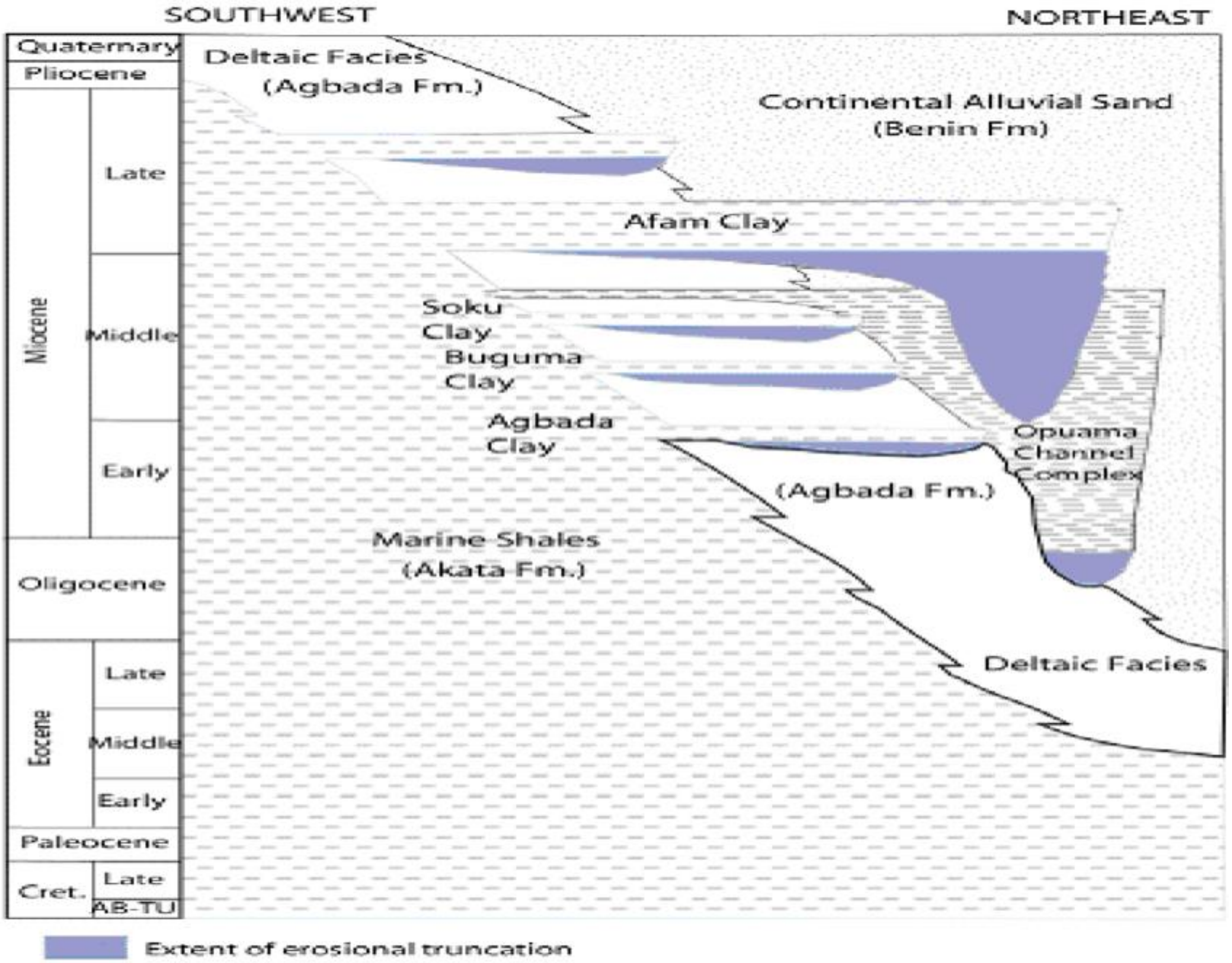

FIGURE 2.1: STRATEGRAPHIC COLUMN SHOWING THE THREE FORMATIONS OF THE NIGER DELTA

Source: Geology Department, UNIBEN

2.3 DRILL CUTTINGS

Drill cuttings are inert fragments of rocks and fine solids penetrated while drilling a hole and brought out to the surface by the drilling mud, (Jodie, 1990). The cuttings consist mainly of clay, sand, sandstone, limestone, dolomite, (Princewill. 1992). The sizes of these fragments depend on the type of drilled rock and the utilized bit. These are separated from the mud by the shale shaker, desander, desilter and cleaner prior to discharge into the mud pits.

The potential sources of pollution of drilling mud and cuttings arise from (Josh, 2019)

i. Spillage and blow-out during drilling (accidental discharges);
ii. Penetration of drilling mud into the sub-surface fresh water aquifer;
iii. Unsound disposal of un-recycled or spent drilling mud and drill cuttings;
iv. Operational routine emission

2.4 ROCK PROPERTIES

2.4.1 POROSITY

Porosity of reservoir is the property that tells how porous a rock is. It is also defined as a measure of the capacity of reservoir rocks to contain or store fluids. The porosity is genetically classified basing on standard sedimentologic description of reservoir rock; there are primary and secondary porosity.

(a) The primary porosity types are:

i) Inter-particle- In this type by which rock content was quickly lost in muds and carbonate sands through compaction and cementation respectively. This type is mostly found as siliciclastic sands.

ii) Intra particle porosity by which the porosity is made of interiors of carbonate skeletal grains.

Secondary porosity, the porosity formed after deposition leads to other couple of reservoirs types.

i) Dissolution porosity type is made of carbonate dissolution and leaching. It is also called carbonate reservoirs.

ii) Fracture porosity which is characterized by not being voluminous.

Porosity can also be classified basing on rock morphology. There are three types of morphologies to the pore spaces which are:

a) Caternary in which the pore open to more than one throat passage

b) Cul-de-sac in which the pore open to only one throat passage

c) Closed pore in which there is no connection with other pores.

2.4.2 TOTAL POROSITY

Total porosity expresses the pore spaces and pore system connected and not connected themselves. The total porosity is the one found in well logging.

$$Total\ porosity = \frac{void\ volume}{bulk\ volume} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .2.1$$

2.4.3 EFFECTIVE POROSITY

It is used in reservoir engineering calculations.Effective porosity is defined as the ratio of the inter-connected pore volume to the bulk volume of a material.

Generally, in core analysis, the effective porosity is the one measured and is performed on full diameter core. It may he calculated from the principle:

$$Effective\ porosity = \frac{E}{axb} \times 100 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.2.2$$

E = Effective pore volume, (cm^3)

a = Cross-sectional area, (cm^2)

b = Length of core sample and volume of fluid in pore space:

2.5 PERMEABILITY(k)

Permeability, capacity of a porous material for transmitting a fluid; it is expressed as the velocity with which a fluid of specified viscosity, under the influence of a given pressure, passes through a sample having a certain cross section and thickness. Permeability is largely dependent on the size and shape of the pores in the substance and, in granular materials such as sedimentary rocks, by the size, shape, and packing arrangement of the grains.Darcy's law, as refined by Morris Muskat, in the absence of gravitational forces and in a homogeneously permeable medium, is given by a simple proportionality relationship between the instantaneous flux {\displaystyle q}q (q = Q/A, unit: (m3 of fluid/s) / m2) through a porous medium, the permeability {\displaystyle k}k of the medium, the dynamic viscosity of the fluid {\displaystyle \mu }\mu , and the pressure drop {\displaystyle \nabla p}\nabla p over a given distance (Wikipedia 2018).

The numerical quantity is the permeability and is measured in darcies.

The mathematical equation may be written as:

$$Q = \frac{K\Delta\nabla \mathrm{P}}{\mu L} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots ...(2.3a)$$

$$K = \frac{Q\mu L}{\Delta\nabla \mathrm{P}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots ...(2.3a)$$

Where,

Q = Flow rate, cc/sec

K= Permeability, Darcies

A = Area of sand lace or flow area, cm

L = Length of sand section or flow length, cm

AP = Pressure drop or gradient, atm

|i= Viscosity of flow fluid, centipoises.

Atwood, (1964) stated that permeability of a material is an indication of the productivity or capacity of a formation rock. Permeability measurement can be determined in the laboratory using perimeters, (Etim,1994), when the following factors are known.

(i) Dimension of the rock formation

(ii) Flow rate and pressure

(iii) Viscosity of the fluid

(iv) The fluid conductance capacity of the Formation rock.

2.6 SLIPPAGE EFFECT

The permeability of a sample to a gas varies with the molecular weight of the gas and the applied pressure, as a consequence of gas slippage at the pore wall. Klinkenberg[1] determined that liquid permeability (kL) is related to gas permeability (kg).The correction parameter b is determined by conducting the test at several flowing pressures and extrapolating to infinite pressure. Alternatively, one can use an empirical correlation established by Jones[2] to estimate b.

"From the above work, the permeability equation of a medium to a single liquid phase completely filling the pores is given by:

$$K_L = \frac{K_g}{1 + \frac{b}{p}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2.4a)$$

$$K_L = K_\infty(1 + \frac{b}{p}) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2.4a)$$

Where

K_L = permeability of liquid passing through the former chamber.

b = Slippage effect, and it is a constant for a given medium.

P = Mean pressure

K_g= permeability of gas

K_∞ = Klinkenbberg permeability

Permeability is strongly affected by grain size, grain shape and orientation, (Davies, 2016). The reservoir permeability values are usually lower than those of core analysis. This is because as overburden increase, permeability decreases. Whereas, if the effect of overburden pressure is ignored, reservoir permeability values may approach core analysis values, (Mathews 2006)

2.7 MUD CIRCULATING AND CUTTINGS SEPARATION PROCESS

The circulation system on the rig is the system that allows for circulation of the Drilling Fluid or Mud down through the hollow drill string and up through the annular space between the drill string and wellbore. It is a continuous system of pumps, distribution lines, storage tanks, storage pits, and cleansing units that allows the drilling fluid to fulfill its primary objectives (these will be discussed later in this lesson). The mud pumps of the circulation system and the drawworks of the hoisting systems are the two largest draws on the power from the power system.Drilling fluid is mixed in the mud pits and pumped by the mud pumps through the swivel, through the blow out preventer (not part of the circulation system) down the hollow drill pipe, through holes (Jet Nozzles) in the bit, up the annular space between drill pipe and wellbore (where it lifts the rock cuttings), to the surface, through the Solids Control Equipment (Shale Shaker, Desander, and Desilter), and back to the mud pits (OSHA 2015).

