A REVIEW OF THE RHEOLOGICAL EFFECTS OF POWER LAW DRILLING FLUIDS ON CUTTINGS TRANSPORTATION IN NON-VERTICAL BOREHOLES

A

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ABSTRACT

Cuttings transportation during in non-vertical boreholes is necessary for oil and gas wells. Adequate cuttings removal from a well in drilling is critical for cost-effective drilling as high annular cuttings buildup often leads to high risk of stuck pipe, reduced rate of penetration and other impediments to standard drilling and completion procedures.

This study investigates how rheological parameters influence the removal of cuttings in non-vertical boreholes. It contributes to work already done to ensure efficient hole cleaning process. In this study, the rheological parameters examined were the flow index (n), consistency index (K), plastic viscosity (PV), mud yield point (YP), YP/PV ratio, apparent viscosity and effective viscosity. Fifteen mud samples, three annular velocities (3.82, 2.86 and 1.91 ft/sec) and three hole angles (30°, 45° and 70°) were considered. An Excel Spreadsheets program was used to determine the parameters.

The results of this study show that, higher annular mud velocities are required for efficient hole cleaning in directional wells than in vertical wells. Increasing values of YP, YP/PV ratio and K promote effective cuttings transport while the value of n should be low. Effective and apparent viscosities also should be high.

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CHAPTER 1

INTRODUCTION

1.1 Problem Definition

Many materials of engineering interest must be handled and transported as slurries or suspensions of insoluble particulate matter. Transportation of cuttings in non-vertical boreholes is of no exception. Almost the same thing occurs whereby the cuttings act as the solids in the drilling fluid. In spite of the many technological advances that have accompanied the drilling of non-vertical boreholes, one significant remaining challenge is effective cuttings transport, particularly in deviated wells.

The transportation of cuttings during drilling has a major influence on the economics of the drilling process. Problems that can occur as a result of inefficient hole cleaning from cuttings include reduced weight on bit, increase risk of pipe stuck and inability to attain the desired reach, reduced rate of penetration (ROP), extra cost because of the need of special additives in the drilling fluid, extra pipe wear, transient hole blockage which can lead to lost circulation and wasted time for wiper tripping. These problems have prompted significant research into cuttings transport during the past 50 years. (Kelessidis, 2004).

Hole cleaning relying on viscous fluids in laminar flow for drilling has proved to be inefficient because of the inability to rotate the string to agitate bedded cuttings. Alternatively, a high fluid flow to induce turbulent flow regime is more effective for hole cleaning, but difficult to achieve because of high friction pressures in the drillpipe. Therefore a bed of cuttings is almost always present in non-vertical boreholes. For laminar flow, the distance that a particle will travel (downstream) before it falls across the annulus clearance can be calculated using Stokes' law and the local viscosity while flowing can also be calculated. This analysis may be easily applied to optimize mud selection and wiper trips. Applying this model to high low-shear rate-viscosity (LSRV) gels shows that they may perform well inside casing but are expected to do a poor job of hole cleaning in a narrow openhole horizontal annulus without rotation.

For turbulent flow in horizontal wells, the concept of using annular velocity (AV) as a measure of hole cleaning is insufficient. A more complete term called AVRD is introduced, which is the product of the AV and the square root of the hydraulic diameter. This term can be used to compare cuttings transport in turbulent flow in horizontal wells of different cross sectional areas. (Leising et al., 1998).

Rheology which is the study of the flow and deformation of fluids is an important contributing factor to these problems. Rheology describes the relationships between shear rate and shear stress. Pilehvari, Azar, and Sanchez[2,16] state that fluid velocities should be maximized to achieve turbulent flow, and mud rheology should be optimized to enhance turbulence in inclined/horizontal sections of the well bore.

The purpose of this study is to investigate how rheological parameters influence the removal of cuttings in non-vertical boreholes.

1.2 Objectives

The objectives of this research are:

- To present a review of cuttings transport in vertical, directional/horizontal well bores.
- To provide a critical review of how rheology affects cuttings transportation in non-vertical boreholes.
- To identify the critical parameters that affect effective removal of cuttings in the drilling of non-vertical boreholes.
- To propose a methodology for analysing the rheological parameters that affect cuttings transportation in non-vertical boreholes.

1.3 Methodology

The methods to be used include:

- Review of relevant literature on the topic.
- Equations associated with the flow of fluids in well bore will be derived and their applications will be demonstrated.
- Some unique features such as the flow index (n), plastic viscosity (PV), mud yield point (YP) and YP/PV ratio of drilling fluids in well bore will be identified and applied to achieve a successful method of improving upon cuttings transportation in non-vertical boreholes.

1.4 Organisation

The layout of this study is as follows: Chapter 1 gives the introduction and description of the problem and how relevant it is to the petroleum industry. Chapter 2 presents the literature review which outlines the theory of the topic. It includes review of past work related to the topic. Chapter 3 is devoted to the development of equations used in carrying out the study. Discussion and analysis of results is shown in Chapter 4. Lastly, Chapter 5 covers the summary, the major conclusions and gives recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Fluid Rheology

Rheology is the study of the flow and deformation of fluids. Deformation is a change in shape in response to an applied force, which can be tension, compression, shear, bending, or torsion. A force applied to an area is called a stress. The fluids are mainly liquids but also soft solids flowing under conditions in which they flow without deforming elastically may be included. Rheology comes from the Greek word "rheos" which means to flow. The rheological characteristics of fluid are important in evaluating its ability to perform a specific function. It describes the relationships between the shear rate and the shear stress that causes movement. The study of rheology shows how materials, particularly liquids, respond to applied stress. Rheological properties depend on the total solids content, temperature, pH-value, chemical conditioning and particle size.

One of the main issues of rheology is the definition and classification of materials. One way of characterizing a material is by its relaxation time, i.e. the time required to reduce the stress in the material by flow. Typical magnitudes of relaxation times for materials are:

Gases	$< 10^{-6}$	seconds
Liquids	$10^{-6} - 10^{2}$	seconds
Solids	$> 10^{2}$	seconds

Another way of defining materials rheologically is by the terms viscous, elastic or viscoelastic. Gases and liquids are normally described as viscous fluids. An ideal viscous fluid is unable to store any deformation energy. Hence it is irreversibly deformed when subjected to stress. It flows and the deformation energy is dissipated as heat, resulting in a rise of temperature. Solids, on the other hand, are normally described as elastic materials. Ideal elastic material stores all imposed deformation energy and will consequently recover totally upon release of stress. A viscous fluid can therefore be described as a fluid which resists the act of deformation rather than the state of deformation, while an elastic material resists the act as well as the state of deformation. A number of materials show viscous as well as elastic properties, i.e. they store some of the deformation energy in their structure while some is lost by flow. These materials are called viscoelastic.

Viscosity is a measure of the resistance offered by a matter to a deforming force. Shear dominates most of the viscosity-related aspects of drilling operations. Because of that, shear viscosity (or simply, ‘‘viscosity’’) of drilling fluids is the property that is most commonly monitored and controlled. Retention of drilling fluid on cuttings is thought to be primarily a function of the viscosity of the mud and its wetting characteristics. Drilling fluids with elevated viscosity at high shear rates tend to exhibit greater retention of mud on cuttings and reduce the efficiency of high-shear devices like shale shakers. Conversely, elevated viscosity at low shear rates reduces the efficiency of low-shear devices like centrifuges, inasmuch as particle settling velocity and separation efficiency are inversely proportional to viscosity. (ASME, 2005).

Drilling fluid with adequate low end rheology will have the following advantages: (Q'Max Solutions Inc., 2009).

1. Will form soft or no cuttings beds when the pump is off.
2. Will minimize torque and drag while drilling.
3. Lowers ECD's by being able to clean the cuttings out of the wellbore.
4. Lessens the chance of becoming mechanically stuck.

5. Easier to log and test.
6. Enhanced ability to correctly identify the right information from cuttings.

2.2 Influence of Temperature and Pressure on the Rheology of Drilling Fluids

The rheological properties of drilling muds under downhole conditions may be very different from those measured at ambient pressures and temperatures at the surface. At depth, the pressure exerted by the mud column may be as much as 20,000 pounds per square inch. The temperature depends on the geothermal gradient, and may be more than 500 °F, (260°C) at the bottom of the hole during a round trip. (Darley and Gray, 1988). Even quite moderate temperatures can have a significant, but largely unpredictable influence on the rheological properties. Muds may be thicker or thinner downhole than indicated at the surface, and an additive that reduces viscosity at the surface may actually increase the viscosity downhole.

Elevated temperatures and pressures can influence the rheological properties of drilling fluids in any of the following ways:

1. Physically: An increase in temperature decreases the viscosity of the liquid phase; an increase in pressure increases the density of the liquid phase, and therefore increases the viscosity. (Darley and Gray, 1988).

2. Chemically: All hydroxides react with clay minerals at temperatures above about 200 °F (94 °C). With low alkalinity muds, such as those treated with caustic tannate or lignosulfonate, the effect on their rheological properties is not significant, except to the extent that the loss of alkalinity lessens the effectiveness of the thinner. But with highly alkaline muds the effect may be severe, depending on the temperature and the species of metal ion of the hydroxide. (Darley and Gray, 1988).

3. Electrochemically: An increase in temperature increases the ionic activity of

any electrolyte, and the solubility of any partially soluble salts that may be present in the mud. The consequent changes in the ionic and base-exchange equilibria alter the balance between the interparticle attractive and repulsive forces, and hence the degree of dispersion and the degree of flocculation. The magnitude and direction of these changes, and their effect on the rheology of mud, varies with the electrochemistry of the particular mud. (Darley and Gray, 1988).

2.3 Flow Patterns for Solid/Liquid Flow in Horizontal Concentric Annulus

During the flow of solid/liquid mixtures in horizontal conduits, the liquid and solid phases may distribute in a number of geometrical configurations that depend on flow rates, conduit shape and size, fluid and solid properties, and inclination. Natural groupings - or flow patterns - exist within which the basic characteristics of the two-phase mixture remain the same. The main parameters determining the distribution of solids in the liquid (i.e., the flow patterns) are the liquid velocity, the solids loading, and the properties of liquid and solids (rheology and density of liquid, diameter and sphericity of solids). Observations of solid/liquid flow in horizontal pipes and annuli, even at low solids concentrations, suggest the flow patterns depicted in Fig. 2.1. (Kelessidis, 2004).

At high liquid velocities, the solids may be distributed uniformly in the liquid; normally, the correct assumption is made that there is no slip between the two phases (i.e., the velocity of the solids is equal to the velocity of the liquid). This flow pattern is normally observed for fairly fine solids (less than 1 mm in diameter) not normally occurring during drilling applications. This flow pattern is called the “fully suspended symmetric flow pattern” (Fig. 2.1a).

While the liquid-flow rate is reduced, there is a tendency for the solids to flow near the bottom of the pipe (or outer pipe of the annulus) but still be suspended, thus creating an asymmetric solids concentration, called the “suspended asymmetric flow pattern,” with the solids still moving with the liquid (Fig. 2.1b).

A further reduction in the liquid-flow rate results in the deposition of solid particles on the bottom of the pipe. The solids start forming a bed, which moves in the direction of the flow. There may be some non-uniformly distributed solids in the liquid layer above. This pattern is called “the moving bed flow pattern.” The velocity below this is commonly referred to as limit-deposit velocity, suspension velocity, or critical velocity (Fig. 2.1c).