FIGURE 2.2: MUD CIRCULATING SYSTEM

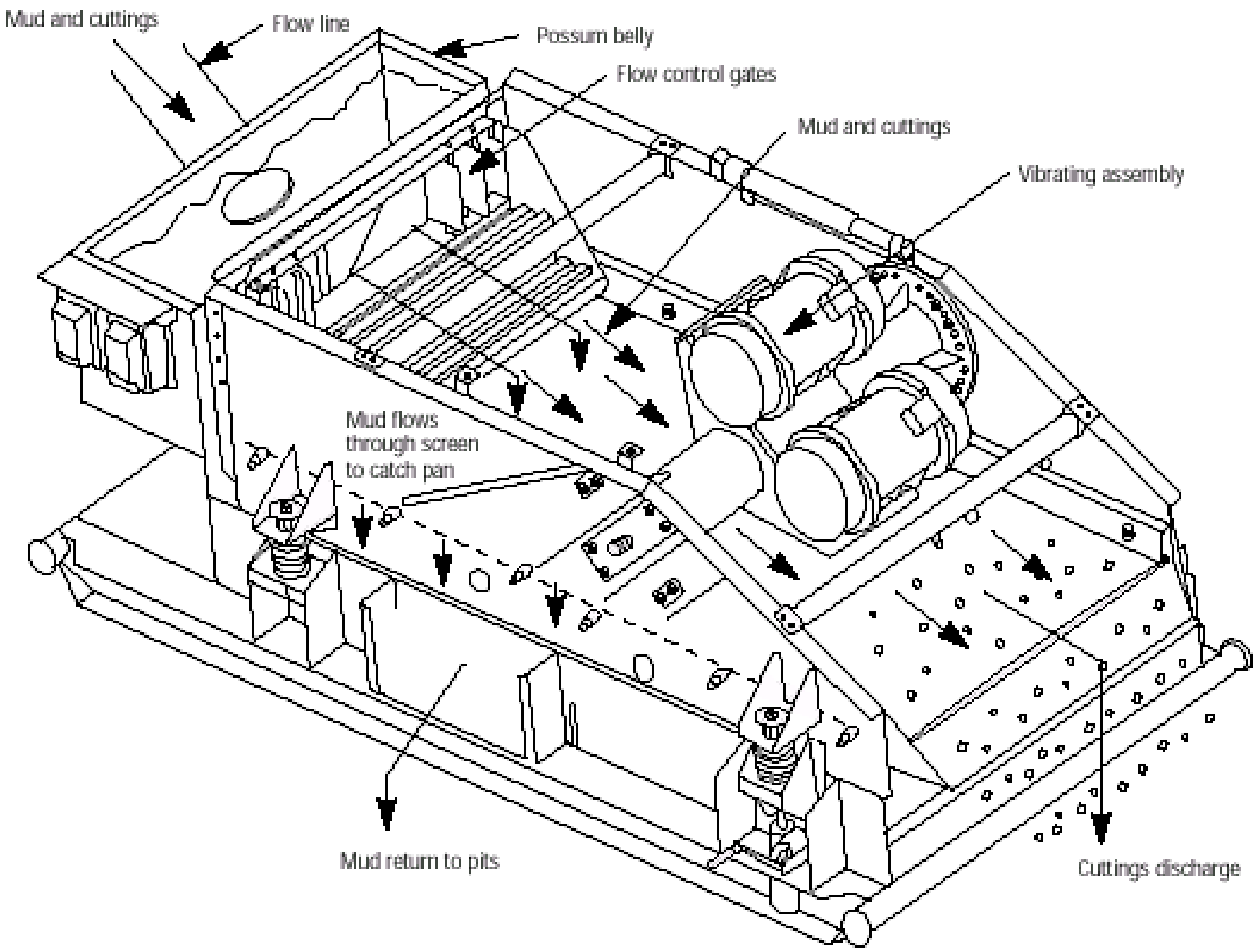

FIGURE 2.3: SCHEMATIC OF A SHALE SHAKER

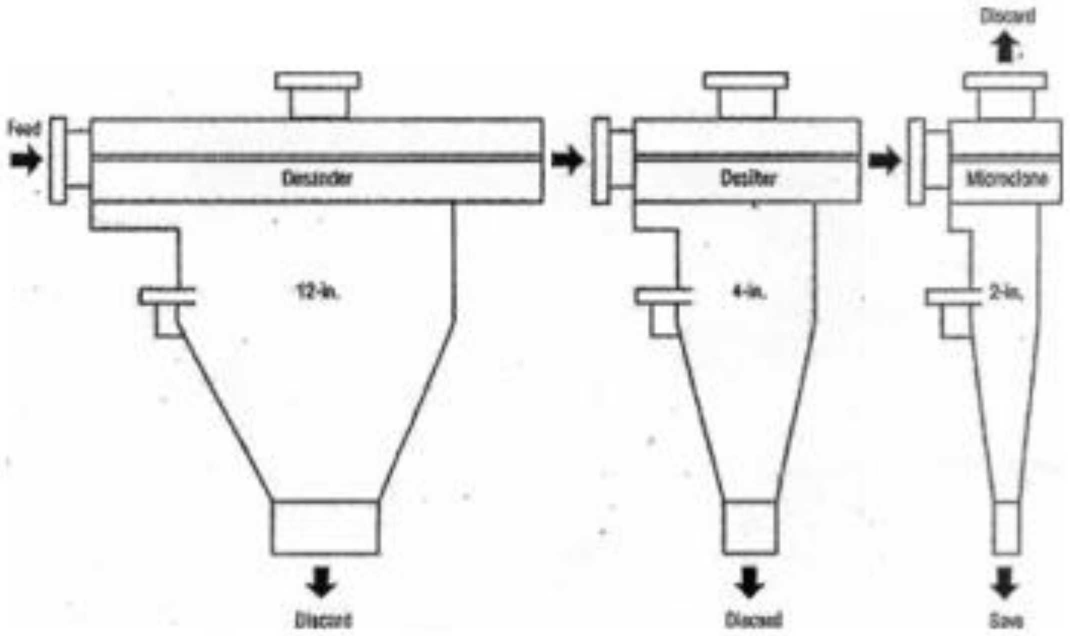

FIGURE 2.4: SCHEMATIC OF A HYDROCYLONE

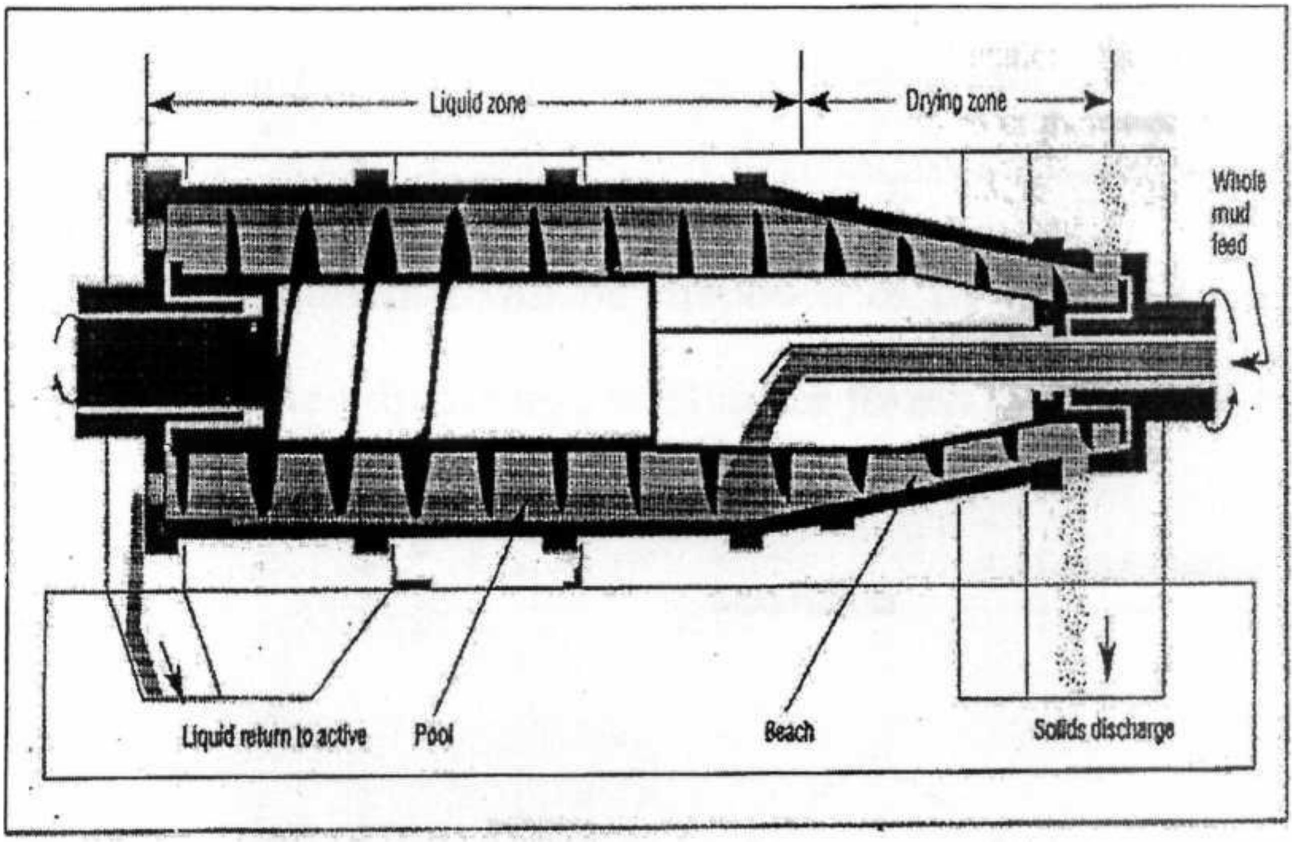

FIGURE 2.5: SCHEMATIC OF A ROTATING CENTRIFUGE

Where secondary treatment is used, the partially dried cuttings may be further processed using specialized equipment called cutting dryers followed by additional centrifugal processing. Figure 2.6 illustrates the most advance type of equipment in use in most oil industries today. Cutting dryers allows wet cuttings, expelled from a shale shaker to be centrifuged and dried before discharged. The design is a configuration of a fine-screen and a rotating basket that generates centrifugal forces. (OSHA 2015)

This way, most of the mud is removed from the cuttings and returned to the active circulating system. Where no secondary treatment is available, partially dried cuttings output will be disposed of by any suitable means such as the ones discussed in chapter four.

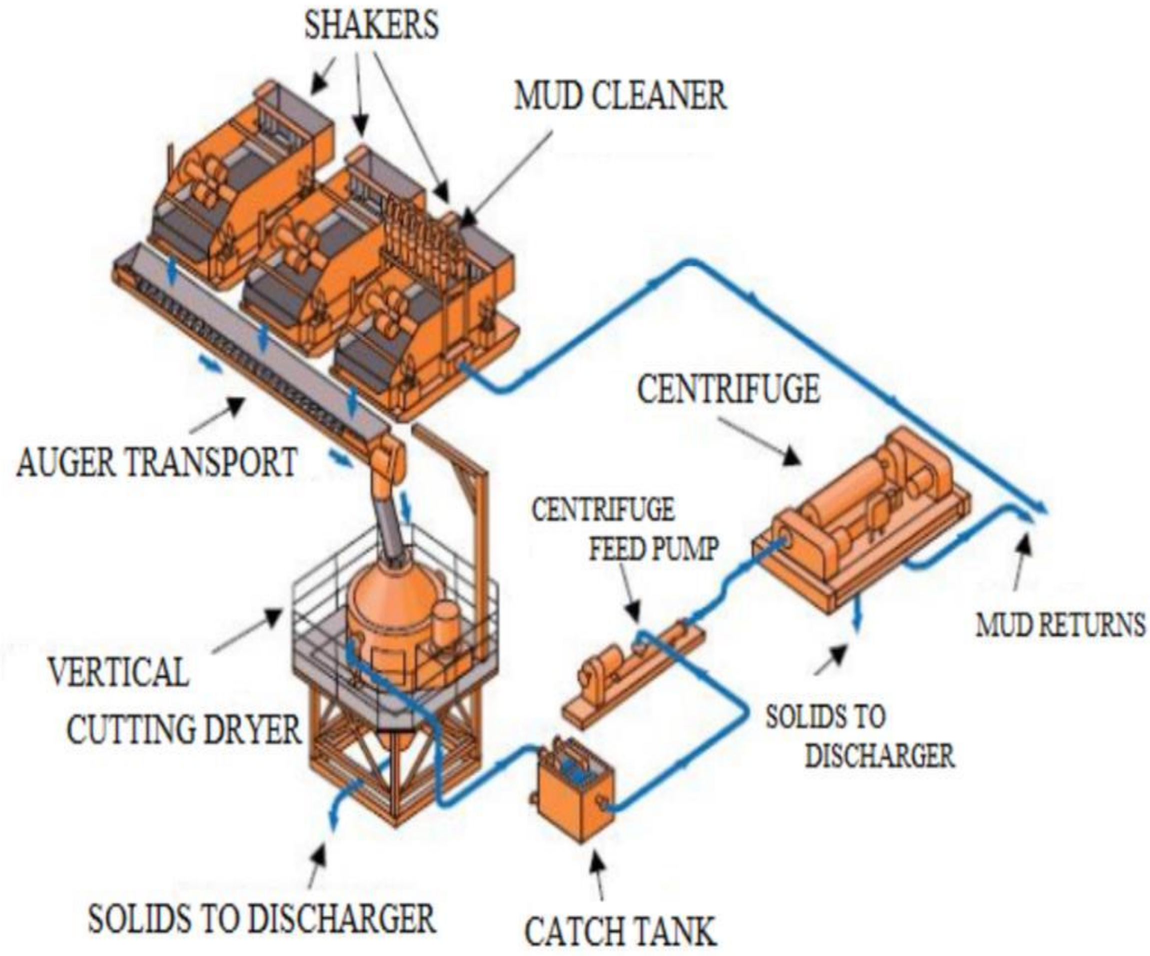

FIGURE 2.6 SCHEMATICS OF CUTTING DRYERS

2.8 EFFECTS OF DRILLING WASTES

Many of the wastes associated with oil and gas well. drilling activities have the potential to impact the environment. The physical and chemical properties of the drilling wastes influence its hazardous characteristics and environmental impact ability (Onwukwe Stanley Ibuchukwu,2012).The most common measure of the potential environmental impact of a material is its toxicity. Table I gives guidance for possible environmentally significant constituents of drilling wastes. The potential impact depends primarily on the material, its concentration after release and the biotic community that is exposed. This also depends on the length of exposure to a substance. The length of exposure to a substance can be divided into descriptive types. Exposure that causes an immediate effect is called acute, while repeated long-term exposure is called chronic. Most concentrations encountered during drilling activities are relatively low, therefore the environmental impact is generally observed only after chronic exposure. Also, the heavy metals associated with the constituents of drilling fluid additives are of concern, although their potential to leach away from the pit and contaminate the groundwater is limited by their low concentration and low solubility]. A typical elemental composition of common constituents of drilling mud is given in Table III. A number of studies have been conducted on the impact of these elements.

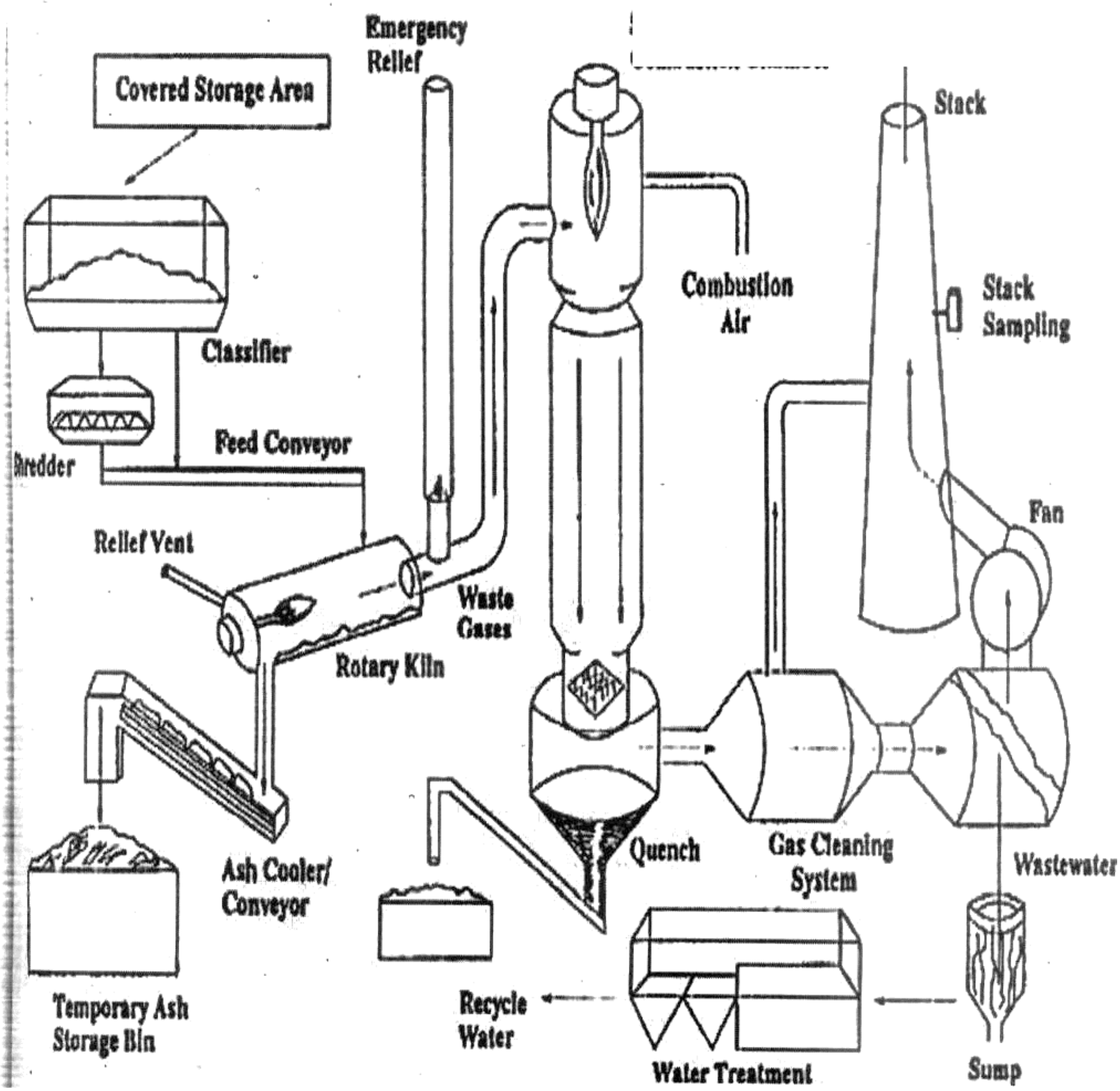

FIGURE 2.7: SHOWS THE FLOW DIAGRAM OF A ROTARY KILN

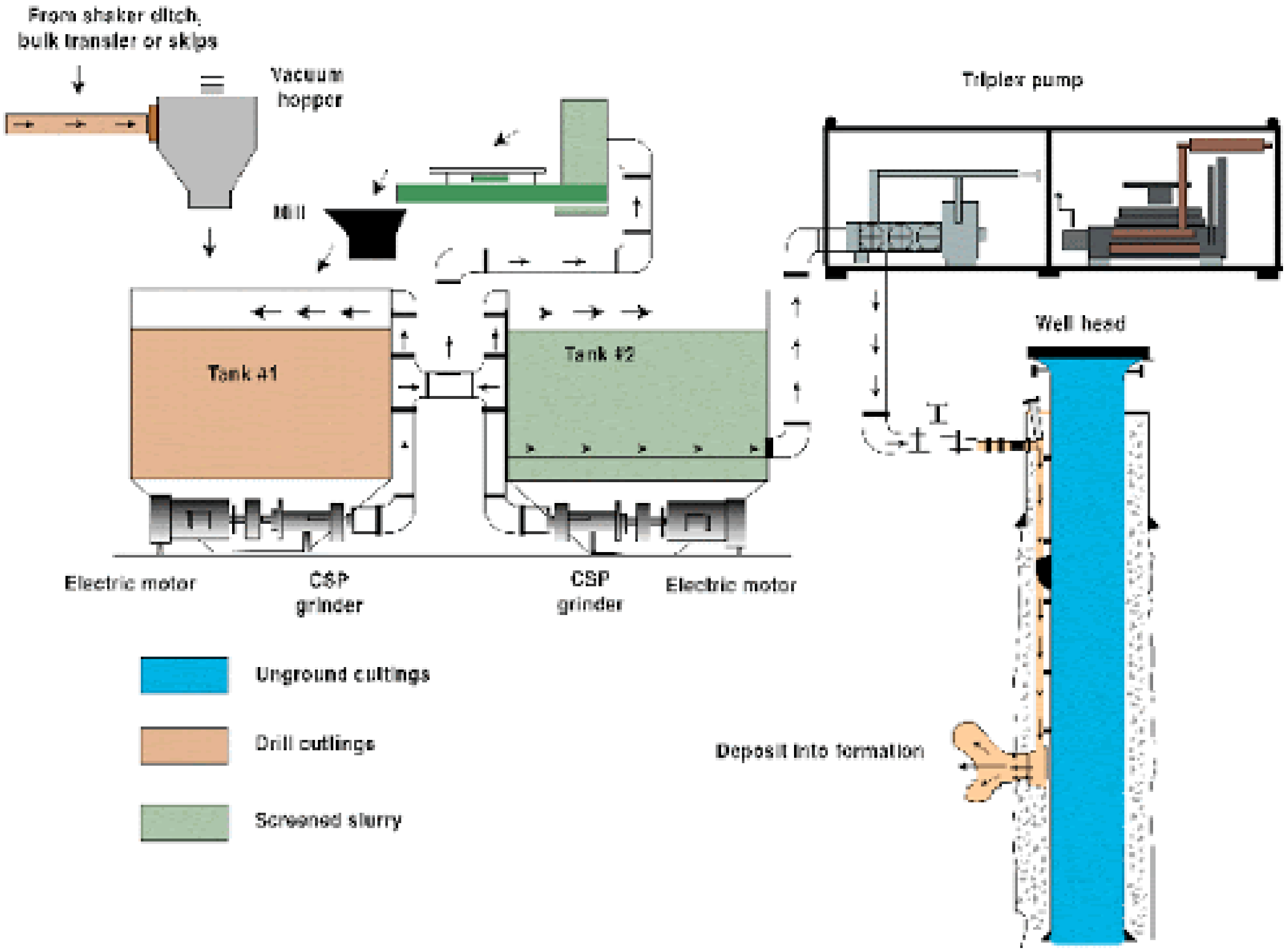

FIGURE 2.8: OFFSHORE CUTTINGS RE-INJECTION EQUIPMENT

CHAPTER THREE

RESEARCH METHODOLOGY

Two measurement systems were used during the experiments to characterize drilling fluids. A Fann 35 viscometer was used to measure the viscosity and an Anton Paar MRC rheometer to measure other rheological parameters.

3.1 Fann 35 Viscometer

In the oil industry the Fann 35 viscometer is the measuring device referred to in the standards API 13D and ISO 10414 (International-Standard 2011). The device was primarily used to keep track of the fluid condition during preparation of the fluids for the flow-loop experiments, and the actual execution of the flow-loop experiments. It is based on a Couette rotational viscometer and the fluids are tested in the annular space between the measuring bob and an outer rotating cylinder. The outer cylinder exerts a viscous drag force to the fluid. The creating torque is measured with the bob and transmitted to a dial reading via a torsional spring. The Fann 35 is operated with six different rotational speeds (600 rpm, 300 rpm, 200 rpm, 100 rpm, 6 rpm, 3 rpm), based on the API recommended practice (API 2010). The measurement procedure starts with a pre-shear period at 600 rpm, afterwards the measurements are taken with decreasing rotational speeds when the dial reading is stable. The final part of the measurement consists of gel-strength measurements after 10 s and 10 min of rest. Measurements were taken at temperatures of 28 °C and 50 °C with a R1 rotor sleeve, a B1 bob, and a F1 torsion spring configuration. 28 °C was the operational temperature of the flow loop and 50 °C the recommended temperature of the standard.

3.2 Anton Paar Rheometer

The Anton Paar MCR 102 and 302 rheometers used in this study provide high accuracy due to high precision air bearings and a powerful, synchronous EC motor drive. For the measuring system a CC27 bob cup set-up (Figure 3) was chosen to minimize evaporation effects at measurements with elevated temperatures. In contrast to Fann 35 viscometers the rheometer enables to measure in the low and very low shear-rate range, and can be operated in oscillation mode. Additionally measurements can either be shear stress or shear rate controlled. A software package gives full control over test settings and provides analysis options. To ensure homogeneous fluids and similar test conditions in the laboratory over several days of testing, a pre-treatment procedure was established.

Every morning the fluid batch was mixed in a Waring blender at about 6000 rpm for 10 minutes, followed by a rest time of 1 hour. From this fluid batch smaller samples were used for the experiments. After each conducted measurement the sample was replaced with an unused one. The temperature was controlled and adjusted by a Peltier element.

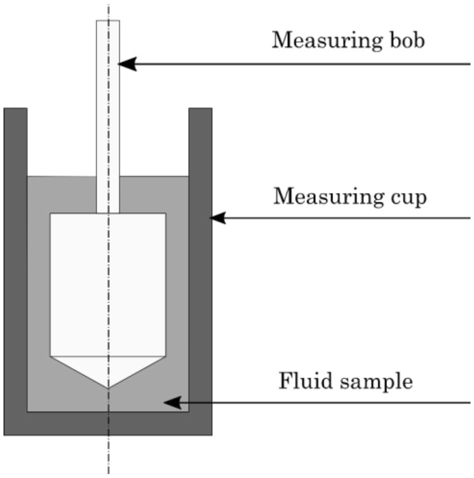

Figure 3. CC27 set-up used in Anton Paar rheometer experiments.

3.3 Rheometer Experiments

To determine viscoelastic properties of drilling fluids different experiments were conducted. All tests were done at temperatures of 28 °C and 50 °C, and some tests additionally at 10 °C. The selection of the different tests described in the forthcoming paragraphs was mainly based on previous studies (Torsvik et al. 2014, Ytrehus et al. 2014).

3.3.1 Flow curves

Flow curves are measured by either controlled shear rate or controlled shear stress and show the viscosity function of the material. Simple flow curves were conducted with linear increasing shear rate from 1 – 1200 1/s and 120 measuring points.

To enhance understanding of the low shear behavior, low shear flow curves in the range of 0.01 – 100 1/s and 0.001 – 100 1/s were done with a logarithmic increase and constant measuring-point duration of 2 s, which resulted in 80 s of total measurement time. Additionally, the 0.001 – 100 1/s experiments were performed with a decreasing measuring-point duration from 30 s to 2 s to avoid transient effects. The total measuring time accounted to 640 s.

3.3.2 Amplitude-sweep tests

Amplitude-sweep tests are oscillatory tests with a constant frequency and increasing amplitude. The frequency was set to 10 1/s and the amplitude increased from 0.001 to 100 % strain with a slope of 5 measuring points per decimal, accounting to 26 measuring points. The outcome of the measurements are curves of the storage modulus (G') and the loss modulus (G''), characterizing the materials elastic, viscous, or viscoelastic behavior. If G' > G'', the elastic behavior dominates over the viscous behavior and the sample shows a solid like character. The relation of the storage to the loss moduli then gives a measure of the stiffness of the material. In the opposite case where G" > G', the viscous behavior is dominating and the sample acts liquid like. If the curves are crossing each other (G' = G"), the point is called *flow point*. The ratio between G" and G' is called the loss factor tan . When tan > 1, the sample shows a more viscous behaviour, and respectively a more elastic behaviour when tan < 1. The length of the linear viscoelastic range (LVER) indicates the minimum strain to initiate breakage of the inner structure and determines the strain value for 3-interval-thixotropy tests.

3.2.3 Interval-thixotropy-tests

3-Interval-thixotropy-tests help to understand the structure-rebuilding character of materials. The tests are performed in 3 steps. During the rest interval the sample is oscillated at a constant frequency and a strain value inside the LVER, as obtained from an amplitude sweep. In the load interval, the sample is sheared at a constant shear rate to break the internal structure. During the terminatory recovery interval, the sample is again oscillated at the same parameters from the rest interval, to investigate the structure rebuilding character of the sample. Test parameters were selected as presented in Table 2.

3.2.4 Temperature-sweep tests

Temperature-sweep experiments show the viscosity dependency of the temperature. The samples were sheared at a constant shear rate of 100 1/s while the temperature was increased from 5 – 50 °C with a slope of 1 K/min.

3.2.5 Shear-stress sweep tests

Experiments with controlled shear stress are used to determine the yield stress of a material. During the tests the shear stress was increased logarithmically from 0.1 – 1000 Pa, with 200 measuring points and a measuring-point duration of 1 s. The yield stress can be estimated where the strain-stress curve deflects from linearity in a shear strain vs. shear-stress diagram.

Table 2. Experimental settings for 3-interval-thixotropy-tests, γ represents the strain and ˙ the shear rate.

	Rest interval	**Load interval**	**Recovery interval**
1	= 0.1 % 10 measuring points, 20 s measuring point duration, 200 s measuring time, f = 10 1/s	˙= 10 1/ 10 measuring points, 0.1 s measuring point duration, 1 s measuring time	= 0.1 % 10000 measuring points, 10 s measuring point duration, 100.000 s measuring time, f=10 1/s

3.4 Definition of Yield Stress and Yield Point

The *yield stress* is an important parameter for structured fluids like drilling fluids (Barnes 1999, Maxey 2007, Boisly et al. 2014). Its value is dependent on the measuring method and/or the regression method and not a material constant (Dinkgreve et al. 2016). Different methods to determine a value are widely discussed in the literature (Cheng 1986, Power and Zamora 2003, Møller, Mewis, and Bonn 2006). In a flow curve, the yield stress is the stress value at zero shear rate. As it is not possible to measure at zero shear rates, a typical method is to measure flow curves and extrapolate to a shear rate of 0 1/s. Modern rheometers allow to measure at very low shear rates which makes the procedure more precise, and also include other yield-stress measurement options, such as amplitude sweeps, or shear-stress sweeps.

In the drilling industry the *yield point* refers to a value obtained by calculations based on Fann 35 viscometer measurements using two high shear values, following the API
(2010).

3.5 Drilling Fluid Composition

During the study 4 different fluids were used, one water-based fluid called KCl fluid, and three oil-based fluids, called OBM A, OBM B, and OBM C. The three OBMs are the commercial *Versatec* fluids by MI-Swaco. The components are shown in Table 3 together with the density and oil-water ratio. All fluids are actual drilling fluids used in drilling operations. After use in the field they were cleaned, reconditioned and shipped to the research facilities of NTNU and SINTEF in Trondheim. Adjustments to the initial *Versatec* fluid had to be made to enable

optimal handling in the separation machine and with the mud pump during flow-loop experiments. The viscosity was too high to separate the sand particles from the fluid with the pre-assembled mesh in the separation machine, also the pump could not pump the fluid. A change in mesh size and dilution from an initial density of 1.37 g/cm^3 with the corresponding base oil EDC 95-11 were chosen as a solution for the problem and resulted in OBM A and OBM B. The problems with the separation machine and the dilution of the fluids resulted in an altered oilwater ratio. Another try was made to conduct experiments with a higher viscosity and density fluid. After finishing the experiments with OBM B, Bentone 128 was added to OBM B and resulted in OBM C. The density was not highly affected by the Bentone 128, but the viscosity increased.

The KCl fluid has the commercial name *Glydril* and was initially planned to match OBM C. During preparation of the flow-loop experiments with the KCl fluid, the fluid was not moved enough in the tank, and heavy particles started to settle on the bottom of the fluid tank. Additionally the fluid level decreased to an insufficient small amount to conduct experiments, due to evaporation. It was decided to add water and xanthan gum in amounts to match OBM B, which was successfully accomplished.

It is not possible to design oil-based and water-based drilling fluids with exactly the same viscosity profile, but it is possible to get quite close. For the comparative hole cleaning experiments of the project, the OBM B and the KCl fluid were chosen. Figure 4 shows their flow curves measured with a Fann 35 viscometer. Both fluids show a similar trend in a shear-rate range between 0 1/s and about 500 1/s (0 to ca. 300 rpm in a Fann 35 viscometer).