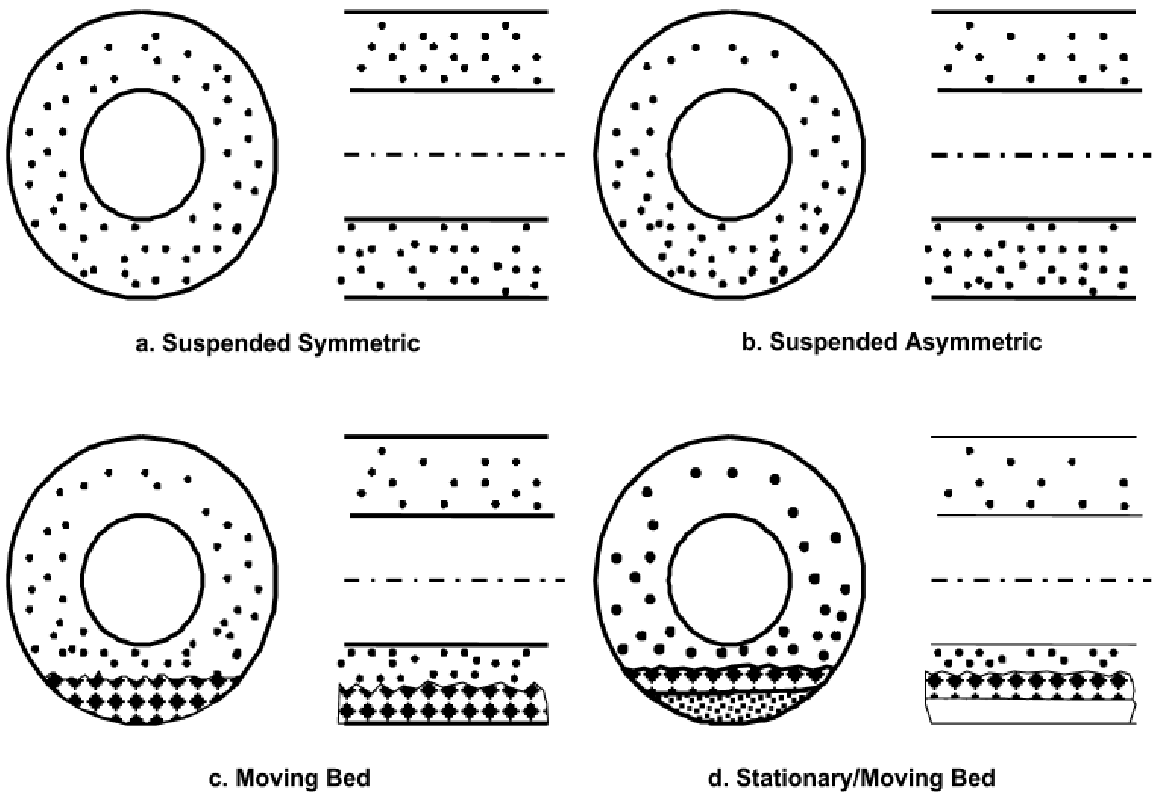

Fig. 2.1: Flow patterns for solid/liquid flow in horizontal concentric annulus. (Kelessidis, 2004).

Reducing the liquid velocity further causes more and more solids to be deposited, resulting in three layers (Fig. 2.1d). A bed of solids that is not moving forms a stationary bed. A moving bed of solids forms on top of the stationary bed with a heterogeneous solid/liquid mixture above. There is a strong interaction between the heterogeneous solid/liquid mixture and the moving bed with some solids depositing on the bed and some re-entraining in the homogeneous solid/liquid mixture. An increase in the height of the solids bed decreases the available area for flow of the heterogeneous mixture. This results in higher mixture velocities leading to an increase in the erosion of the bed by the mixture, thus establishing equilibrium for this flow pattern.

At lower liquid velocities, the solids pile up in the pipe (or annulus), and full blockage may occur. Experimental evidence and theoretical analysis indicate that this may occur at a relatively high solids concentration not encountered during normal drilling operations. It may also occur if cuttings transport is inefficient and results in high solids concentration, especially in sections in which large cross-sectional areas exist, example in annulus washouts. (Kelessidis, 2004).

2.4 Theory of Cuttings Transport

The ability of a drilling fluid to transport cuttings to the surface is generally referred to as “carrying capacity”. From an engineering point of view, cuttings transport is dependent on well bore inclination, cuttings slip velocity, flow regime, rotary speed of the drill pipe, fluid rheology, fluid flow rate, rate of penetration, cuttings size and shape, wellbore geometry and other drilling parameters.

One of the primary functions of the drilling fluid is to bring drilled cuttings to the surface in a state that enables the drilling-fluid processing equipment to remove them with ease. To achieve this end, quick and efficient removal of cuttings is essential. In aqueous-based fluids, when drilled solids become too small to be removed by the solids-control equipment, they are recirculated downhole and dispersed further by a combination of high-pressure shear from the mud pumps, passing through the bit, and the additional exposure to the drilling fluid. (ASME, 2005).

The maximum flow rate available for hole cleaning in non-vertical wellbores is limited by the pressure at the surface and the flow rate limitation of the downhole motor/bottom hole assembly (BHA). Typical $2\frac{7}{8}$ - in. positive displacement downhole motors (PDM) have flow rate limitations in the range 2.0 – 3.0 bpm (318 – 477 L/min). Surface pumping pressures (SPP) are typically limited to 3500 to 4000 psi while drilling. (Leising et al., 1998). The use of viscosified fluids can reduce annular velocity. A simple rule of thumb for vertical wells is that the annular fluid velocity should be twice the cuttings fall velocity. (Leising et al., 1998). Clearly lower velocities are required for more viscous fluids and smaller cuttings. This rule of thumb cannot capture the complicated physics that contribute to cuttings transport, particularly in highly deviated wells, and for that reason they can never provide a correct guide regarding favourable conditions for efficient hole cleaning. (Leising et al., 1998).

An increase in annular velocity improves the hole cleaning regardless of the flow regime. Although this is evident in turbulent flow, in laminar flow the outcome is not so clear. Increased flow rate results in an increase in settling velocity (owing to shear thinning) and consequently a decrease in settling time, which is offset by more rapid axial transport. (Leising et al., 1998). The traditional guidelines for hole cleaning using unweighed, unviscosified fluids are a minimum annular velocity of about 50 ft/min (0.254 m/sec) in vertical holes and about 100 ft/min (0.508 m/sec) in horizontal holes. (Leising et al., 1998). These values are lower than would normally be applied in conventional drilling due to the high downhole motor revolutions per minute (rpm) and low weight on bit (WOB), resulting in small cuttings. Annular velocities can be reduced further if using viscosified fluids.

The rheological properties and pump rates can be determined from a careful examination of the mechanisms of hole cleaning in different geometries that occur in the drilling of non-vertical boreholes. Of these geometries, the most difficult to clean are openhole annulus near the bit and typically at a high inclination and casing annulus farther up the well and typically at a lower inclination. (Leising et al., 1998).

There are two major points of departure that distinguish hole cleaning in conventional rotary drilling from hole cleaning in Coiled Tubing drilling : (Leising et al., 1998).

- In rotary drilling the drilling fluid must be able to support the cuttings while the pumps are switched off while making a connection; in Coiled Tubing drilling shutting down flow infrequent.
- In rotary drilling the rotation of the drillpipe contributes to hole cleaning by continually entraining cuttings back into the mainstream from the lower side of the hole; in Coiled Tubing drilling the pipe does not rotate above the motor.

2.5 Hole Cleaning

Efficient hole cleaning is especially important in drilling non-vertical boreholes since problems can be exacerbated due to the smaller clearances between the drilling BHA and wellbore. For good hole cleaning, vertical flow is preferable because cuttings fall in the opposite direction to the drilling mud flow. For an inclined well, the direction of cuttings settling is still vertical, but the fluid velocity has a reduced vertical component. This decreases the mud’s capability to suspend drilled cuttings. At a high angle of inclination a particle that sediments through the mud has a short distance to travel before striking the borehole wall. Once it reaches the wall, the particle has little chance to be entrained because local fluid velocities near the wall are very low and insufficient to re-entrain the particle into the flow. Consequently, the residence time of the particle in the annular space increases significantly resulting in a higher concentration of cuttings in the wellbore. This brings about formation of a cuttings bed that creates operational problems. (Sifferman and Becker, 1990).

Generally, turbulent flow provides more efficient cleaning and particle-carrying characteristics but occurs at higher fluid velocities than laminar flow. Geometries and fluid properties commonly encountered in drilling non-vertical boreholes mean that it is often difficult, and frequently impossible, to achieve turbulent flow. (Williams et al., 2001). Maximum flow rate in non-vertical boreholes operations is typically constrained by the downhole motor specification and limitations on surface pressure.

In hole cleaning, the optimum flow regime will vary depending upon the hole angle at which the wellbore is situated. Hole cleaning in highly deviated wellbores is more challenging and critical than in vertical wells. In inclined wells, the fluid velocity has a reduced vertical component that may not be sufficient to transport all the cuttings particles to the surface. These conditions cause the formation of a “cuttings bed” on the low side of the wellbore. The most difficult angle to clean is from 30 – 60 degrees from vertical, where a laminar or turbulent regime works equally well (or poorly). The optimum regime for the vertical (< 30 degrees) and highly deviated (> 60 degrees) wellbores are laminar and turbulent, respectively. (Q'Max Solutions Inc., 2009).
Since cuttings which originate from a highly deviated or horizontal well must travel through all of the wellbore angles and finally to vertical before leaving the well, the safest rheological profile is one with a laminar flow regime. A turbulent pattern will also work as long as the annular velocity can be maintained.

Hole cleaning techniques may be divided into three classes:

- high-viscosity gel-like fluids in laminar flow
- medium-viscosity fluids in laminar/turbulent flow
- low viscosity fluids in turbulent flow

2.5.1 High-viscosity (LSRV) fluids in laminar flow

The power law index (n) of high - Low Shear Rate Viscosity (LSRV) fluids is low, typically around 0.2, which leads to a velocity profile in laminar flow that is much flatter in a central region than for fluids with larger values of n. Consequently, near the wall the shear rate is high and the viscosity is relatively low, and in the central (plug) region, the shear rate is low and the viscosity is high. (Leising et al., 1998).
It is believed that this structure is conducive to good hole cleaning even in highly deviated wells. The argument in support of the use of high-LSRV fluids is that the high wall shear stirs the cuttings up from the bed and entrains them in the core where

they are held the by the high LSRV.

However, Kenny et al., 1996, has also pointed out that cleaning the hole on the narrow side of an eccentric annulus using a power law fluid with a low value of n is particularly difficult because the flow is preferentially diverted to the wider side of the annulus, which outweighs any advantage offered by its higher suspension capability. It is apparent that the advantage of a fluid with a low power law index (e.g., n = 0.2) is that the shear rate remains very low over a central core extending about half way across the pipe. Nevertheless, over a large cross section the shear rate is comparable with the shear rate at the wall, especially in an eccentric annulus.

2.5.2 Medium-viscosity fluids in laminar/turbulent flow

In an inclined hole, with fluids of low to moderate viscosity, drilled cuttings fall quickly to the bottom of the hole and form a bed. Increasing the viscosity reduces the settling velocity and thereby increases the time taken for the particle to fall to the bed, but viscosity on its own cannot prevent the formation of a bed. Increasing the annular velocity, but remaining in laminar flow, has no impact on the time taken for the particles to fall to the bottom (except if the fluid is shear-thinning where the effective viscosity will be reduced). As the bed builds up it constrains the fluid to flow in a narrow cross section above the bed until at a critical depth an equilibrium is reached between particles falling to the bed and particles being removed from the bed by hydrodynamic action.

At low flow rates particles are transported only in bed transport, which includes saltation (the process of continual lifting and falling of particles close to the bed), gross bed motion (cuttings avalanche), and rolling and sliding of individual grains along the bed. (Leising et al., 1998).

At higher flow rates, sand transport takes place while the particles are in suspension. Thus, the sediment is maintained in suspension against the gravitational fall velocity by the diffusion of turbulence from the bed. The rate if cuttings transport is too small to be effective. If a low- to medium-viscosity fluid is pumped in laminar flow, the cuttings will inevitably form a bed. Cuttings transport occurs, if at all, by the mechanisms of rolling, sliding, or saltation. (Leising et al., 1998)

2.5.3 Low-viscosity fluids in turbulent flow

Low-viscosity fluids such as water provide little viscous support and must therefore be pumped at high rates to generate sufficient turbulent activity to support the particles. Zamora and Hanson[22] pointed out that thin fluids in turbulent flow provide superior hole cleaning in high-angle wells. This is the optimum cuttings transport method if an adequate flow rate can be achieved in all areas of the hole.
Generally speaking, cleaning wells in turbulent flows requires pump rates that are considered “high”. Water cannot be pumped at more than a few barrels per minute through most drillstrings, and these rates are certainly too low to remove the cuttings without forming a bed. In a vertical well the standard rule of thumb for efficient hole cleaning is based on a critical annular velocity. (Leising et al., 1998).