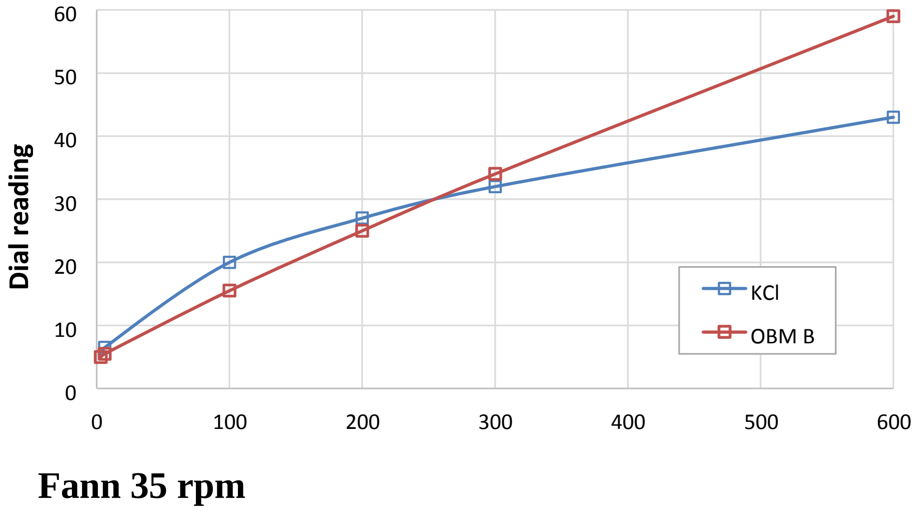

Figure 4. Fann 35 measurements for OBM B and the KCl fluid for 28 °C.

Table 3. Components and properties of OBM A, OBM B, OBM C, and the KCl fluid.

		OBM A	OBM B	OBM C	KCl
Components		Base oil EDC 95-11 Barite Salt ($CaCl_2$) Organophillic clay (Bentonite) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent	Base oil EDC 95-11 Barite Salt ($CaCl_2$) Organophillic clay (Bentonite) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent	Base oil EDC 95-11 Barite Salt ($CaCl_2$) Organophillic clay (Bentonite) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent Bentone 128	Fresh water KCl Glycol Xanthan gum Polyanionic cellulose Starch Soda ash Barite
Oil-water ratio		Initially 80/20	Initially 80/20	95/5	Not applicable
Density [g/cm^3]		1.11	1.26	1.27	1.19
Regression parameters 28 °C	τ_0	2.9124	3.271	9.9282	-
	K	0.040533	0.80284	0.14637	0.42975
	n	0.88813	0.10001	0.7983	1.0362
	R^2	0.99975	0.99849	0.99947	0.99596
Regression parameters 50 °C	τ_0	1.8705	2.2522	4.9226	-
	K	0.037147	0.054883	0.13747	0.49331
	n	0.84388	0.1999	0.75246	0.55456
	R^2	0.99935	0.99643	0.99984	0.99426

Table 4. Fann 35 dial readings for OBM A, OBM B, OBM C, the KCl fluid, and ES values for the oil based fluids.

Fluid	**Temperature [°C]**	**Fann 35 rotational speeds [rpm]**								**ES**
		600	**300**	**200**	**100**	**6**	**3**	**10 s**	**10 min**	
OBM A	28	40	23	17	11	3.5	3	-	-	Not measured
	50	-	-	-	-	-	-	-	-	
OBM B	28	59	34	25	15.5	5.5	5	-	-	800-900
	50	34	19	14	9	3	2	3	5	
OBM C	28	94	56	41	26	8	7	11	22	1500-1900
	50	64	39	29	19	6.5	6	9	19	
KCl	28	43	32	27	20	6.5	5	5	6	Not applicable
	50	36	27	23	17	5	4	4	5	

CHAPTER FOUR

DISCUSSION AND ANALYSIS OF RESULTS

4.1 Preconditioning Procedures for the Rheological Characterization of Oil-Based and Water-Based Drilling Fluids

The time and stress dependence of thixotropic fluids is characterized by decomposition and regeneration of the samples structure. The measurement outcome will depend on which phase the sample`s structure is in at the start of the experiment. Therefore it is important to have a consistent pretreatment procedure when conducting rheological measurements on such fluids. The shear history can affect the results, and influence reproducibility.

Flow curves and amplitude-sweep tests were conducted using a Fann 35 viscometer and an Anton Paar MCR 302 rheometer with various pretreatment procedures to quantify the effects of pre-shearing, no pre-shearing, and rest on the results. The first set of experiments was done without pre-shear, and different waiting times of 1 hr, 2 hr, 4, hr, 6 hr, 8 hr, and 24 hr. The second set of experiments included a 10 min pre-shear interval (600 rpm, 1022 1/s) after the waiting time, and prior to the measurement. All experiments were done at temperatures of 28 °C and 50 °C with OBM C (Table 5).

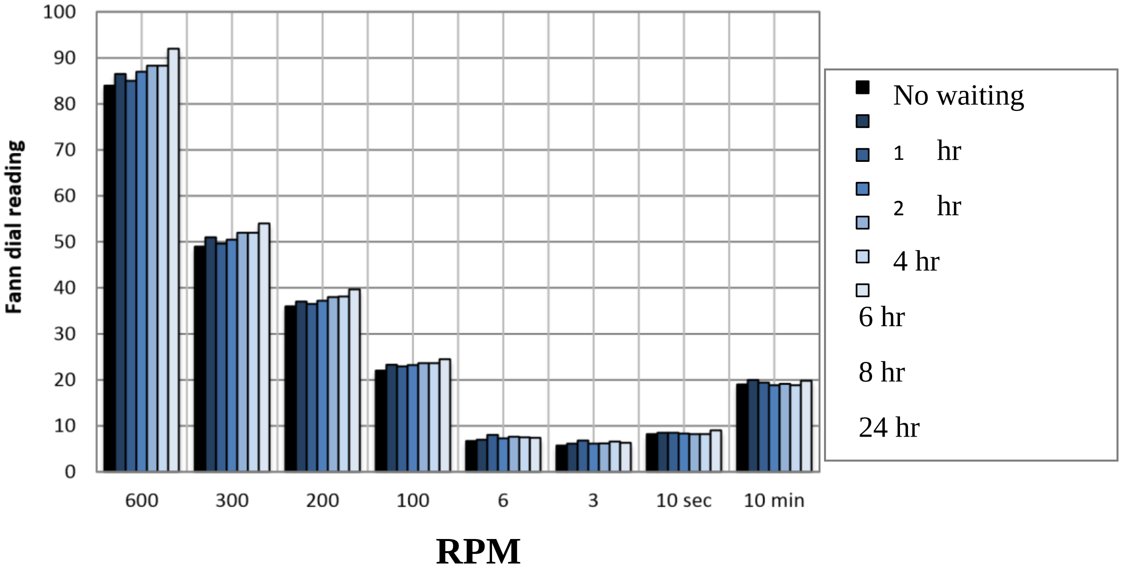

Figure 5. Fann 35 dial readings of OBM C taken without pre-shear at a temperature of 28 °C. Waiting times as indicated, the lighter the color, the longer the waiting time.

Table 5. Test matrix for preconditioning experiments

Set	Procedure
1 – No pre-shear	Waiting time of 1 h, 2h, 4 h, 6 h, 8 h, 24 h No pre-shear
2 – Pre-shear	Waiting time of 1 h, 2h, 4 h, 6 h, 8 h, 24 h 10 min pre-shear (600 rpm, 1022 1/s)

Figure 5 shows a plot of Fann 35 dial readings without pre-shear at 28 °C. The difference in dial-reading values for 600 rpm was a 9 % increase from no waiting time to 24 hr waiting time, and between 2 % and 10 % for 300 rpm to 100 rpm. The values for 6 rpm and 3 rpm appeared stable and not effected by the waiting time. This is also true for the 10 s and 10 min gel-strength readings. The fluid has been sheared significantly before these last four measurements which could be an explanation for the stable values.

A flatter trend is visible for experiments with pre-shear, as shown in Figure 6. The maximum increase in dial reading values was 4 % (at 600 rpm).

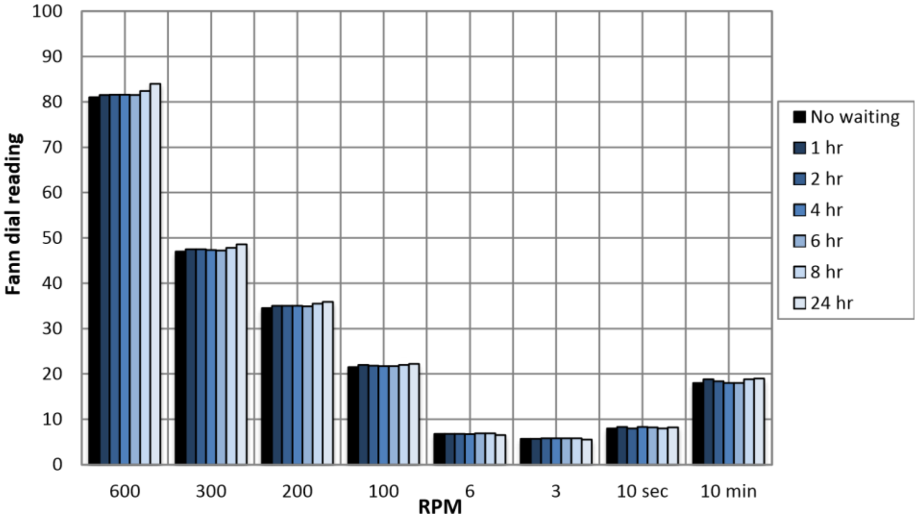

Figure 6. Fann 35 dial readings of OBM C taken with pre-shear at a temperature of 28 °C. Waiting times as indicated, the lighter the color, the longer the waiting time.

When comparing Figure 5 and Figure 6, it is clear that pre-shearing leads to more reproducible results, except for the measurements with the longest waiting period of 24 hr. The same trends

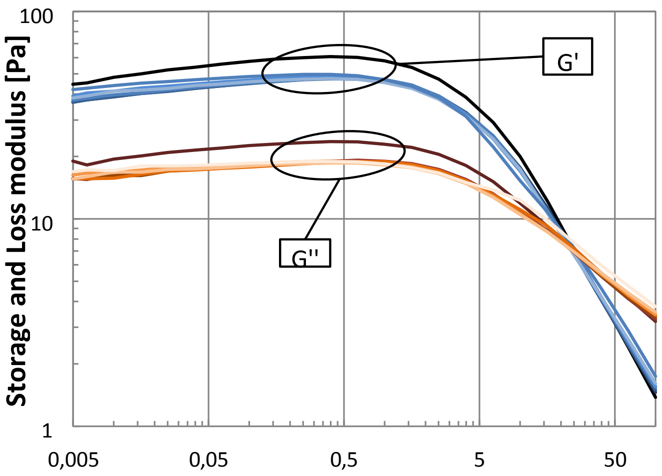

Figure 7. Amplitude sweeps without pre-shear of OBM C at 28 °C. Waiting times as indicated, the lighter the color, the longer the waiting time, measured with Anton Paar MCR 302.

were seen in the 50 °C measurements and also in the flow curves conducted with the Anton Paar rheometer, which are not presented here but can be seen in paper 1.

Figure 7 shows amplitude sweeps without pre-shear and Figure 8 shows amplitude sweeps with pre-shear for 28 °C. When comparing the two graphs it is observed that the reproducibility was improved by pre-shearing. The curves in Figure 8 are much closer to each other than the curves in Figure 7. The cross-over point did not change, but the end of the LVER was moved to higher strain values, meaning that the fluid was able to tolerate more strain before the structure started to break down. Figure 9 and Figure 10 show the amplitude-sweep curves for a temperature of 50 °C. Here pre-shearing also resulted in more identical curves than without pre-shearing, indicating an increased reproducibility. At the higher temperature the cross-over point was shifted to ca 20 % higher strain values, and the LVER increased as well.

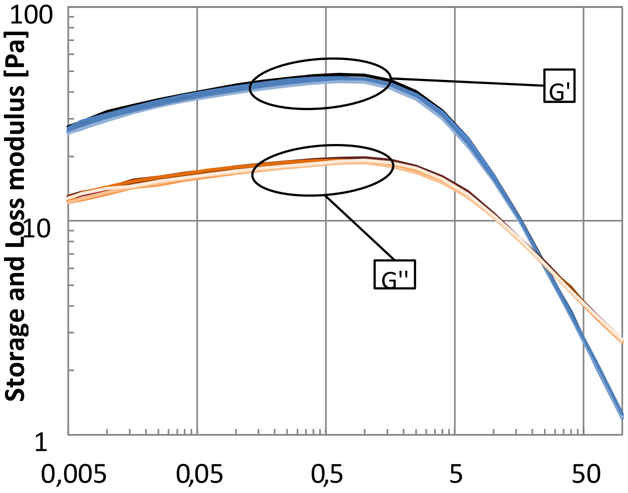

Figure 8. Amplitude sweeps with pre-shear of OBM C at 28 °C. Waiting times as indicated, the lighter the color, the longer the waiting time, measured with Anton Paar MCR 302.

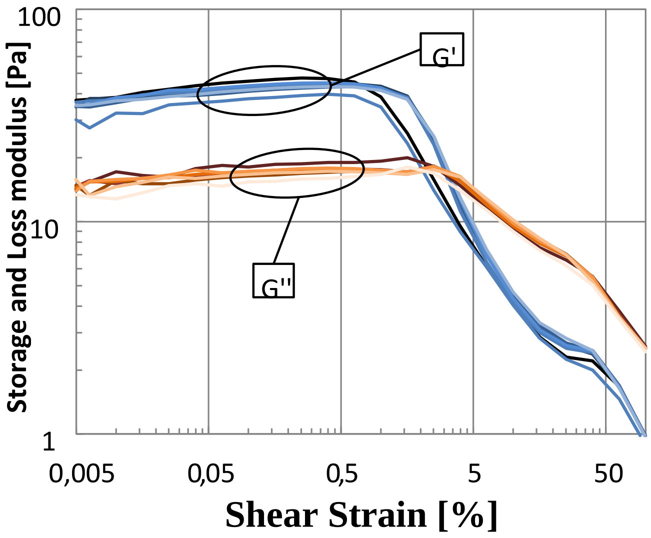

Figure 9. Amplitude sweeps without pre-shear of OBM C at 50 °C. Waiting times as indicated, the lighter the color, the longer the waiting time, measured with Anton Paar MCR 302

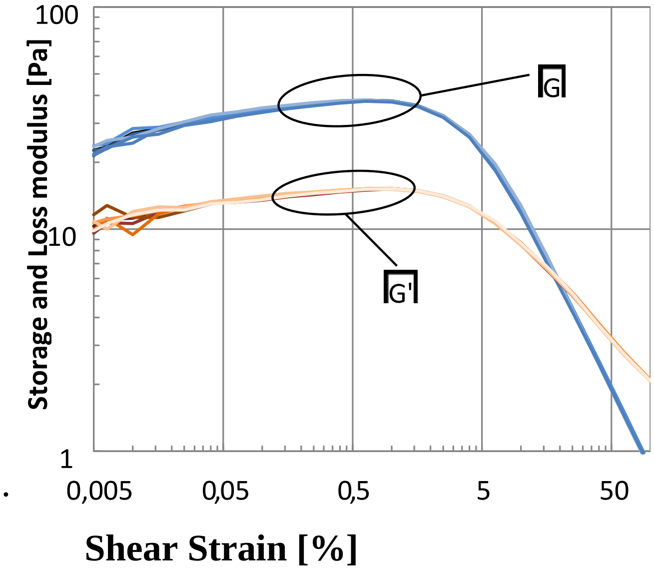

Figure 10. Amplitude sweeps with pre-shear of OBM C at 50 °C. Waiting times as indicated, the lighter the color, the longer the waiting time, measured with Anton Paar MCR 302.

A similar investigation of the pre-conditioning effects like those of the oil-based fluid was performed with water-based fluids containing laponite. The fluids were aqueous suspensions of laponite with varying concentrations of xanthan gum and NaCl. The aim of the investigation was to quantify the impact of pre-shear and waiting time, and how this is affected by temperature, salinity and the addition of polymer. The composition is shown in Table 6. Pre-shearing was done for 2 min at a shear rate of 1020 1/s. The preshearing time was reduced from 10 min to 2 min, because in the experiments with OBM C it was seen that 2 min is enough. For experiments with waiting time, a period of 24 hr was chosen.

Table 6. Fluid composition of laponite suspensions.

Fluid	1		2		
Component	a	b	a	b	c
Water	Deionized water				
Laponite RD [wt %]	1.5	1.5	1.5	1.5	1.5
Xanthan Gum [wt %]	0	0	0.1	0.1	0.1
NaCl [g/l]	0	0.6	0	0.6	12
NaOH [mmol/l]	0.1	0.1	0.1	0.1	0.1
Biocide	0	0	0.1	0.1	0.1
pH value	10.07	10.31	10.51	10.21	9.31
Conductivity [mS]	0.576	1.525	0.546	1.382	17.7

The Fann 35 results showed that pre-shearing for fluids without salt content was not sufficient to reproduce the values obtained without waiting time. Pre-shearing was more efficient for a NaCl concentration of 0.6 g/l (Figure 11). For experiments without waiting time the pre-shear treatment did not show much effect. The observations from the Fann 35 viscometer could be confirmed with the Anton Paar rheometer. Compared to the corresponding Fann 35 measurement an increased slope could be seen after exceeding a shear rate of 450 1/s (black circle in Figure 12) in the Anton Paar measurement. A likely explanation for this increase could be Taylor instabilities. Taylor instabilities are vortices formed in rotating Taylor-Couette flow (Taylor 1923) when the critical Taylor number (Ta_{crit}) is exceeded. They are caused by an exchange of stabilities and the result is a stable secondary flow pattern. The Taylor number was calculated with equation (2), where ω is the angular velocity, a the radius of the outer cylinder, b the radius of the inner cylinder, and ν the kinematic viscosity. The Taylor number accounted to 1322, which is slightly below the critical Taylor number (White 2006).

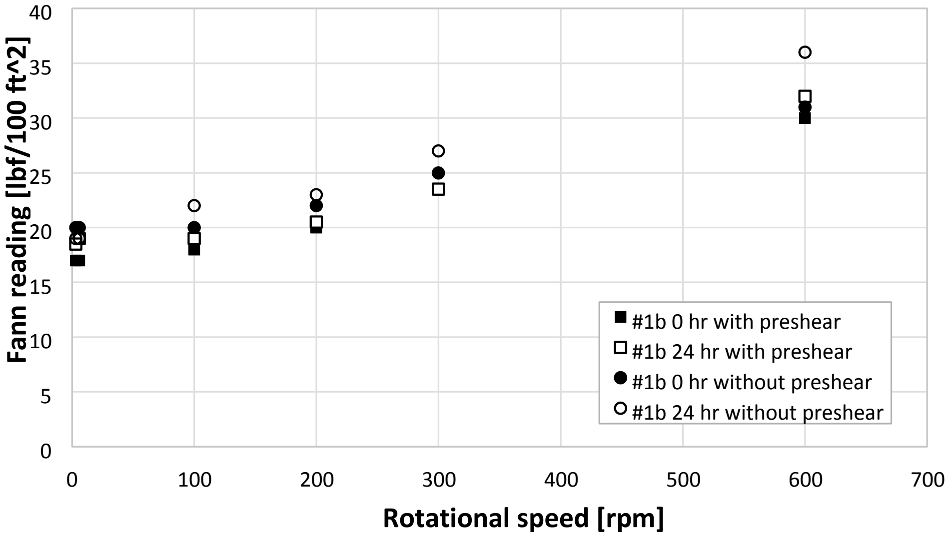

Figure 11. Fann 35 measurements for the laponite suspension #1b at 24 °C.

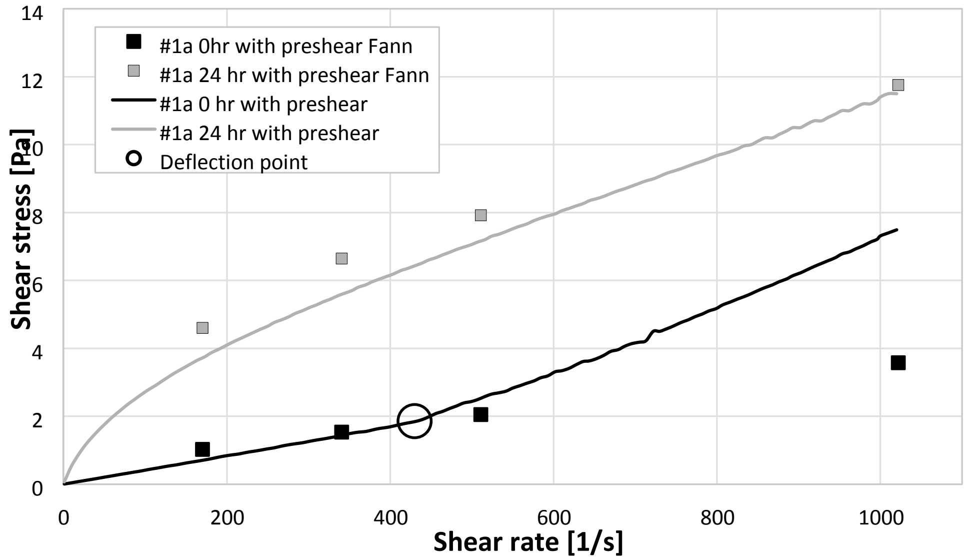

Figure 12. Comparison of Fann 35 and Anton Paar measurements for laponite suspension #1a at 24 °C (the dots represent the Fann 35 measurements and the lines the rheometer measurements).

The results from these experiments show the importance of consequent pretreatment of thixotropic fluids to obtain reproducible results. The effects of pre-shear and/or waiting time should ideally be tested for each fluid, but the results are expected to be valid for most oil-based drilling fluids. When testing viscoelastic properties, pre-shearing should be avoided, because the structure of the fluid will otherwise be destroyed. The viscoelastic properties were found to be most sensitive to pre-shear, especially at higher temperatures.

4.2 Flow Curves

The flow curves presented in Figure 13 were taken with the Anton Paar rheometer. All fluids showed a non-Newtonian trend and the OBMs showed yield stresses. The KCl fluid followed a Power-law trend, although a very small yield stress was visible. This yield stress is considered to have no practical relevance. The OBMs followed HerschelBulkley trends. All oil-based fluids exhibited lower shear stresses for 50 °C than for 28 °C. The details in the figure show the flow curves in a shear-rate range from 0 1/s to 100 1/s and the crossing point with the y-axis.

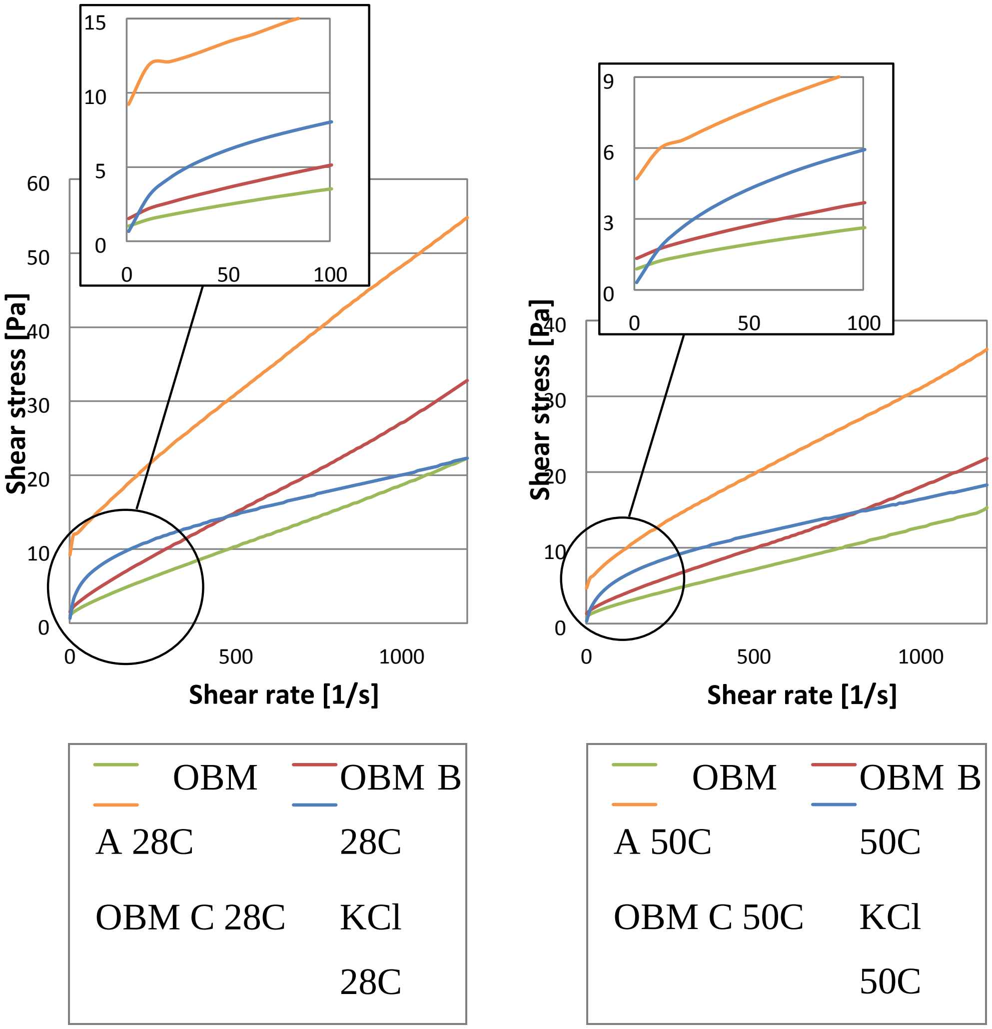

Figure 13. Flow curves measured with the Anton Paar rheometer for the OBMs A, B, C and the KCl fluid at 28 °C and 50 °C, measured with Anton Paar MCR 302.

When measuring flow curves with the Fann 35 a deviation from the rheometer results was seen. The Fann 35 curves showed lower shear-stress values than the Anton Paar curves for the same shear rates. To investigate the underlying reason, a Fann 35 measurement was imitated with an Anton Paar rheometer. A 10 min pre-shear interval at 1022 1/s (600 rpm in Fann 35) was followed by measurements of shear stress at the corresponding Fann 35 rotational speed order of 600 – 300 – 200 – 100 – 6 – 3 rpm. The plots are presented in Figure 14. The imitated Fann readings taken with the rheometer corresponded well with the initial Fann 35 measurements. The deviation between the solid and the dotted line is most likely caused by the differing measuring direction. The Anton Paar flow curves were done with increasing shear rate, whereas the Fann 35 measurements are done with decreasing shear rates. A shear history is induced into the fluid when measuring with a Fann 35 viscometer, resulting in lower shear-stress values, especially at lower shear rates. These findings correspond well with the results of the preconditioning study, where the pre-sheared samples showed lower shear-stress values compared to the not sheared samples.

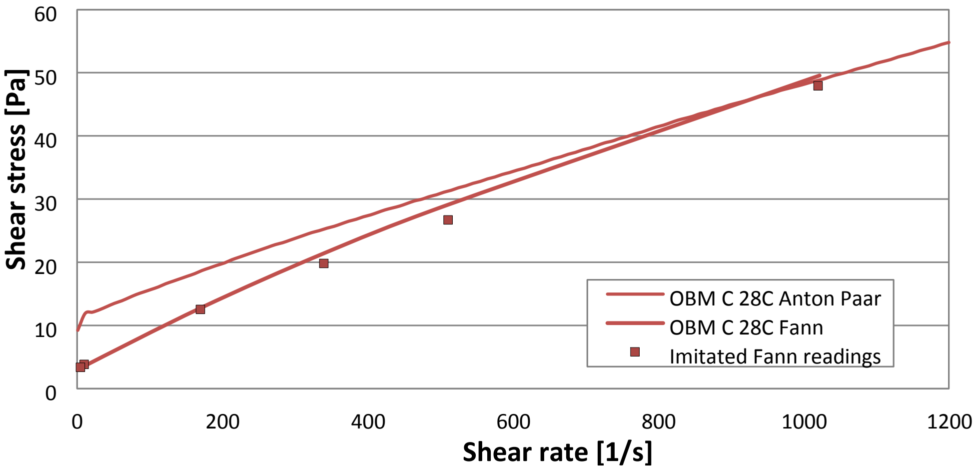

Figure 14. Comparison of OBM C flow curves measured with Fann 35 and Anton Paar, and imitated Fann 35 readings in the rheometer.