In hole cleaning, the rate at which a rising column of fluid will carry solid particles upwards depends on the difference between the velocity of the fluid and the tendency of the particle to fall through the fluid under the influence of gravity.
In a still liquid, a falling particle soon acquires a constant downward velocity, known as the *terminal settling velocity,* which depends on the difference in density between the particle and the liquid; the size and shape of the particle; the viscosity of the liquid, and on whether or not the rate of fall is sufficient to cause turbulence in the immediate vicinity of the particle. (Darley and Gray, 1988).

2.6 Particle Transport in Drilling Environments

One of the biggest factors affecting particle transport is hole angle. Three basic regions exist in which particle behaviour varies; (Power, 2009).

3 Vertical, or near vertical, less than 20 degree angle

4 Deviated, between 20 and 70 degrees

5 Horizontal, greater than 70 degrees

These regions can be differentiated according to particle settling characteristics.

1. Vertical - particles settle within the fluid, settling rates are generally low.
2. Deviated - particles settle out of the fluid, contact the borehole wall and rapidly slide downwards (Boycott settling).
3. Horizontal – particles settle out of the fluid but do not move after this.

2.7 Key Factors in Hole Cleaning

1. Fluid velocity/pump rate: Fluid velocity is an important player in the hole cleaning equation. However for fluids in laminar flow, fluid velocity alone cannot efficiently remove cuttings from the deviated wellbore. Fluid velocity can disturb cuttings lying in the cuttings bed and push them up into the main flow stream. However, if the fluid has inadequate carrying capacity, then many of the cuttings will quickly fall into the cuttings bed once again and the cycle repeats. (Patrick et al., 1996).

2. Downhole Rheology**:** Drilling fluid theological properties are normally measured at 120 °F [49 °C] and at atmospheric pressure. However, in a drilling situation the circulating drilling fluid is exposed to a varied set of temperature and pressure conditions. Data collected over many years shows that drilling fluid viscosities vary with temperature and pressure, something especially important for invert emulsions. For best results when studying fluid flow behaviour and evaluating problems in the field, it is important to apply the drilling fluid rheological parameters either measured or calculated under the actual downhole conditions. (Patrick et al., 1996).

3. Drillpipe Eccentricity: In a deviated well, the drillstring will usually not lie in the

center of the hole (as is often assumed), but will fall toward the lower side of the hole due to gravitational effects. Hence, the position of the drillstring can be described as eccentric. The narrow gap of the eccentric annulus usually lies on the low side of the hole under the drillpipe and the wide gap usually lies above the drillpipe. Drillpipe eccentricity is usually considered positive when the narrow gap lies below the drillpipe and negative when it lies above. Researchers have investigated the effect of drillpipe eccentricity on velocity distribution in the eccentric annulus and have shown it to have major impacts.

In order to limit the development of cuttings beds, it is desirable to maintain certain levels of fluid velocity where the beds may accumulate. In deviated wellbores, cuttings beds largely accumulate under the eccentric drillpipe in the narrow gap. For that reason attention should be paid to optimising fluid velocities under the eccentric drillpipe to better clean the deviated annulus of drilled cuttings. (Patrick et al., 1996).

4. Particle Settling Velocity**:** The rate at which drilled cuttings fall through a static drilling fluid has great importance for cuttings transport in vertical and deviated wellbores. Accurate prediction of particle settling rates is especially critical for highly-deviated wellbores because the vertical gaps below the drillpipe can be quite narrow when the drillpipe is in a highly eccentric position. (Patrick et al., 1996).

5. Pipe Rotation**:** Pipe rotation of the drillstring can aid in cleaning the wellbore of drilled cuttings. The movement of the drillstring through the cuttings bed forces the cuttings into the main flow stream, where they can be carried farther up the deviated annulus. The bending and whipping action of the drillpipe during rotation and backreaming causes frequent fluctuations in drill pipe eccentricity.

6. Vertical and Near Vertical Intervals**:** In near vertical wellbores the cuttings particles generally remain in suspension the whole time they are in the

wellbore. When the pumps are on and the drill string is rotating the particles may be assumed to be distributed uniformly throughout the fluid, though variations in cuttings concentration with measured depth may occur with varying rates of penetration (ROP). In addition, cuttings may accumulate at higher concentrations in regions where the hole diameter goes through an expansion and the annular velocity subsequently decreases, such as a washout or in a drilling riser.

Many hole cleaning problems in vertical wells occur due to excessive ROP overloading the annulus. Overloading the annulus with cuttings can lead to a number of problems. In deepwater, where the fracture gradients are typically low, a high ROP and large concentration of cuttings can result in an equivalent circulating density (ECD) greater than the fracture gradient, leading to formation breakdown and loss of fluid. A second problem that can be associated with high ROP is cuttings settling around the bottom hole assembly (BHA) during connections. If the concentration of cuttings is high, the settled cuttings can lead to a pack-off around the BHA during the connection and subsequent breakdown of the formation when drilling recommences. (Power, 2009).

This problem can often be avoided by circulating for a brief period before the connection. This provides an opportunity for the cuttings to clear the BHA. When drilling with an invert mud system, the cuttings shape is typically finger-like in appearance, i.e., high length to diameter ratio. If the drill bit has aggressive cutters, a high concentration of large cuttings is generated, often resulting in cuttings build up that can be difficult to manage. A solution to this problem may involve selecting cutters that are less aggressive and subsequently produce smaller cuttings. Doing so does not necessarily compromise drilling efficiency or ROP, but may in fact improve the efficiency. The smaller cuttings are easier to transport and thus improve the rate of cuttings removal from the well.

7. Deviated Intervals: Deviated angles typically lead to some of the most troublesome hole cleaning problems. More time is required to transport a single particle through 5,000 ft of a high angle well, than for the same 5,000 ft in a vertical well. Particles can typically remain suspended in high angle wells provided the drill pipe rotation is sufficiently high to agitate the cuttings and the annular flow rate is sufficient to provide lift. Problems can rapidly develop under static conditions or if the flow rate and pipe rotation are not adequate, allowing cuttings to accumulate in beds.

   The process known as Boycott settling occurs under static or low flow conditions where particles rapidly settle out of suspension in deviated wells, accumulate to a critical mass and avalanche back down the annulus. The avalanching phenomenon can be problematic when making connections. The static flow, settled bed of particles and axial drill string movement create ideal conditions for bed slumping or avalanching. (Power, 2009).

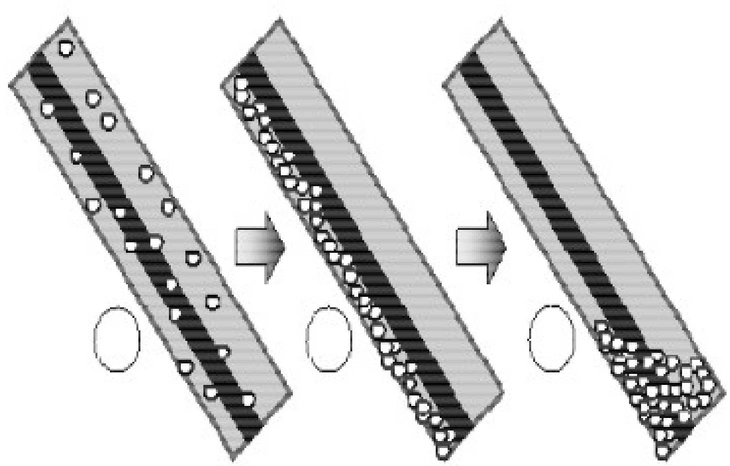

Fig. 2.2: Boycott settling of particles (Power, 2009).

   When drilling deviated sections, or if a deviated section exists higher up the wellbore, weighted sweeps become the pill of choice for improving hole cleaning performance. The weighted sweep is able to better penetrate regions of the annulus below the drill string that may not have the necessary flow to move cuttings that have entered this region. (Power, 2009).

8. Horizontal Intervals: In horizontal sections, the particles settle into a bed and do not move from that position unless there is a disturbance. The transport efficiency or solids removal rate is low in horizontal sections. Adequate flow rate is essential for transporting cuttings in horizontal sections. High density pills are again recommended as a tool to help improve the solids removal efficiency in horizontal intervals.

   Although particles cannot avalanche in horizontal intervals, pack-offs can still be induced if the drillpipe is moved axially in the interval with a cuttings bed present. Hole cleaning should be performed prior to tripping out of the hole so that the drill string is not dragged through a cuttings bed or the cuttings are not pushed up into the build section where avalanching can occur. (Power, 2009)

2.8 Detection of Hole-Cleaning Problems

Historically, the combination of the necessity to pump or backream out of the hole and a notable absence of cuttings coming over the shale shaker prior to pulling out of the hole has been a reliable indicator of poor hole cleaning. When some cuttings are observed, however, the quantity of cuttings itself does not adequately reflect hole-cleaning efficiency. The nature of those cuttings, on the other hand, provides good clues: Good cuttings transport is indicated by sharp edges on the cuttings, whereas smooth and/or small cuttings can indicate poor hole cleaning and/or poor inhibition. With the advent of pressure while drilling (PWD) tools and accurate flow modelling, a number of other indicators have come to light that foreshadow poor hole cleaning and its attendant consequences. (ASME, 2005).

CHAPTER 3

HOLE CLEANING MODELLING

3.1 Rheological Models

Rheological models combine developments in the fields of particle settling and rheology to provide a useful tool for the planning of hole cleaning. Various models are used to describe the shear-stress versus the shear-rate behavior of drilling fluids. The most commonly used are the Power Law, Bingham Plastic, and Herschel-Bulkley.

5.1.1 Power Law Fluid (PLF) Model

Power law model which is also known as Ostwald-de Waele is the simplest and most popular model available today for characterizing fluid rheological behaviour. The main benefit of the generalised power law equation is its applicability to a great number of non-Newtonian fluids over a wide range of shear rates. The mathematical relationship between the shear stress and shear rate of Power Law Fluids can be expressed as shown in Eq. 3.1

$$\tau = K(\gamma)^n \tag{3.1}$$

where, n is the power-law flow index and K is the power-law consistency index.

The Power Law model underestimates the low-shear-rate viscosity. In this model, the value of τ at zero shear rate is always zero. This model describes the behaviour of both the pseudoplastic as well as dilatant fluids. For pseudoplastic fluids $n < 1$, dilatant fluids $n > 1$ and when $n = 1$, it reduces to a Newtonian fluid with $K = \mu$. The rheogram (τ vs. γ) of these power law fluids is shown in Fig. 3.1

Fig. 3.1: Rheogram (τ vs. γ) of Power-Law Fluids

Pseudoplastic (Shear-thinning) fluids have a lower apparent viscosity at higher shear rates, and are usually solutions of large, polymeric molecules in a solvent with smaller molecules. It is generally supposed that the large molecular chains tumble at random and affect large volumes of fluid under low shear, but that they gradually align themselves in the direction of increasing shear and produce less resistance.

Dilatant (shear-thickening) fluids increase in apparent viscosity at higher shear rates. The dilatant effect occurs when closely packed particles are combined with enough liquid to fill the gaps between them. At low velocities, the liquid acts as a lubricant, and the dilatant flows easily. At higher velocities, the liquid is unable to fill the gaps created between particles, and friction greatly increases, causing an increase in viscosity.

The apparent or effective viscosity of a power law fluid is given by Eq. 3.2:

$$\mu_{eff} = K(\gamma)^{n-1} \tag{3.2}$$

The ***flow index,*** n, measures the degree to which the fluid is shear-thinning or shear-thickening.

K and n can be determined by making a logarithmic plot of the effective viscosity versus shear rate where (n^{-1}) will be the slope and the consistency index, *K* will be the effective viscosity at unity shear rate.