Figure 15 displays low shear-rate flow curves for the OBMs at 28 °C and 50 °C. At very low shear rates, just above 0.001 1/s, shear thickening tendencies are visible. Similar peaks also occurred after redoing the experiments and starting from a higher shear rate of 0.01 1/s (Figure 16). The reappearance of these peeks indicates rather a transitional effect than an increase in viscosity. A possible explanation could be the self-arrangement of water droplets in certain patterns, depending on the flow conditions in the dispersion. In the static case Brownian forces may reposition the water droplets of the emulsion to reach a state where the droplets have, on average, the furthest possible distance to each other (Figure 17). This would result in a crystal like structure and high viscosity. Between 0.05 1/s and 0.2 1/s, a plateau like area is dividing the curves into two sections. Such behavior was also seen by Herzhaft et al. (2002), who found a transition between Newtonian behavior at low shear rates and non-Newtonian behavior at higher shear rates.

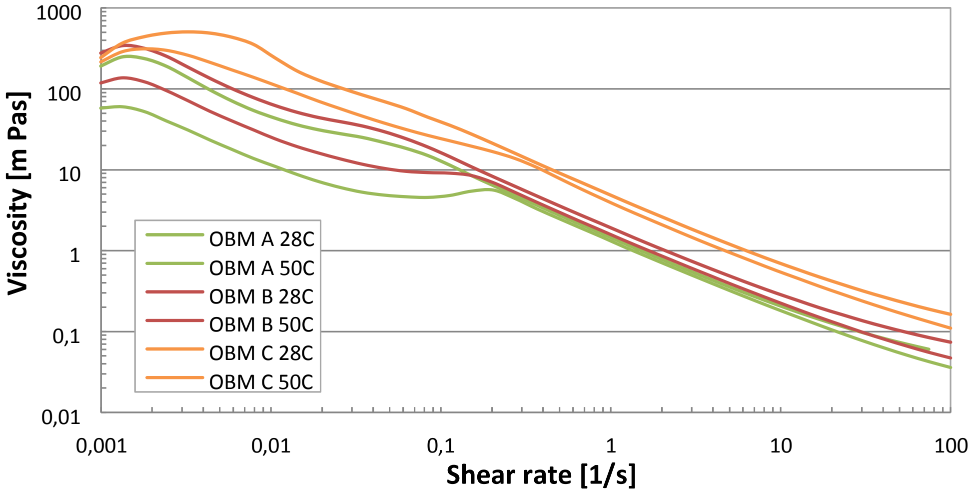

Figure 15. Low shear-rate flow curves in a shear-rate range of 0.001 - 100 1/s with decreasing measuringpoint duration of 30 s – 2 s for OBM A, B, and C at 28 °C and 50 °C, measured with Anton Paar MCR 302.

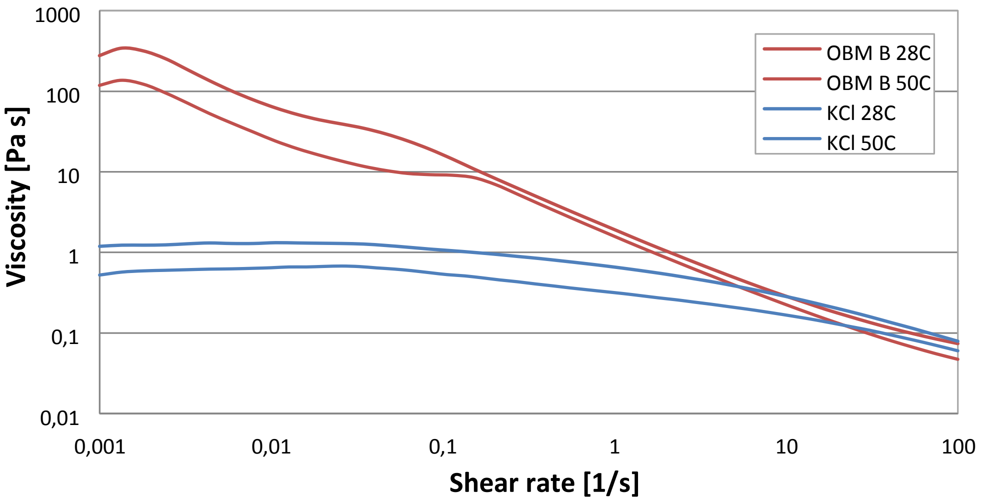

Figure 16. Low shear-rate flow curves in a shear-rate range of 0.001 - 100 1/s with decreasing measuringpoint duration of 30 s to 2 s for OBM B and the KCl fluid at 28 °C and 50 °C, measured with Anton Paar MCR 302.

Another possible explanation could be the one from Ackerson (1990) made during light scattering studies of suspensions of hard colloidal spheres. He found that for very low shear rates the Brownian motion positions the water droplets in a more regular structure in the mean, which then appears as a crystalline structures. This explanation was extended by Saasen (2002) while researching barite sag in oil-based drilling fluids. He found the crystalline structure to stay intact, as long as the Brownian motion showed a dominant behavior. When the shear rate increases, the Brownian motion is no longer able to reconstruct the crystalline structure of the water droplets and the individual droplets will then have to get redirected. This results in chaotic motion and an increase in viscosity which leads to the peak at very low shear rates. To get a more complete understanding of the case an extended investigation is needed. The measuring direction could be changed to conduct tests from high to low shear rates. Foss and Brady (2000) describe a competition between hydrodynamic forces and Brownian forces, where at very low shear rates, even lower than tested here, shear thinning can be observed.

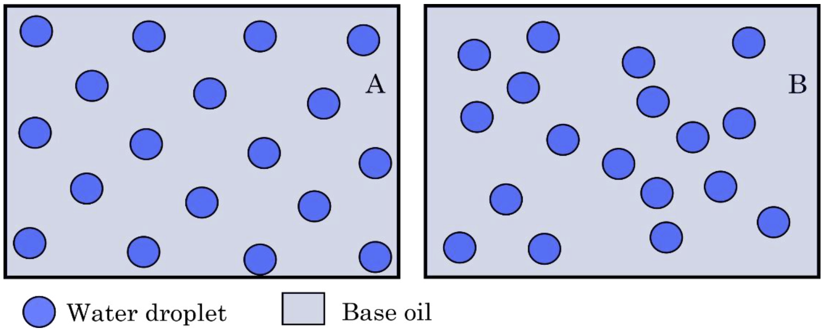

Figure 17. A) Self-arranged water droplets creating a crystal like structure at very low shear rates B) Chaotic motion results in redirected water droplets at higher shear rates.

4.3 Amplitude Sweeps

Figure 18 presents a comparison of the storage and loss moduli from amplitude sweeps for the OBMs A, B, and C at 28 °C and 50 °C. OBM C showed the highest G' and G" values, as well as the highest strain tolerance and the longest LVER for both temperatures. At 28 °C the G" of OBM A develops a peak just before the flow point, indicating an increasing portion of deformation energy. According to Mezger (2014), this deformation energy is initiating a breakdown of the internal structure already before the final breakdown occurs. At 50 °C similar peaks can be seen also in the G' curves of OBM A and B. The peaks are occurring after the flow point and indicate an extra network structure being built.

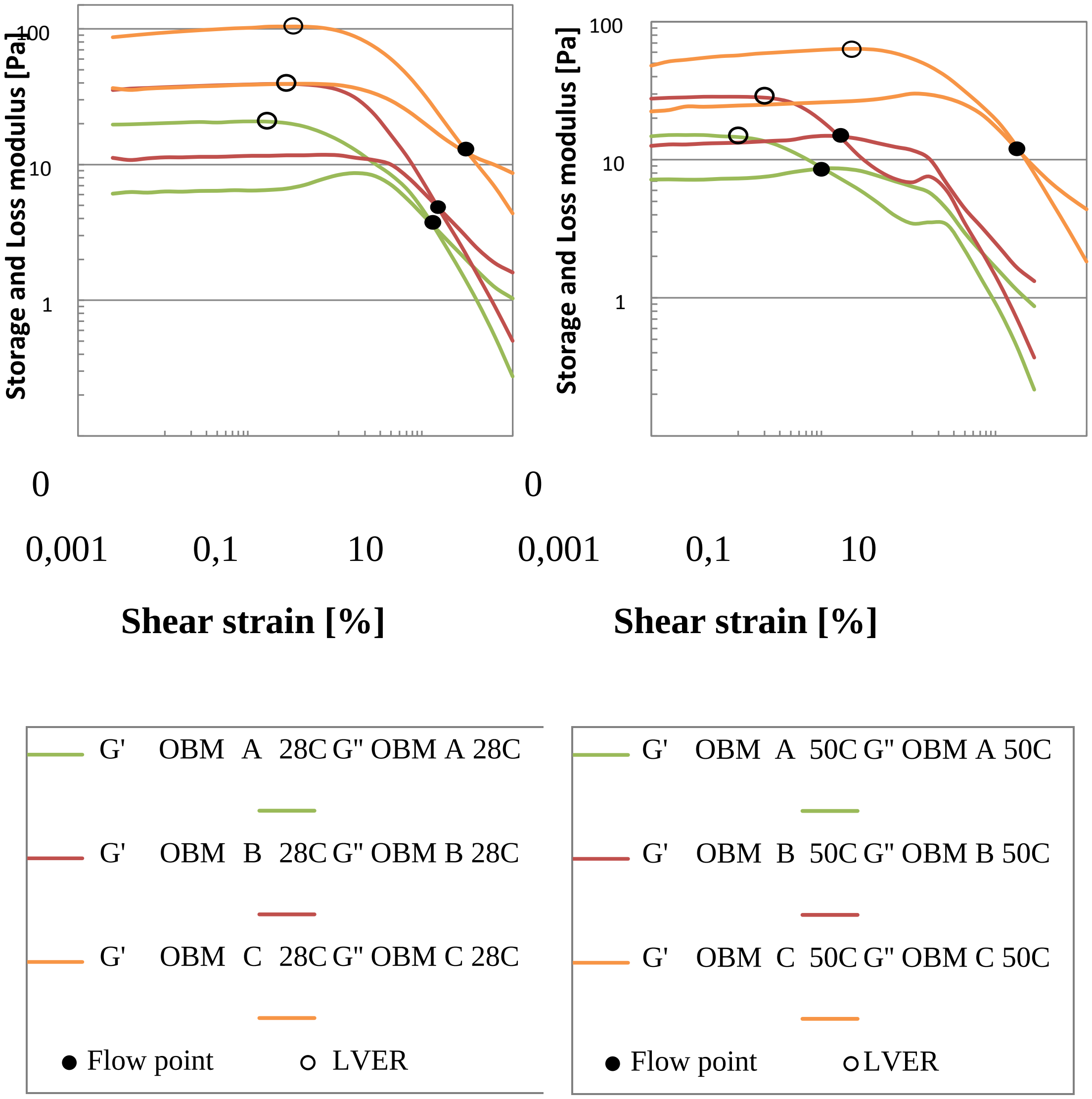

Figure 18. Storage and loss modulus of fluids OBM A, B, and C for 28 °C and 50 °C, measured with Anton Paar MCR 302. Flow point (filled circles) and the end of LVER (open circles) are marked.

Figure 19 shows a comparison of amplitude sweeps of the KCl fluid and the OBM B for 28 °C and 50 °C. The KCl fluid curves differ from the OBM curves. For both temperatures the storage modulus is lower than the loss modulus over the whole shear strain range, and no cross-over point is found. Such characteristics indicate a dominant viscous behavior over the elastic behavior. Although no cross-over point exists, a flow point can still be found where the G' deflects from linearity. This behavior is typical for viscoelastic fluids such as polymer solutions. Their molecular chains are entangled (Figure 20) inducing some degree of structure in the fluid, but no consistent network of forces throughout the bulk. Table 7 contains G' and G" values at the end of the LVER, tan , and the LVER itself. Tan represents the loss factor, defined as the ratio of G" to G'. When tan >1, the sample shows a more viscous behavior, and respectively a more elastic behavior when tan <1. This can also be seen in Figure 21, where tan is plotted over the shear strain range. The internal friction changes when the curve deflects from linearity.

The G' values of the OBM B have a constant value until a strain of about 10 % is reached. This reflects that the fluid is constructed as a pure dispersion and emulsion. As long as the strain is less than around unity, the particle and droplet positions are kept in a position trying to reach an energy minimum. When the strain becomes larger the particles and droplets start to leap frog; totally destroying the structure and hence decreasing the G' values. Here, the elasticity works on short range distances. The shear strain of the KCl fluid shows ca. 50 to 100 times higher values than the OBM B before the G' starts to deflect, indicating that the elasticity is not destroyed by rearrangement of the particle positions in the sample.

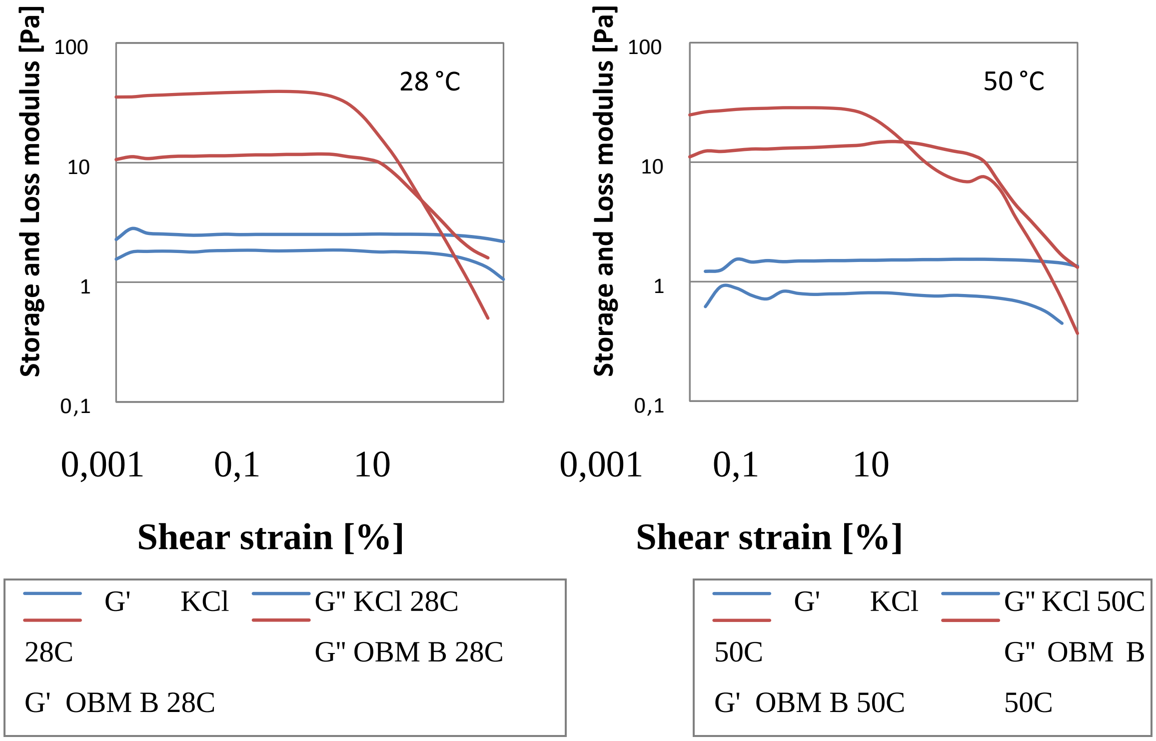

Figure 19. Amplitude sweeps showing the storage and loss moduli of the KCl fluid and the OBM B fluid for temperatures of 28 °C, and 50 °C, measured with Anton Paar MCR 302.