5.1.2 Bingham Plastic Fluid (BPF) model

This is a two-parameter flow model which is characterized by a straight line when a rectilinear plot of shear stress versus shear rate is made but this straight line does not pass through the origin. This model has a yield stress that must be overcome before the fluid will flow. Thus, a certain pressure would have to be applied to the mud to initiate movement. The Bingham plastic model, because of its simplicity is widely used to characterize drilling muds and cement slurries.

The positive intercept on the shear stress axis gives the yield stress. The equation describing a Bingham plastic fluid is given by:

$$\tau = \tau_0 + \mu_p (\gamma) \tag{3.3}$$

where, μ_p is plastic viscosity and τ_0 is the yield stress.

In the Bingham Plastic Fluid model, the plastic viscosity is represented by the ratio between the shear stress above minimum yield stress and shear rate. Plastic viscosity is used as an indicator of the size, shape, distribution and quantity of solids, and the viscosity of the liquid phase. The yield stress is a measure of electrical attractive forces in the drilling fluid under flowing conditions.

The apparent viscosity, however, is the ratio between the shear stress and shear rate. It is also called shear viscosity if it depends on the rate of shear. A Bingham plastic fluid is a viscoplastic material that behaves as a rigid body at low stresses but flows as a viscous fluid at high stress.

5.1.3 The Herschel-Bulkley Rheological Model

The behaviour of nearly all common drilling fluids having fluids measurable shear stresses can be simulated using the Herschel-Bulkley or Yield-Power Law (YPL) rheological model. This three-parameter model may be thought of as a hybrid between the Power Law and Bingham Plastic models. In fact, it is essentially the Power Law model with a yield stress. The Bingham plastic model cannot describe fluids that exhibit a yield point and viscosity that is either shear stress or shear rate dependent. To correct this deficiency, the second term in` Eq. 3.3 is replaced by the power law expression. A fluid's rheological behaviour according to Herschel-Bulkley model is described by the following equation:

$$\tau = \tau_0 + K(\gamma)^n \quad (3.4)$$

where,

- τ is the measured shear stress at a specific shear rate.
- τ_0 is the yield stress at zero shear rate.
- γ is the specific shear rate.
- K is the consistency index (plastic viscosity).
- n is the fluid flow index.

When n =1, the YPL model reduces to the Bingham Plastic model. When the fluid yield stress (τ_0) is zero, the YPL model becomes the Power Law model.

Figure 3.2 shows the rheogram for Newtonian, Bingham Plastic, Power-Law Fluid and Typical Drilling Fluid Models.

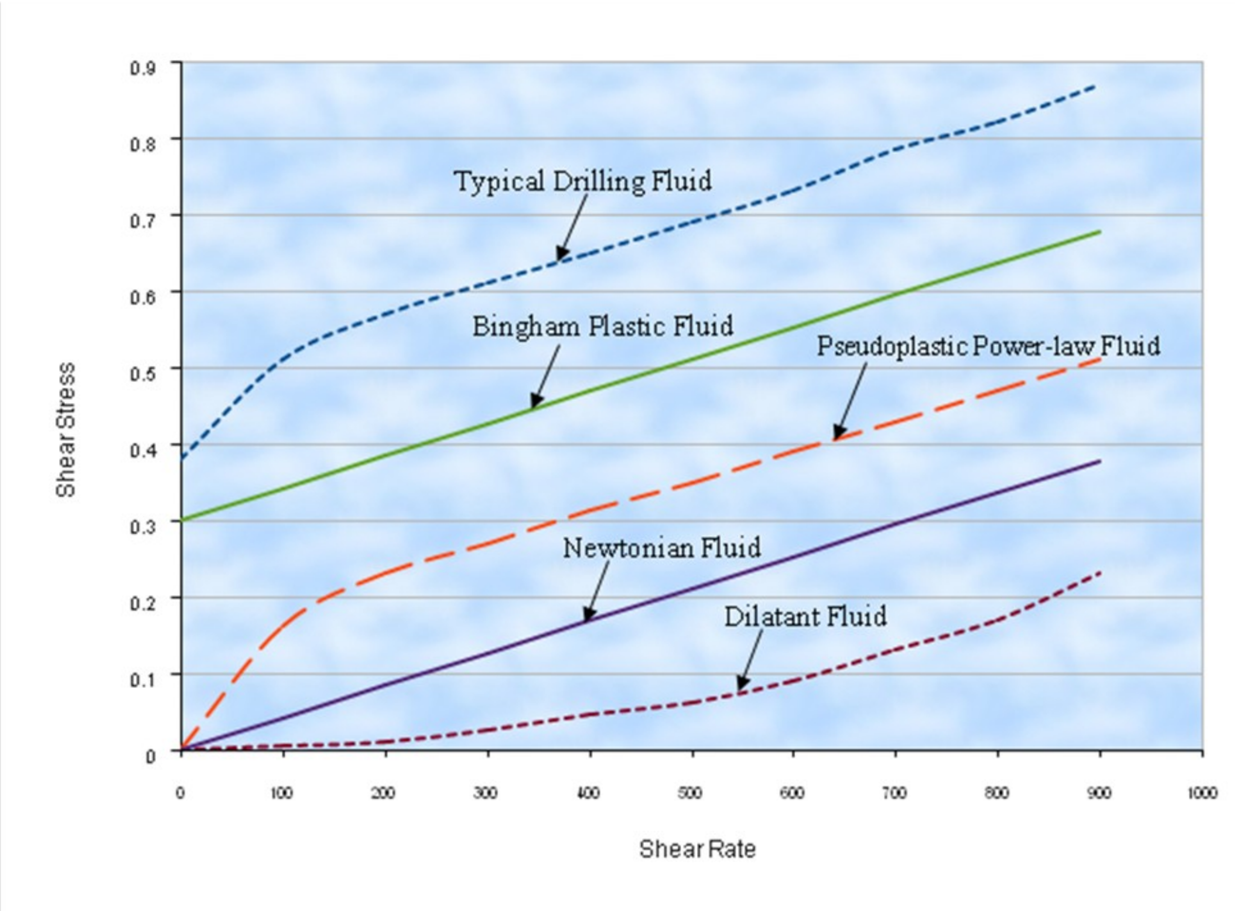

Fig. 3.2: Rheogram of Newtonian, Bingham Plastic, Power-Law and Typical Drilling Fluids.

3.2 Cuttings Slip Velocity, Cuttings Net Rise Velocity and Transport Efficiency

Drilled cuttings have the tendency to fall down (slip) through the fluid medium at a velocity referred to as the ***cutting slip velocity*** *(Vs).* For the fluid to lift to the surface, the fluid annular velocity (AV) must exceed the cutting slip velocity (Vs). The relative velocity between fluid annular velocity and cutting slip velocity is known as the ***cutting net rise velocity*** ***(V_t)***.

Cuttings transport efficiency (E_t), is simply the ratio of cuttings transport to annular velocity. It is perhaps more important than an actual cuttings transport value and it is given by:

$$E_t = \frac{V_t}{AV} \times 100 = \left(1 - \frac{Vs}{AV}\right) \times 100 = 100\, R_t \qquad (3.5)$$

Where R_t is the cuttings transport ratio

3.3 Axial and Radial Components of Particle Slip Velocity

The behaviour of cuttings in inclined wells is very different from that in vertical wells. In a vertical hole, slip velocity acts parallel to the axis of the hole. In inclined holes, slip velocity has two components, an axial one and a radial one. According to gravity laws, only the axial component of the slip velocity exists in the case of a vertical annulus:

$$Vs = Vsa \qquad (3.6)$$

This situation changes while the annulus is inclined gradually. The component of the slip velocity appears as

$$Vsa = Vs\ Cos\theta \qquad (3.7)$$

and $Vsr = Vs\ Sin\theta$

(3.8)

This situation is shown in Fig. 3.3

Obviously, as the angle of inclination is increased, the axial component of the slip velocity decreases, reaching zero value at the horizontal position of the annulus. At the same time, the radial component reaches a maximum in the position mentioned.

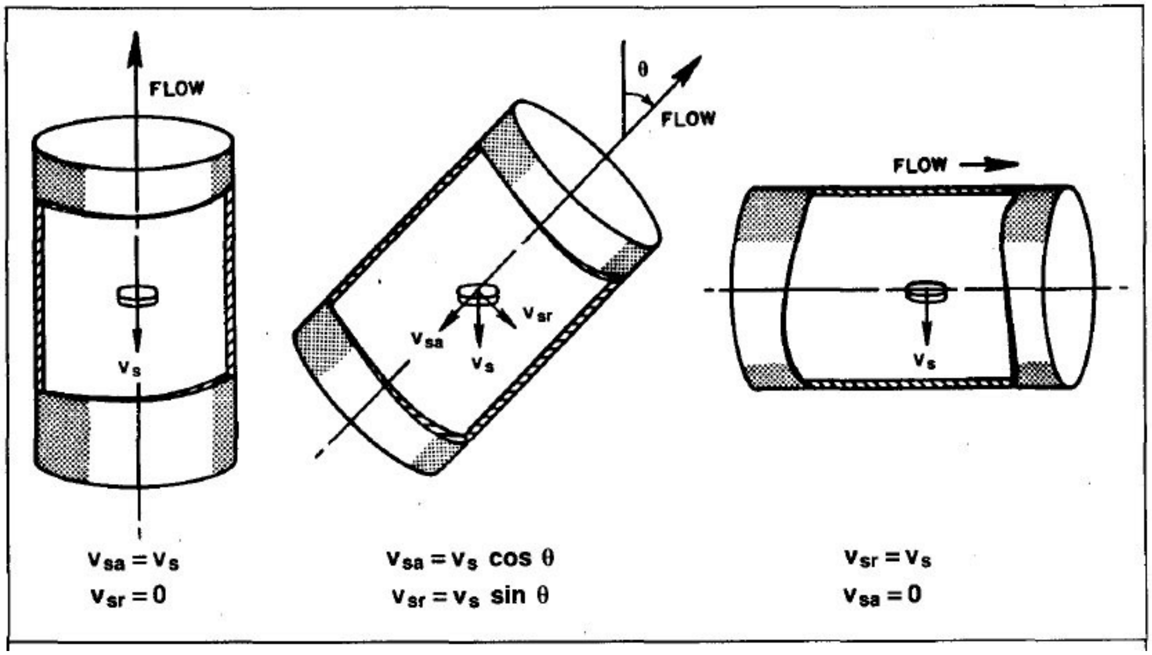

Fig. 3.3: Particle settling velocity in an inclined annulus **(**Okrajni and Azar, 1986)

3.4 Cuttings Concentration, (vol %)

Due to the slip velocity of cuttings in the annulus, the concentration of cuttings in the annulus depends upon the transport efficiency as well as the volumetric flow rate and the rate at which cuttings are generated at the bit (ROP and hole size). Experience has shown that cuttings concentration in excess of five (5) volume % can lead to a pack-off, tight hole, or stuck pipe. (Baker Hughes, 2006). When drilling in soft formations, where pipe connections in the drillstring are made as rapidly as possible, the cuttings concentration may easily exceed 5%, if ROP is uncontrolled. (Baker Hughes, 2006).

The cuttings concentration is calculated by:

$$C_a = \frac{(ROP)\, d_h^2}{14.71 (E_t) Q} \times 100 \tag{3.9}$$

where,

Ca = cuttings concentration, (vol %)
d_h = hole diameter, (in.)

E_t = transport efficiency, (%)

Q = flow rate, (gal/min)

ROP = rate of penetration, (ft/hr)

(Baker Hughes, 2006).

Other equations, their development and applications can be seen in appendix A.

CHAPTER 4

DISCUSSION AND ANALYSIS OF RESULTS

4.1 Introduction

A wide range of cuttings concentration was observed in this study. The rheological parameters examined were the power law flow index, consistency index, plastic viscosity (PV), mud yield point (YP), YP/PV ratio, apparent viscosity, effective viscosity and the Fann viscometer dial readings. Power law fluid was used in this study. Three annular mud velocities were considered, (3.82, 2.86 and 1.91 ft/sec). Hole inclinations of 30°, 45° and 70° from the vertical were taken into account.

The values of the other variables used in this study are shown in Table 4.1 while the muds used and their parameters are shown in Table 4.2

Inside diameter of casing or hole size (d_h)	5 in.
Outside diameter of pipe or tubing (d_p)	2 in.
Diameter of cuttings (DialP)	0.25 in.
Density of cuttings (DensP)	22 ppg
Rate of Penetration (ROP)	50 ft/hr

Table 4.1: Values of other variables used in the annulus cleaning study

4.2 Effects of some of the rheological parameters on critical annular velocity

Plots of critical annular velocity versus some of the major rheological parameters mentioned above were made from which a lot of valuable information can be deduced. For effective lift and transportation of the cuttings, the critical annular mud velocity should be greater than the settling velocity of the largest cutting. Low critical annular velocity will lead to an undesirably high concentration of cuttings in the annulus.

In Fig. 4.1, it can be shown that, an increase in the flow index (n) increases the critical annular velocity. The amount of cuttings concentration in the annulus will therefore be on the decrease as the value of n increases because of the tendency of n to cause an increase in the fluid velocity in the annulus.

Mud No.	Density (lbm/gal)	Dial Readings Fann Rotary Speed, rev/min (Shear Rate, seconds^{-1})						App. Viscosity (cp)	PV (cp)	YP (lbf/100 ft^2)	YP/PV	na	Ka (lbf-sec^n)/ft^2
		ϴ3	ϴ6	ϴ100	ϴ200	ϴ300	ϴ600						
1	8.45	1	1	8	14	18	30	15	12	6	0.5	0.6276	1.8357
2	8.45	1	1	7	10	12	18	9	6	6	1.0	0.5396	2.1192
3	8.45	1	2	6	8	9	12	6	3	6	2.0	0.4771	2.3465
4	8.45	1	2	14	24	30	50	25	20	10	0.5	0.7386	1.5318
5	8.45	1	2	12	17	20	30	15	10	10	1.0	0.6505	1.7684
6	8.45	2	3	11	14	15	20	10	5	10	2.0	0.4375	5.0060
7	8.50	2	3	23	38	48	80	40	32	16	0.5	0.6901	3.3156
8	8.50	2	4	18	28	32	48	24	16	16	1.0	0.6021	3.8277
9	8.50	4	6	17	23	24	32	16	8	16	2.0	0.3891	10.8356
10	8.50	2	6	26	45	60	100	50	40	20	0.5	0.7386	3.0636
11	8.50	6	8	21	34	40	60	30	20	20	1.0	0.4120	15.6580
12	8.50	7	10	22	29	30	40	20	10	20	2.0	0.3160	21.3624

Table 4.2: Mud Parameters used for the study (Becker et al., 1991)

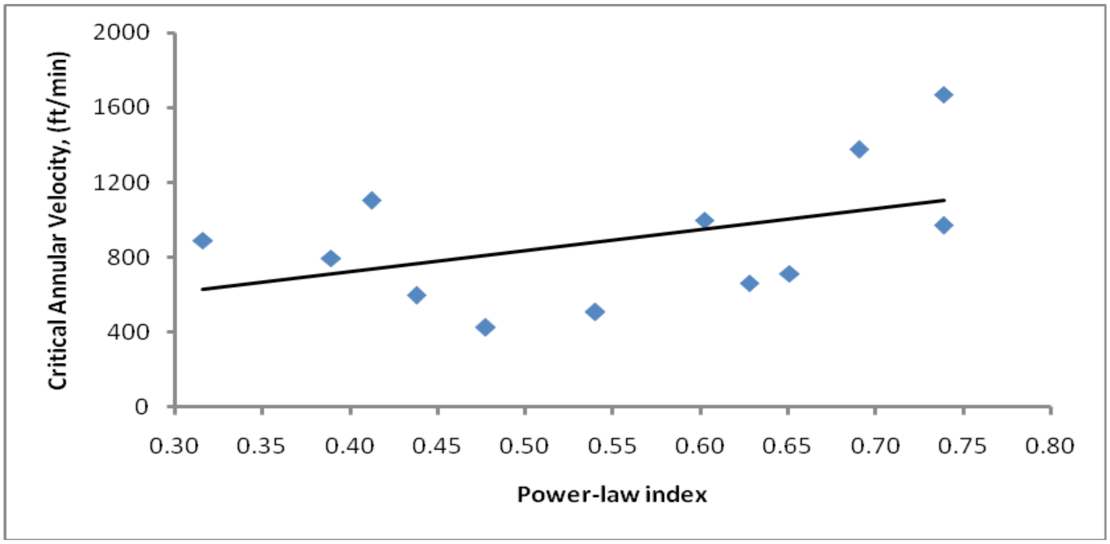

Fig. 4.1: Effect of power-law index on critical annular velocity

Fig. 4.2 shows how the power-law consistency index influences the critical annular velocity which aids in efficient hole cleaning process. According to this study, the effect of consistency index corrected for the annulus on the critical annular velocity is minimal. Thus, the figure shows that increasing values of K increase critical annular velocity but only slightly. It can be said that the critical annular velocity is directly proportional to the consistency index.

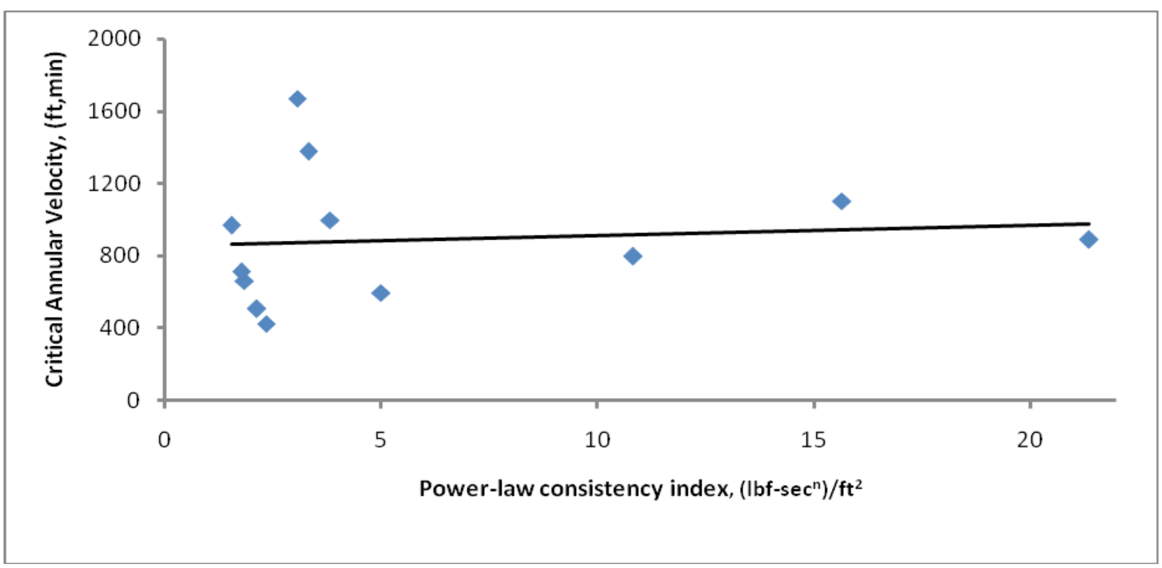

Fig. 4.2: Effect of power-law consistency index on critical annular velocity

Critical annular velocity is seen to increase significantly with an increase in plastic viscosity. This is depicted in Fig. 4.3. To ensure effective and successful cuttings removal from the annulus it is then advisable to increase the plastic viscosity which will indirectly increase the critical annular velocity required to accomplish the hole cleaning purpose.

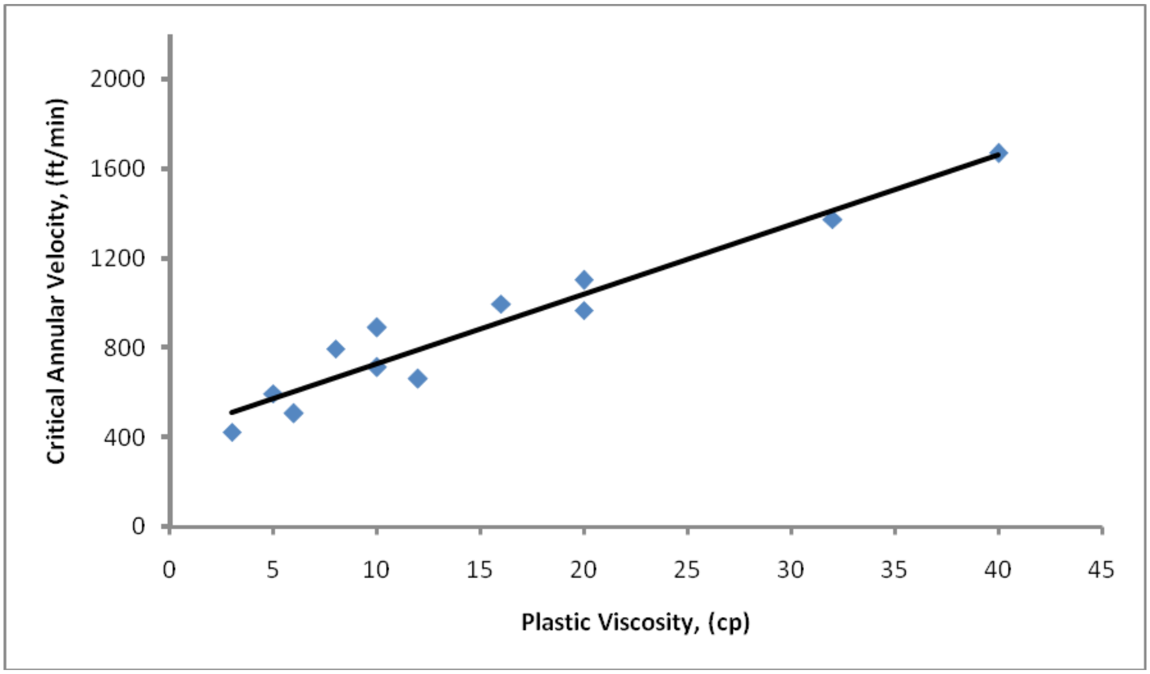

Fig. 4.3: Effect of plastic viscosity on critical annular velocity

A graph of critical annular velocity versus yield point can also be seen in Fig. 4.4. The trend of this plot is similar to that in Fig. 4.3. It shows a significant increase in critical annular velocity as the yield point is increased. Therefore a high yield point will ensure a good hole cleaning process.

The combined effect of yield point and plastic viscosity on the critical annular velocity was also investigated under this study. This was done by plotting a graph of YP/PV ratio against the critical annular velocity. This is shown in Fig. 4.5.

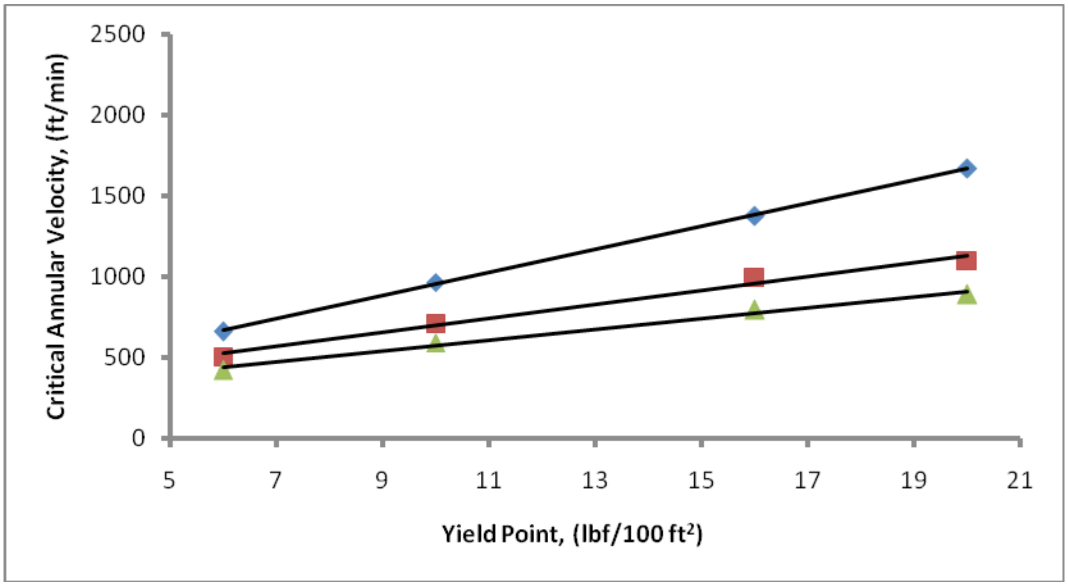

Fig. 4.4: Effect of yield point on critical annular velocity

As it was seen from Figures 4.3 and 4.4 that critical annular velocity increases with increase in plastic viscosity and yield point respectively, then by the combination of these information and that from Fig. 4.5, it can therefore be said that the PV value must be increased as well as the YP value but in a way that the critical annular velocity can bring about a good cuttings transportation.