The domination of the loss moduli over the storage moduli, and the corresponding loss factor of tan >1 in the amplitude-sweep tests for the KCl fluid indicate a viscous character. This is in accordance with other results presented here. The OBM shows a dominant elastic behavior, indicating a microstructure in the fluid.

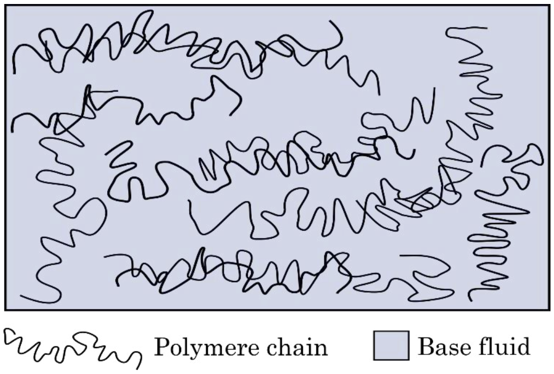

Figure 20. Illustration of entangled polymer chains in base fluid.

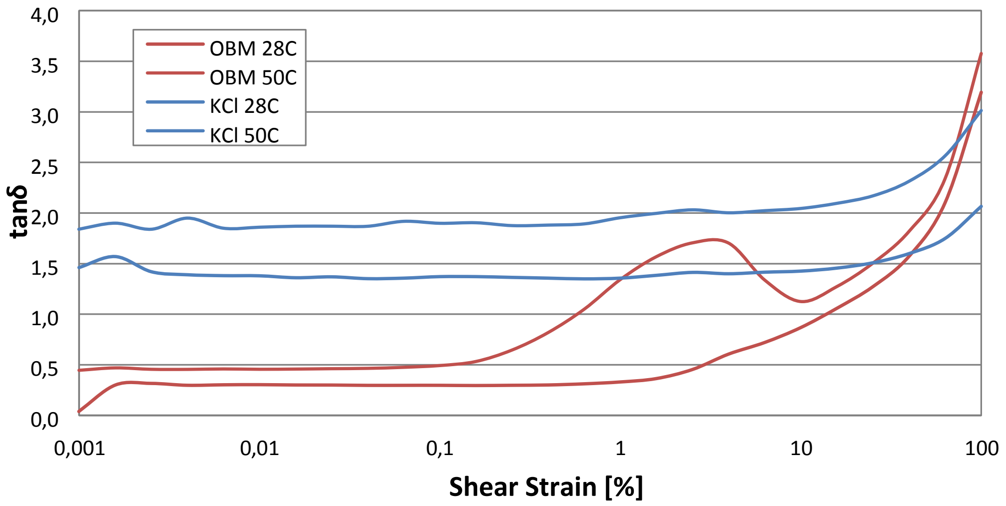

Figure 21. Ratio of the loss to the storage moduli plotted over the shear strain range.

Table 7. Storage and loss moduli, loss factor, and LVER of the OBMs and the KCl fluid for 28 °C and 50 °C.

Fluid	Temperature [°C]	G' [Pa]	G" [Pa]	tan	LVER (%/Pa)
OBM A	28	20.2	6.3	0.3	0.01/20.2
	50	14.1	7.4	0.5	0.06/14.1
OBM B	28	37.6	11.3	0.3	0.02/37.6
	50	27.8	13.7	0.5	0.1/27.8
OBM C	28	104	39.1	0.4	0.3/105
	50	63.4	26.4	0.4	0.2/63
KCl	28	1.8	2.5	1.4	6.3/1.8
	50	0.8	1.5	1.9	6.3/0.8

4.5 Temperature Sweeps

Figure 22 presents temperature-sweep curves of all four fluids in a temperature range from 5 °C to 50 °C. The KCl fluid, the OBM A and the OBM B show an almost linear decrease in viscosity with increasing temperature, whereas OBM C decreases clearly nonlinearly. OBM C also shows the highest temperature dependency of the viscosity, probably due to a higher concentration of base oil in the fluid. A gas chromatogram of the base oil was made and revealed a high concentration of long chained hydrocarbons (C16 or higher). When lower temperatures are reached, these long chained hydrocarbons may start to crystalize and therefore increase the viscosity.

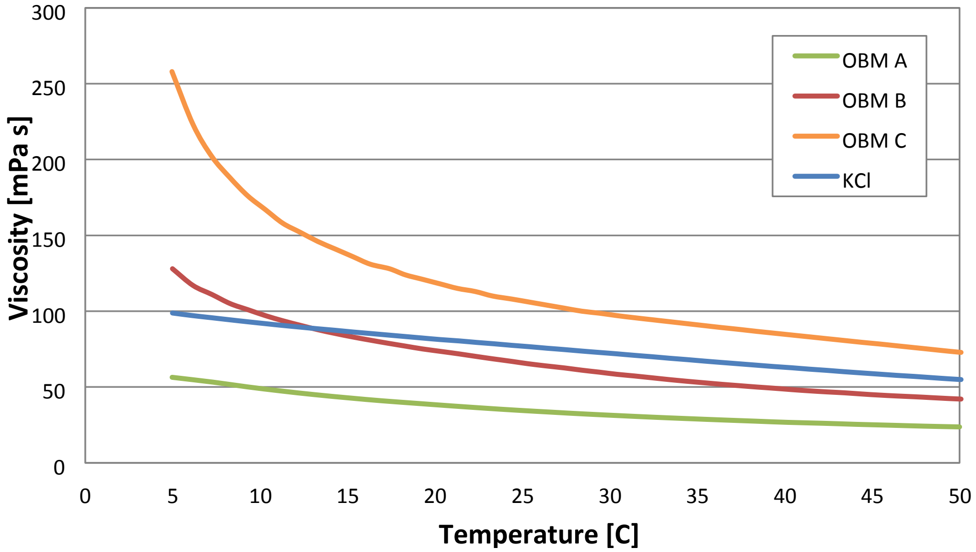

Figure 22. Temperature-sweep curves for OBMs A, B, C, and the KCl fluid measured with Anton Paar MCR 302.

4.6 Thixotropy

Figure 23 presents the storage and loss moduli for OBM A, measured with 3-intervalthixotropy tests. The rest interval was performed inside the LVER. During the recovery interval the fluid showed a structure buildup which exceeded the values from the rest interval. This happened for both temperatures. At 50 °C the storage modulus started to decrease after about 3000 s, indicating an unstable structure for the timeframe of this test. After 7000 s the value of G' has dropped to 55.8 % of the maximum value. Only a slight decrease in storage modulus was observed for the 28 °C measurement, where G' was reduced to 91.7 % of the maximum value. Knowledge about structure development is important during operation when the fluid circulation has to stop. When structural decomposition happens too early, cuttings may settle and accumulate on the down side of the wellbore.

The slight decrease of the G' values for both temperatures during the initial rest interval are not quite understood. It could be that the changes in the fluid structure happen relatively fast. The structure rebuild after the first 200 s of the recovery interval is already at 100 % of the initial rest interval.

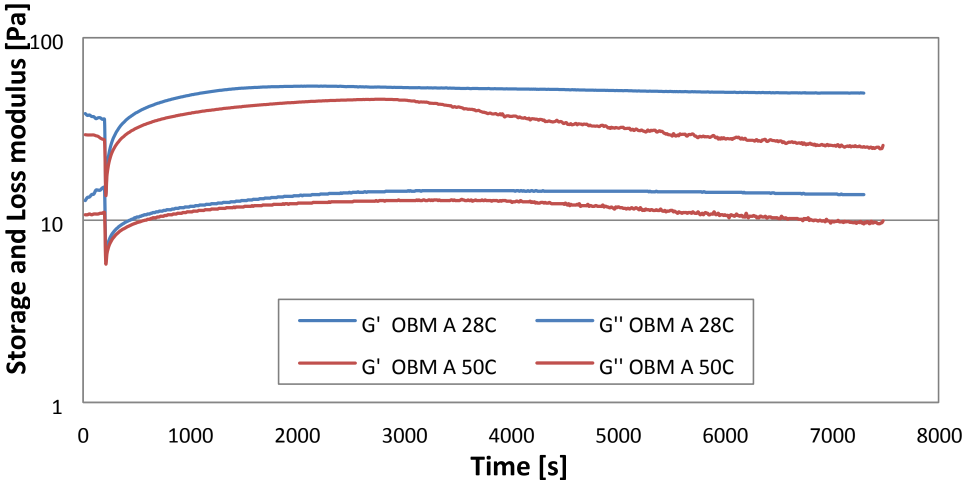

Figure 23. 3-interval thixotropy tests for OBM A at 28 °C and 50 °C measured with Anton Paar MCR 302.

In Figure 24 the results are shown for the KCl fluid. Similar to the observations from the amplitude sweeps, the storage modulus is also lower than the corresponding loss modulus. Interestingly, the storage modulus is increasing throughout the recovery interval and approaching the loss modulus. This happened for both temperatures. At 10 °C the curves are actually crossing each other. The cross-over point could not be determined directly because the G' and G" are crossing each other several times between 6000 s and 8000 s before the G' finally takes over. The test at 28 °C seems to have a more moderate structure increase. The temperatures of 10 °C and 28 °C were chosen because they represent each side of the crossing-point observed in the temperature-sweep test (Figure 22).

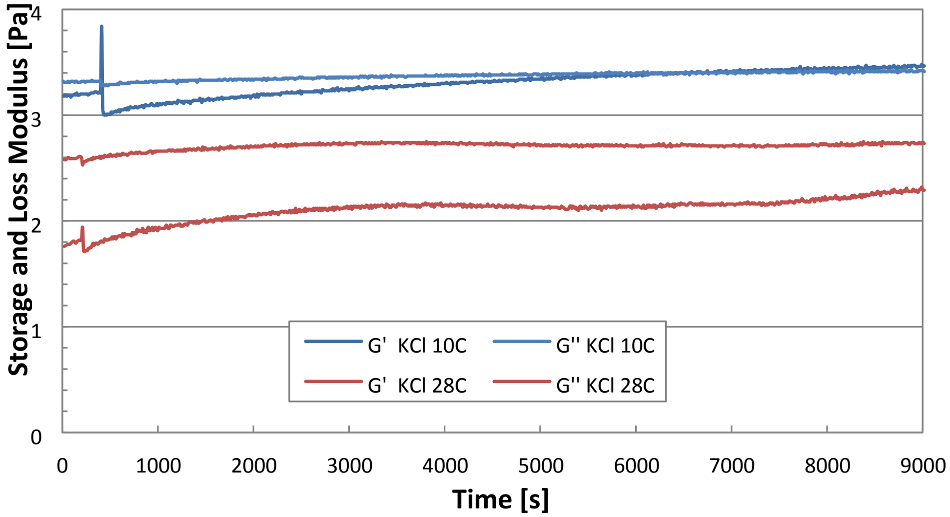

Figure 24. 3-interval-thixotropy tests for the KCl fluid at 10 °C and 28 °C measured with Anton Paar MCR 302.

4.7 Shear-Stress Sweeps

Figure 25 contains shear-stress sweeps of the OBMs at temperatures of 28 °C and 50 °C. All graphs show clear yield stresses where the curves deflect from linearity. The yield stresses are marked with dots. For 28 °C the yield stresses are higher than for 50 °C, and with increasing density the yield stress rises as well. The slight deflection before 1 Pa is probably due to a transition state and can be disregarded.

The controlled shear-stress sweeps for the KCl fluid (Figure 26) develop a linear plateau and do not deflect from that in the higher shear-stress area, therefore no yield stress can be determined. This is in conformity with the results from the amplitude-sweep tests, where the crossing point (flow point) of the storage and loss moduli can be interpreted as a yield stress. During the current measurements no crossing point was found due to the dominating loss modulus, hence no yield stress could be determined either. The decrease of viscosity and elasticity with increased temperature was also observed by Bui et al.

(2012).

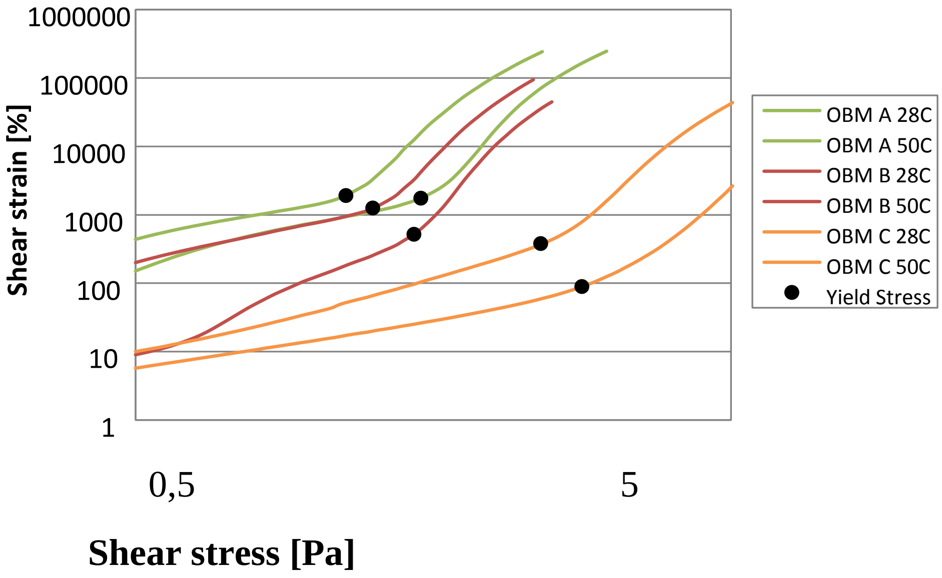

Figure 25. Shear-stress sweeps of OBM A, B, and C for temperatures of 28 °C and 50 °C, measured with Anton Paar MCR 302.