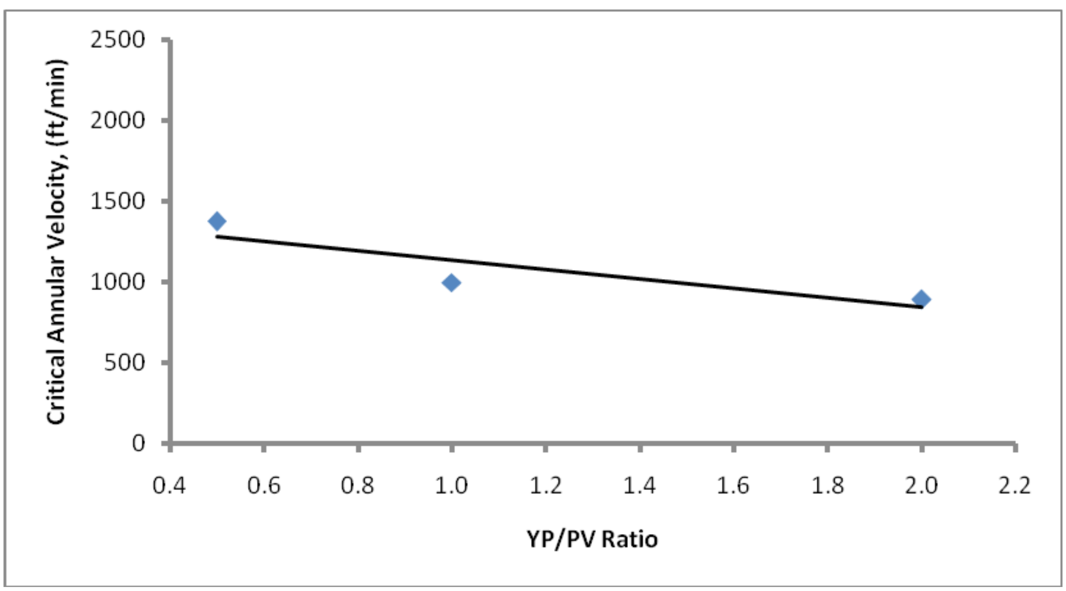

Fig. 4.5: Effect of YP/PV ratio on critical annular velocity

4.3 Effects of rheological parameters on cuttings concentration

In order to know the influence that rheological parameters have on the amount cuttings generated in the annulus, various plots were made.

Figures 4.6 (a) and (b) are plots of cuttings concentration versus apparent viscosity. Both plots show that, cuttings concentration declines with increasing value of apparent viscosity. Again, it was observed that, Fig. 4.6 (b) which has a lower annular mud velocity recorded higher values of cuttings concentration when compared to Fig. 4.6 (a). For efficient hole cleaning process, it is then important to resort to high apparent viscosity values while maintaining a high annular mud velocity. See similar plot for annular velocity of 1.91 ft/sec in Fig. C9

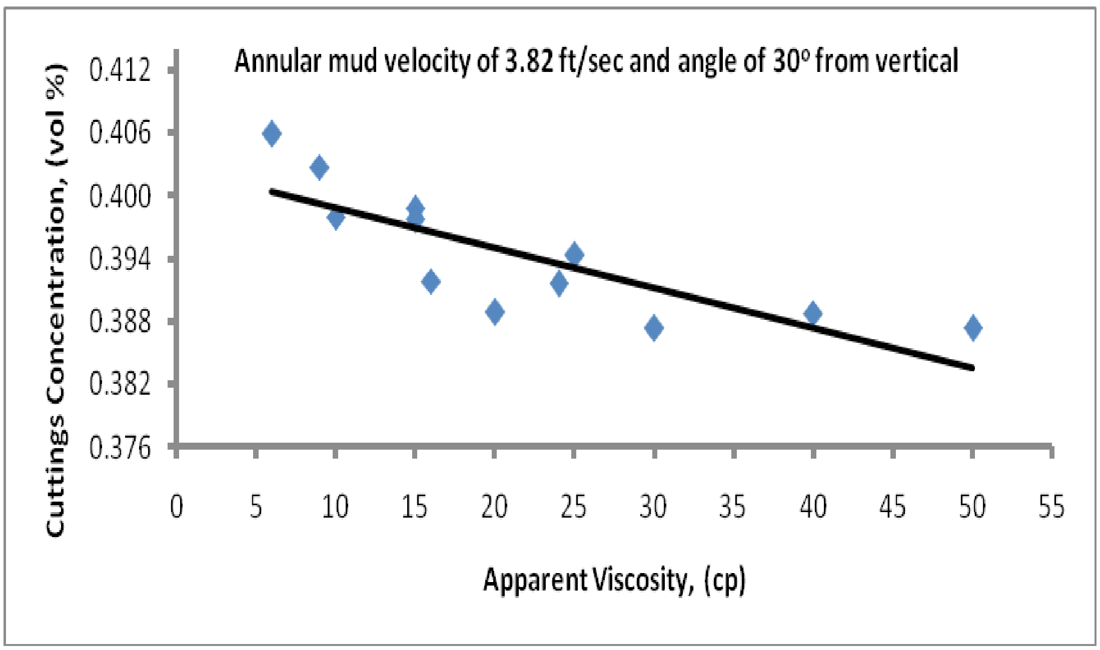

Fig. 4.6 (a): Annular cuttings concentration vs. Apparent viscosity for annular velocity of 3.82 ft/sec and angle of 30° from vertical

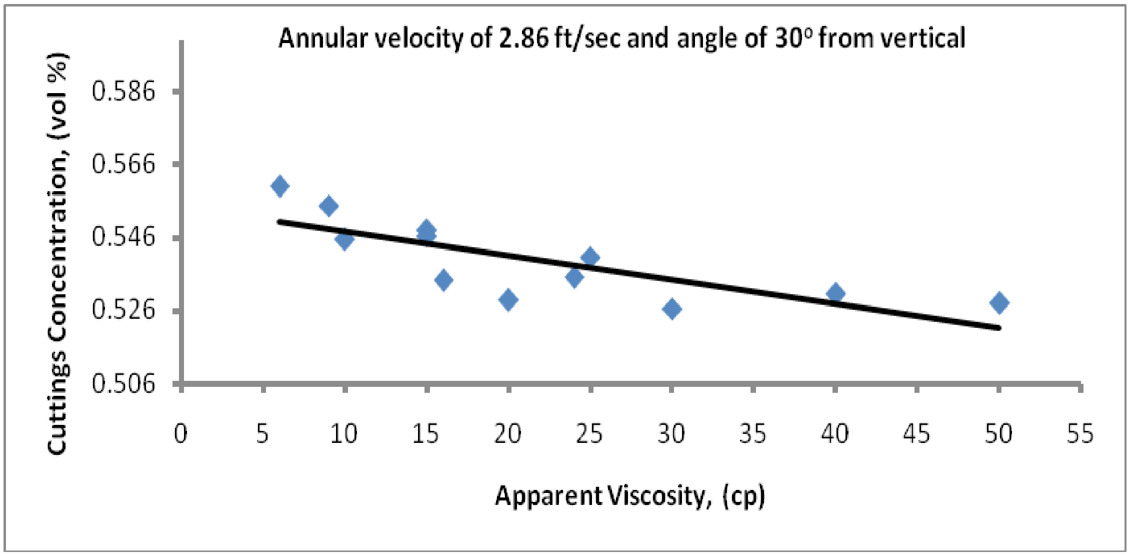

Fig. 4.6 (b): Annular cuttings concentration vs. Apparent viscosity for annular velocity of 2.86 ft/sec and angle of 30° from vertical

In Figures 4.7 (a) and (b), similar trends as in Fig 4.6 are shown. These figures are as a result of plot of cuttings concentration versus effective viscosity. It can be deduced from these plots that increasing effective viscosity and increasing annular mud velocity help in promoting good and efficient cuttings removal.

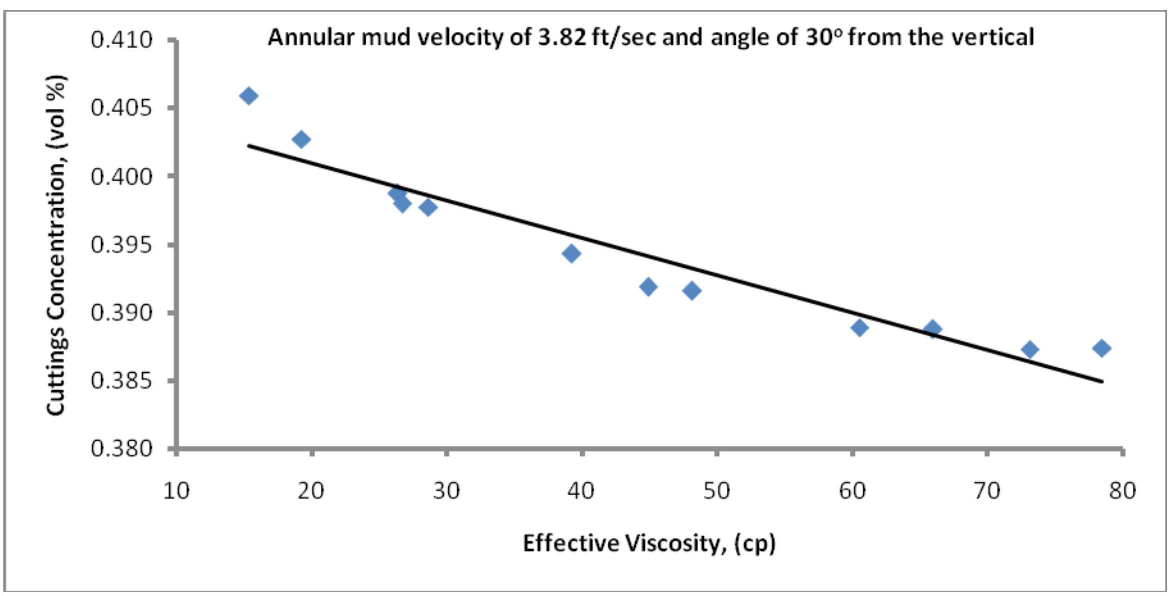

Fig. 4.7 (a): Annular cuttings concentration vs. Effective viscosity for annular velocity of 3.82 ft/sec and angle of 30° from vertical

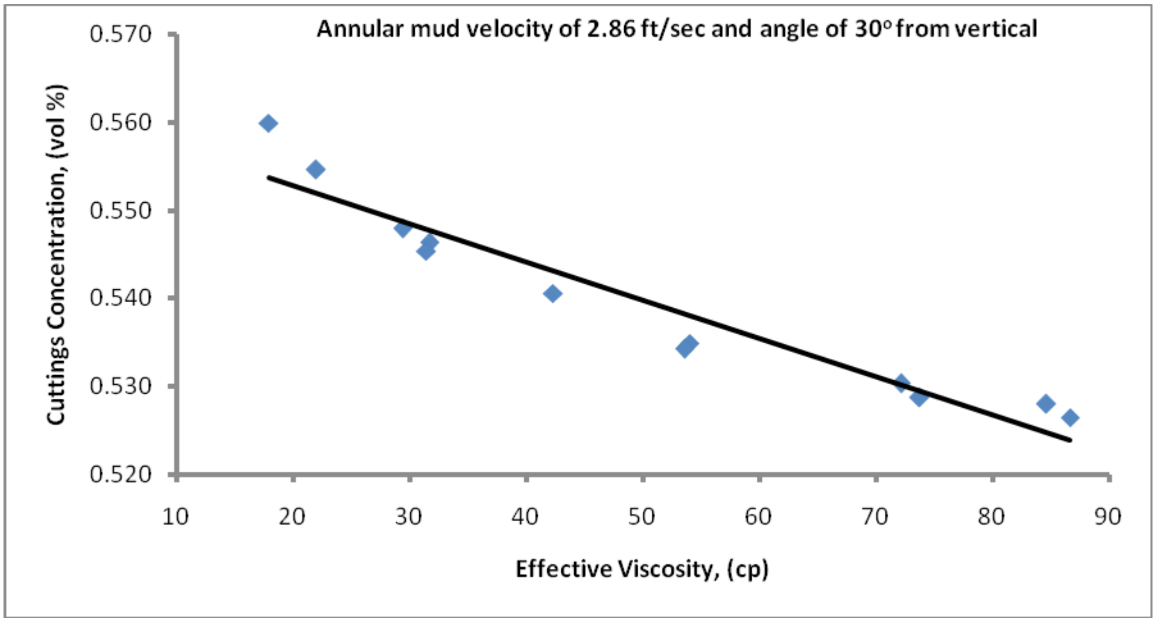

Fig. 4.7 (b): Annular cuttings concentration vs. Effective viscosity for annular velocity of 2.86 ft/sec and angle of 30° from vertical

In the plots that follow, the cuttings accumulation in the annulus have been plotted against the rheological parameters taken into accounts the angle of inclination of the drilled hole.

Fig. 4.8 shows the effects of the power-law flow index on the cuttings concentration at the selected annular mud velocities for $\theta = 30°$ from vertical. From this plot, it can clearly be shown that the higher the annular mud velocity, the lower the cuttings concentration. Increasing values of the power-law flow index will also lead to an increase in cuttings concentration. Similar trend is obtained for hole angles 45° and 70° from vertical. (See Fig. C1 and C2 of appendix).

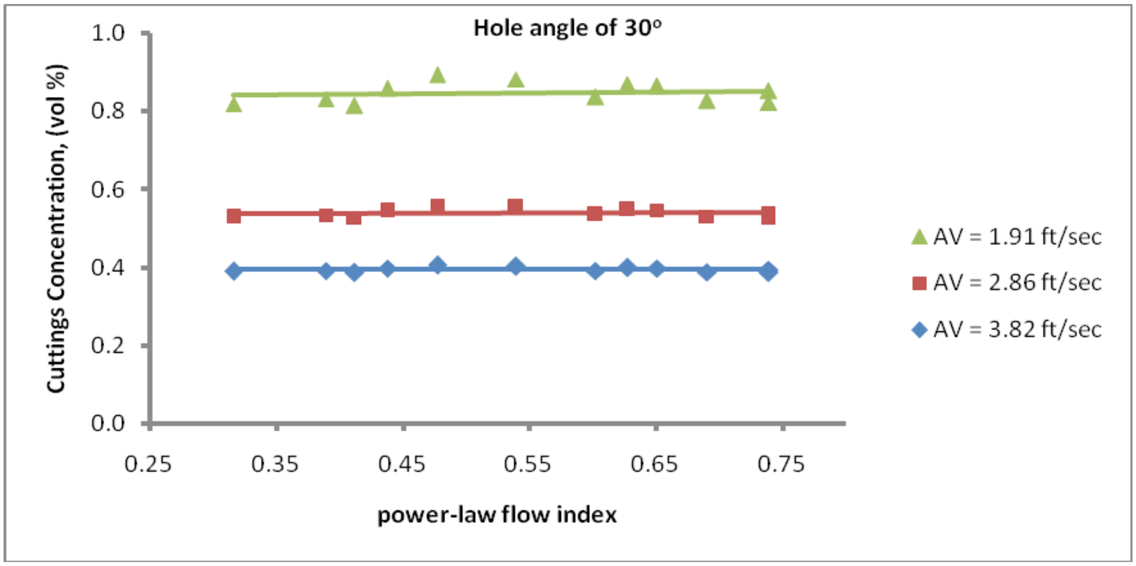

Fig. 4.8: Combined effect of power-law flow index on cuttings concentration (θ =30°)

In addition, Figures 4.9 (a) and (b) also show how the power-law flow index (n_a) affects cuttings concentration. This time, all the hole angles are considered for each annular velocity. For all the angle of inclinations, it is observed that power-law flow index increases cuttings concentration as its value increases. The plots at θ = 70° from vertical gave the lowest amount of cuttings concentration followed by that at θ = 45° while θ = 30° gave the highest.

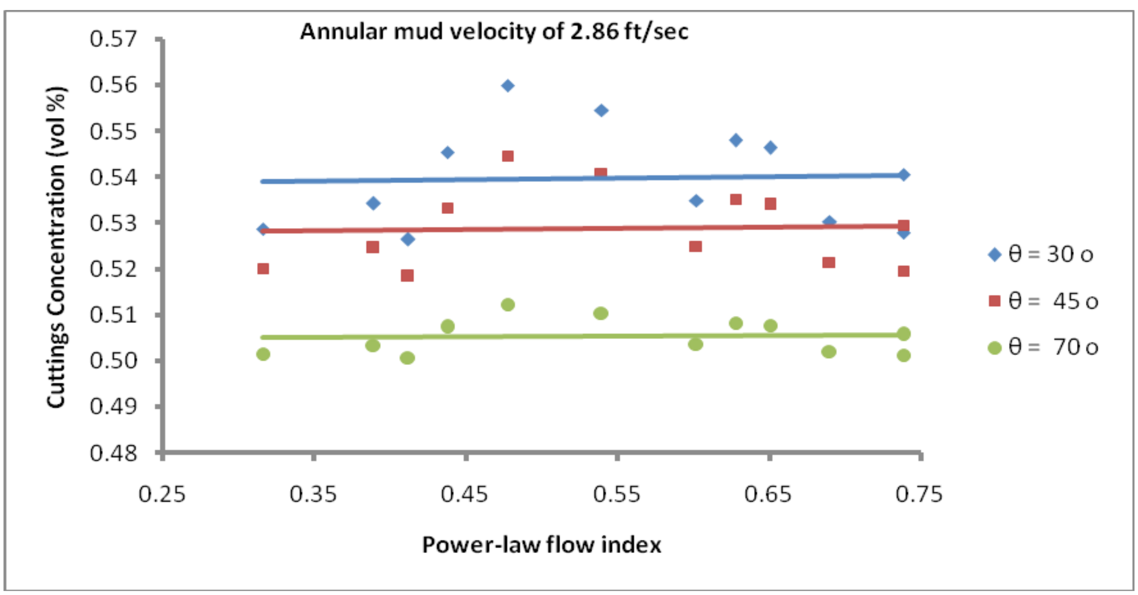

Fig. 4.9 (a): Annular cuttings concentration vs. Power-law flow index for annular velocity of 2.86 ft/sec

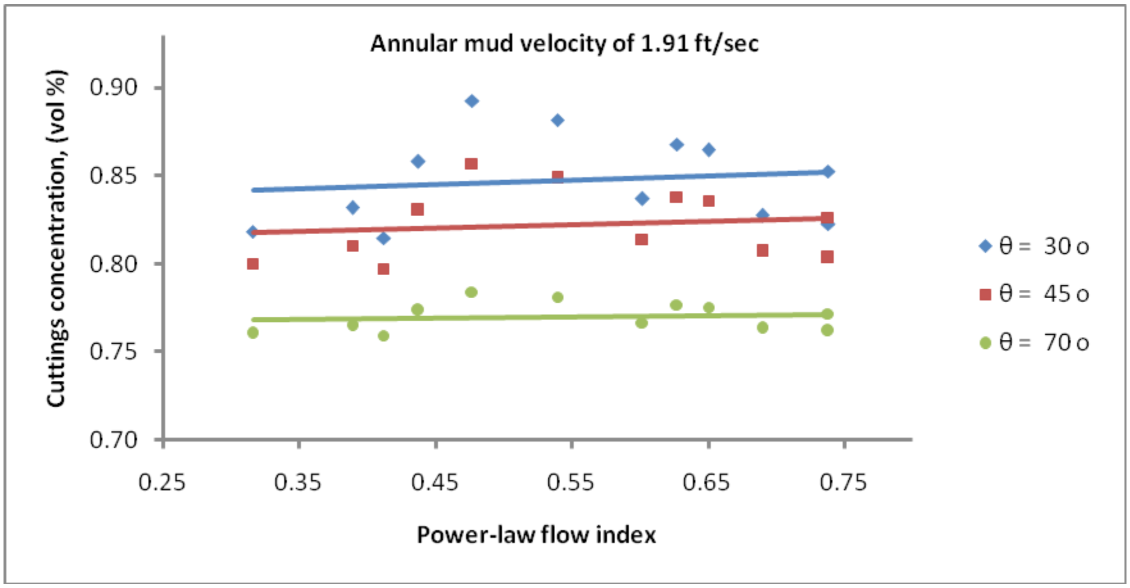

Fig. 4.9 (b): Annular cuttings concentration vs. Power-law flow index for annular velocity of 1.91 ft/sec

Considering the graph of the combined effect of power-law consistency index on cuttings concentration for hole angle of θ = 30° from vertical, an opposite pattern to that shown in Fig. 4.8 was obtained. (See Fig. 4.10). Thus cuttings concentration reduces with increasing power-law consistency index. Also the annular mud velocity greatly influences the cuttings concentration. The higher its value the lower is the volume of cuttings generated. Similar plots for θ = 45° and θ = 70° are shown in Figures C3 and C4 in the appendix.

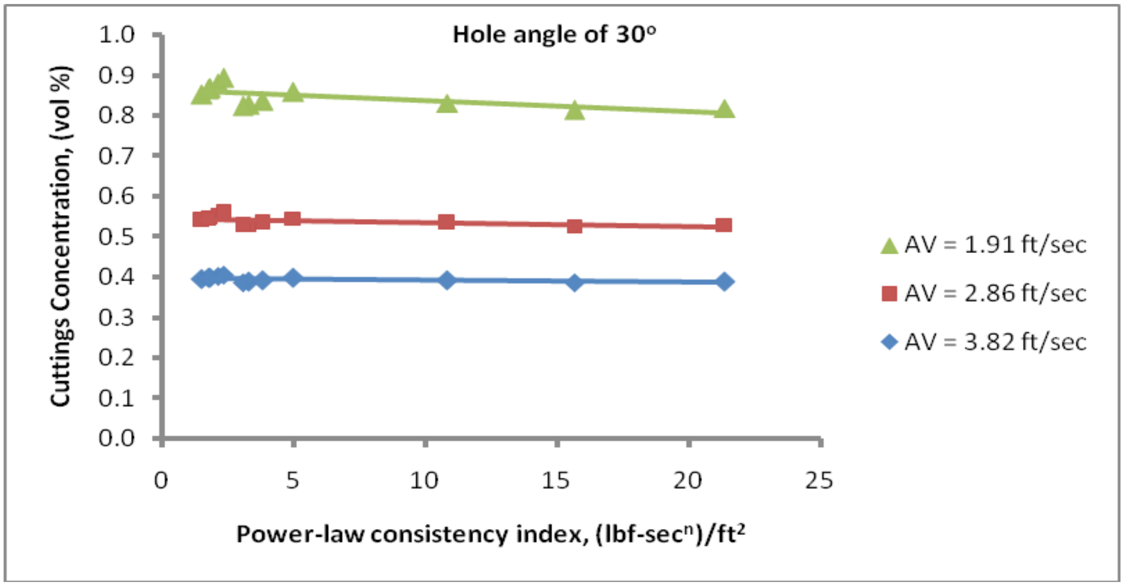

Fig. 4.10 (a): Combined effect of the power-law consistency index on cuttings concentration for hole angle of 30°