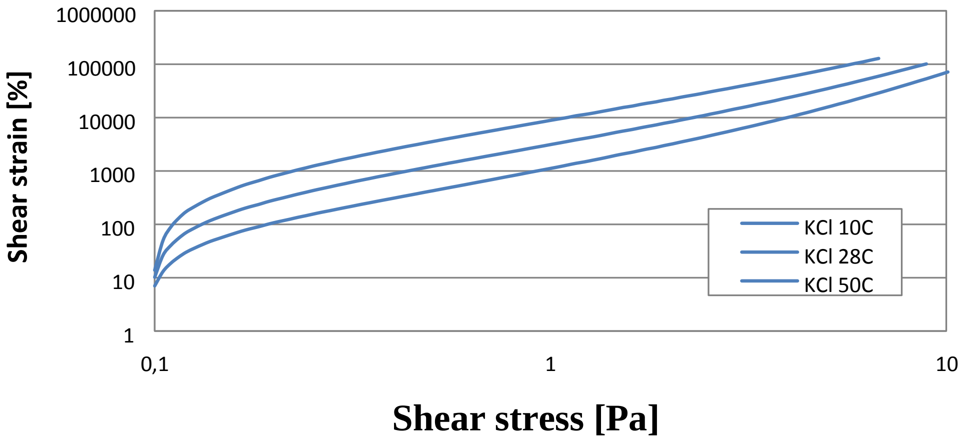

Figure 26. Shear-stress sweeps of the KCl fluid for temperatures of 10 °C, 28 °C, and 50 °C, measured with Anton Paar MCR 302.

4.8 Yield Stress

The yield stress is an important parameter characterizing drilling fluids in static condition. The value of the yield stress is not a material constant and strongly dependent on the measuring method and/or the regression method. Here three different common methods were used to compare results. Method 1 (M1) was a shear-stress sweep. The yield stress can be found in the resulting shear strain vs shear stress plot, where the curve deflects from linearity. Regression with the Herschel-Bulkley model was used as method 2 (M2). The third method (M3) were amplitude-sweep tests, where the crossover points of the storage and loss moduli were used. In amplitude-sweep tests two possibilities exist for determining the yield stress. The end of the LVER is the beginning of the structural degradation, but still a rest network structure is present. First after the crossover point (G'=G") the fluid is flowing as a whole and the viscous forces are dominating. Using the crossover point is a more practical approach, as from this point on the structure is broken to an extent that the fluid actually flows. The range between the end of the LVER and the crossover point is also called the yield zone (Mezger 2014).

Table 8 shows the yield-stress values for the OBMs at 28 °C and 50 °C. The KCl fluid did not show a yield stress. For the higher temperatures the values are consistently lower for all three fluids. The highest values were obtained with method 2. For OBM A and B the difference between the methods was the least between M1 and M2, while M3 showed much lower values. For OBM C the M3 values did not deviate to such an extent.

Table 8. Yield stresses of OBM A, B, and C for temperatures of 28 °C and 50 °C determined by three different methods, M1 – shear-stress sweep, M2 – regression with Herschel-Bulkley model, M3 – amplitude-sweep test.

Fluid	OBM A		OBM B		OBM C	
Temperature [°C]	28	50	28	50	28	50
Yield stress M1 [Pa]	2.1	1.4	2.0	1.7	4.7	3.8
Yield stress M2 [Pa]	2.9	1.8	3.3	2.2	9.9	4.8
Yield stress M3 [Pa]	0.61	0.05	0.95	0.12	5.4	2.9

4.9 Results of the Flow-Loop Experiments

Figure 27 shows the sand holdup for different average fluid velocities for experiments with and without drill-string rotation. A high impact on cuttings removal can be seen for experiments with a drill-string rotation of 150 rpm for both fluids. The drill-string rotation is dominating the flow related properties. The rotation is destroying the particle interactions and therefore reducing the resistance of the bed. Additionally the turbulences created by the rotation counteract the resettling of the sand particles in the test section.

At a fluid velocity of 1.2 m/s and without drill-string rotation, the difference in sand holdup is largest between OBM B and the KCl fluid, and OBM B gave a 5% lower sand holdup than the KCl fluid. OBM B removes the sand bed better, leaving less sand in the test section for all tested fluid velocities, without drill-string rotation.

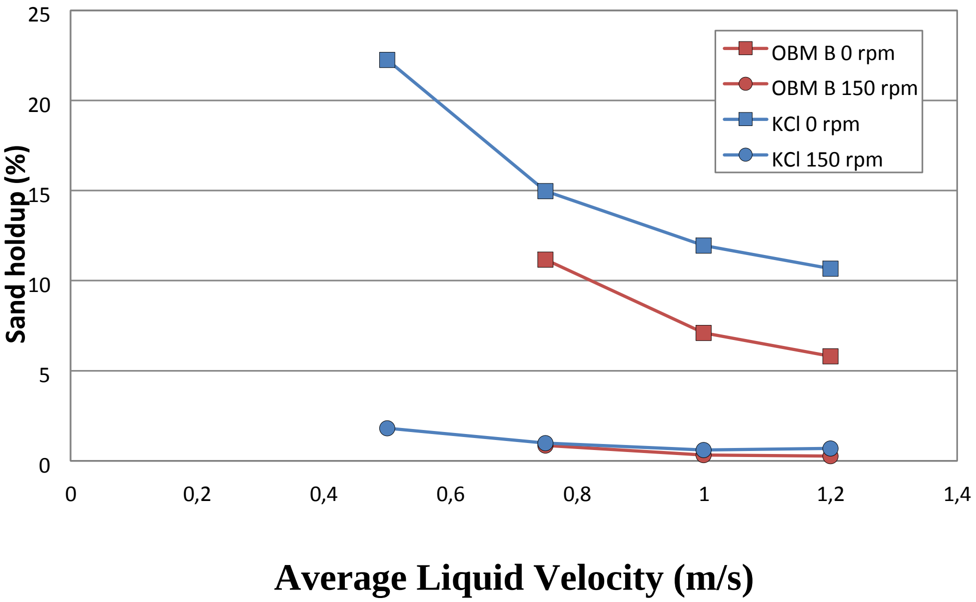

Figure 27. Sand holdup versus superficial liquid velocity for the KCl fluid and OBM B with and without drill-string rotation (OBM B data collected from Sayindla et al. 2016, KCl fluid data from Sayindla et al. (Submitted))

When evaluating the results seen in the flow-loop experiments (Figure 27), two cases can be differentiated. One case with drill-string rotation and higher flow velocities, and one case without drill-string rotation and lower flow velocities. Considering the lower flow velocities, the importance of fluid interaction with the cuttings while flowing becomes less relevant, and the cutting-beds resistance to erosion becomes more important. The viscosity profiles of the KCl fluid and the

OBM B are similar in the relevant shear-rate range of the flow-loop experiments, but different rheological behavior could be seen in the rheological investigation. The interpretation of the results of the low shear-rate rheology experiments helps to understand the suspension characteristics and the differing cuttings-transport behavior of the fluids.

In experiments without drill-string rotation OBM B showed a better performance. This can be explained by how the fluids affect the sand bed and influence its resistance to erosion. The OBM B is a water in oil emulsion with a yielstress, and the KCl fluid is built as a polymer in brine suspension (Table 3). The polymers and the water in the KCl fluid increase the interactive forces in the sand bed by creating stronger inter-particle forces, which further increase the resistance to erosion. During amplitude sweeps (Figure 19), the KCl fluid showed that it can tolerate up to 100 times more strain deformation than the OBM B. This elasticity holds back the sand particles and makes entrainment in the fluid flow more difficult. Saasen (1998) found similar behavior in fluids containing xanthan gum. In case of the OBM B, the yield stress is responsible for the strength of the sand bed. This yield stress is comparably weaker than the elasticity in the KCl fluid. Cuttings erosion from the sand bed with OBM B is thus easier, and the sand particles are released more immediately. A schematic drawing is presented in Figure 28 where the thick black arrow represents the yield stress for the case of OBM, and the thinner spring-like arrows represent the elasticity in the KCl fluid. Additionally the amplitude sweeps for each fluid and the flow curves are shown.

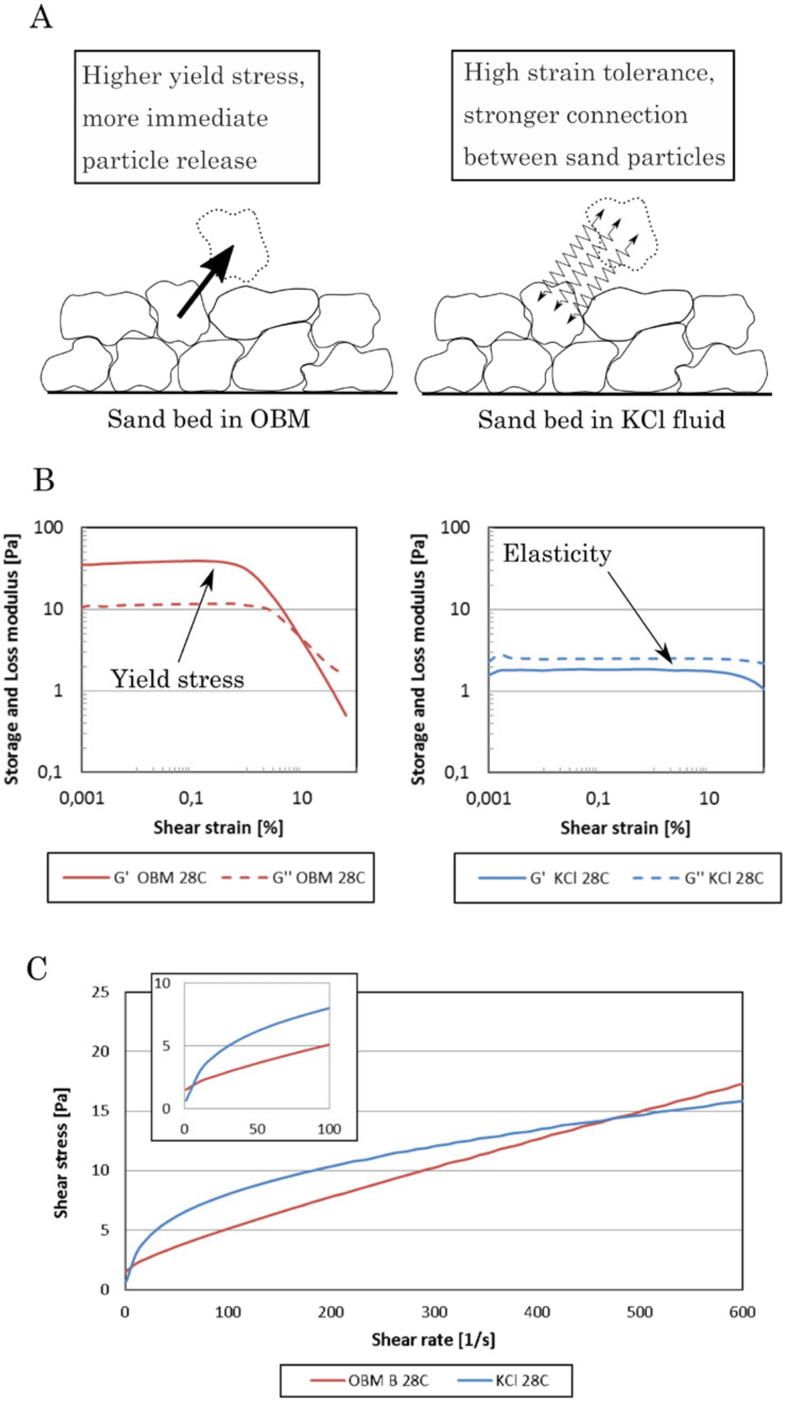

Figure 28. Schematic drawing presenting A) the cuttings behavior in the OBM B and KCl fluids when exposed to low flow conditions together with B) the amplitude sweeps showing the yield stress in the OBM and the elasticity in the KCl fluid, and C) the flow curves

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The main concluding points are:

1. The viscoelastic properties of the tested drilling fluids seem to have only little impact on the cuttings transport. They are more likely to have an impact on the strength of the cuttings bed and its resistance to the drilling-fluid flow.
2. The results of the comparative flow-loop experiments suggest that emulsionbased fluids, exhibiting low yield stresses and light internal structures at low shear rates, are the better option for hole cleaning.
3. The resistance in a cuttings bed is affected by the yield stress of the drilling fluid.
4. The resistance in a cuttings bed is affected by the elasticity and strain tolerance in the drilling fluid. This effect is stronger than the yield-stress influence.
5. The performance of OBM B may profit from the absence of polymers that otherwise consolidate the cuttings bed and make the cuttings removal more difficult.
6. Drill-string rotation will dominate the flow-related properties.

5.2 Recommendation

Parameters influencing hole cleaning are manifold. The prediction of hole cleaning cannot be done from a single flow or rheological parameter alone and linking all the parameters together also requires to understand their individual behavior. The rheological analysis of this thesis involved characterization of oil-based and water-based drilling fluids with Anton Paar rheometers measuring different flow curves, amplitude sweeps, temperature sweeps, and thixotropy. A Fann 35 viscometer was used to keep control of the fluid condition during periods of flow-loop experiments. During these flowloop experiments the hole-cleaning capabilities of drilling fluids were investigated and the oil-based drilling fluid showed superior cuttings-transport abilities.

The OBMs of this study are water in oil emulsions with a yield stress and a linear viscoelastic range indicating a light structure in the low shear-rate range. The KCl fluid is a polymer-containing water-based fluid with a strain tolerance up to 100 times larger than the OBM.

The results of the comparative flow-loop experiments suggest that emulsion based fluids, exhibiting yield stresses and light internal structures at very low shear rates, are the better option for hole cleaning. In a cuttings bed created in OBM B, the yield stress of the fluid may initially require higher forces to remove a cutting from of the bed, but when the yield stress is overcome the cutting will immediately enter the fluid flow. On the other hand, the larger elasticity and strain tolerance in the KCl fluid, caused by the polymers, will hold back the cutting and thus making it more difficult to remove the cutting from the bed and entrain the fluid flow.

High-velocity fluid flow and drill-string rotation are certainly two dominating parameters for the removal of cuttings from a wellbore. The flow-loop experiments with drill-string rotation demonstrated the dominating effects of the drill-string rotation over the flow-related properties during cuttings transport. The particle interactions were destroyed and the resistance of the sand bed reduced. With a lower resistance the particles were easier brought into the fluid flow and cuttings transport improved. Turbulences created by the drill-string rotation and fluid flow may in addition counteract the particle settling.

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