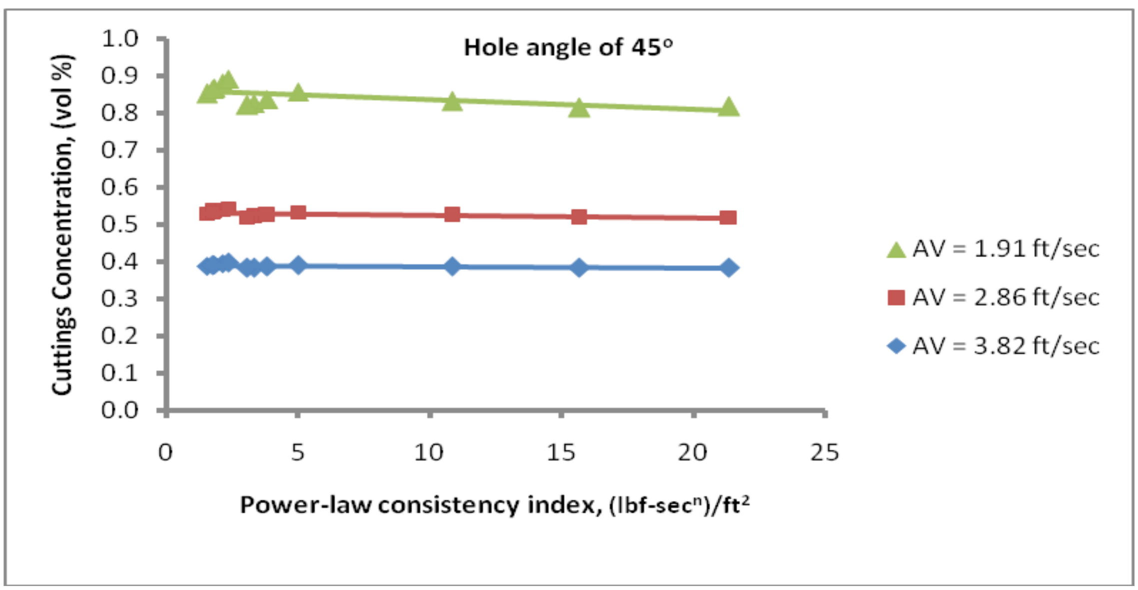

Fig. 4.10 (b): Combined effect of the power-law consistency index on cuttings concentration for hole angle of 45°

With regards to how the power-law consistency index affects the cuttings concentration at a given annular velocity and varying hole angles, this can be seen in Fig. 4.11 (a) and (b) below. The cuttings concentration again on this round decreases as the power-law consistency index (K_a) increases no matter the angle of inclination.

An increasing value of K_a is therefore required to ensure successful cuttings transportation.

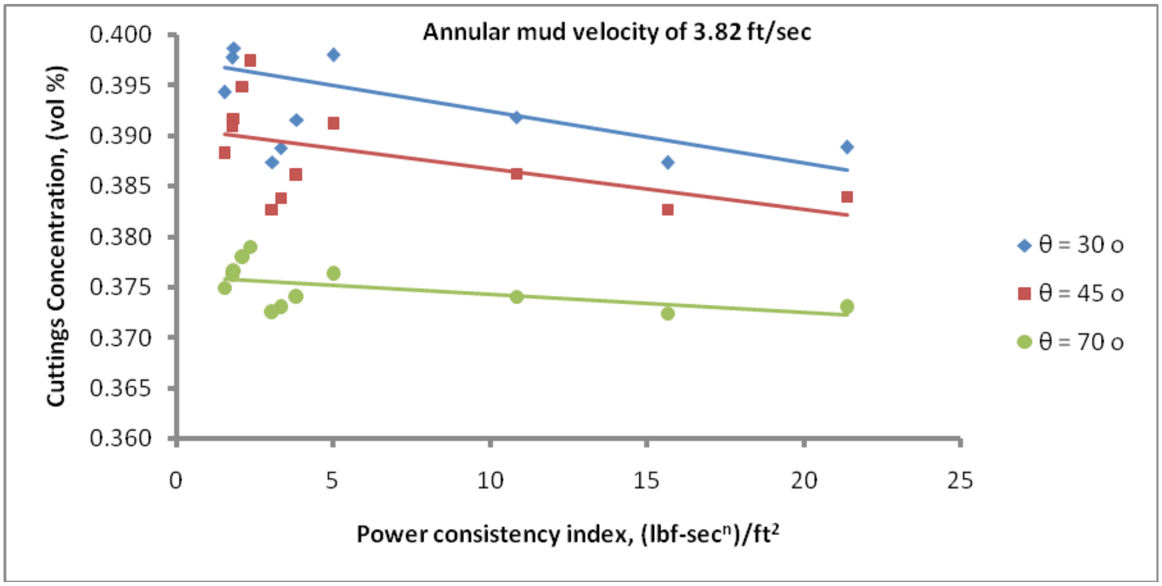

Fig. 4.11(a): Annular cuttings concentration vs. Power-law consistency index for annular velocity of 3.82 ft/sec

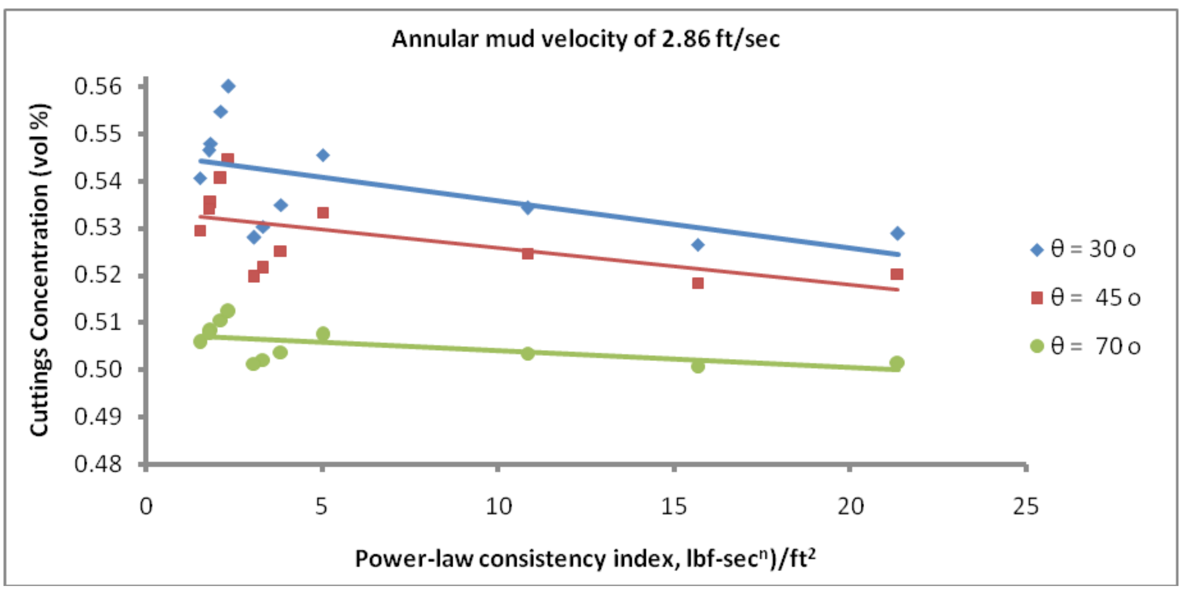

Fig. 4.11(b): Annular cuttings concentration vs. Power-law consistency index for annular velocity of 2.86 ft/sec

Figures 4.12 (a) and (b) below show the effect of plastic viscosity on the cuttings concentration. In both plots, the cuttings concentration declines as the plastic viscosity increases. By the combination of information obtained from these plots and that from Fig. 4.3, it is obvious that an increasing critical annular velocity together with increasing plastic viscosity will bring about an excellent hole cleaning.

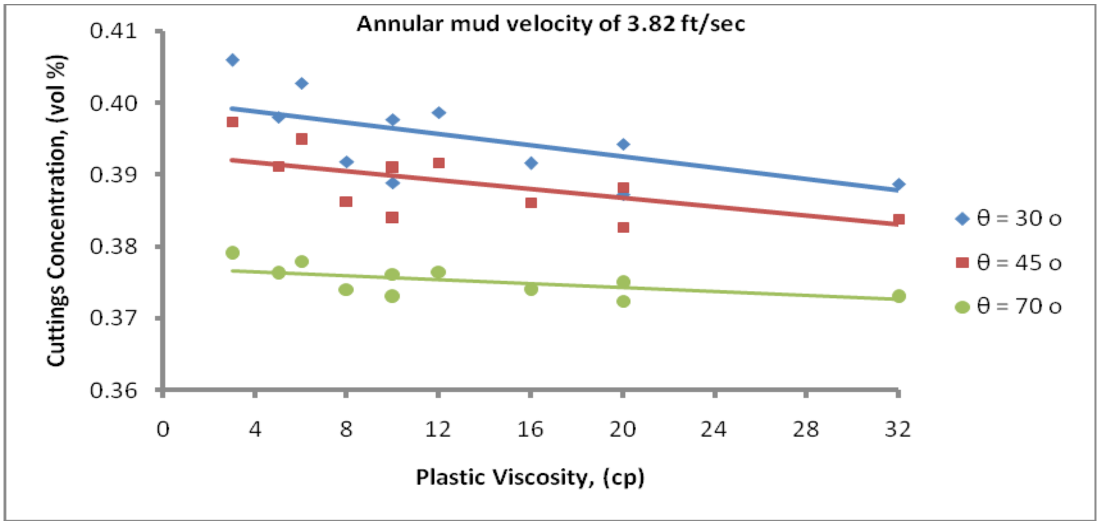

Fig. 4.12 (a): Annular cuttings concentration vs. Plastic viscosity for annular velocity of 3.82 ft/sec

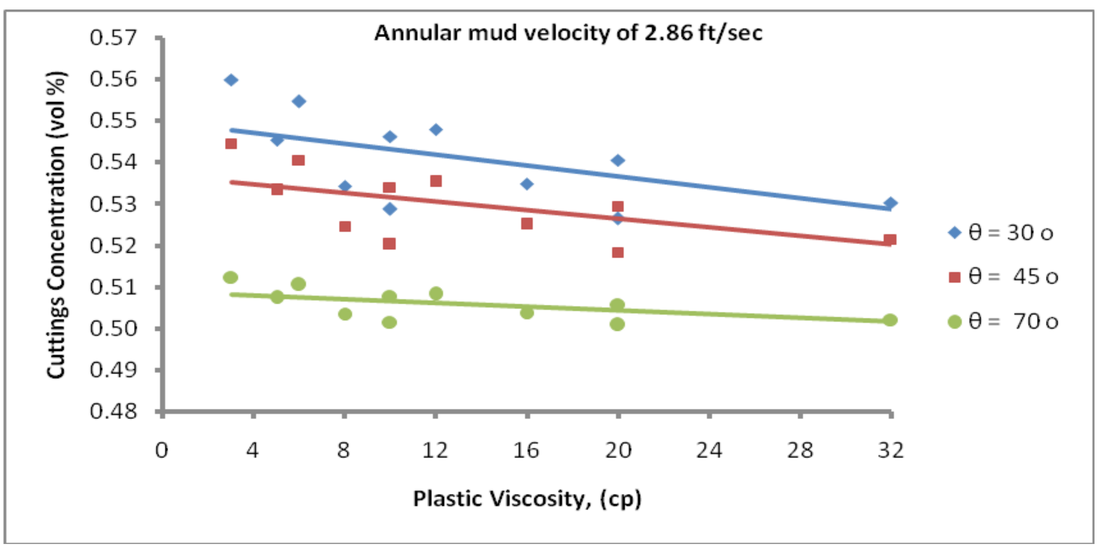

Fig. 4.12 (b): Annular cuttings concentration vs. Plastic viscosity for annular velocity of 2.86 ft/sec

The effect of yield point (YP) on the cuttings concentration (C_a) was also investigated. Fig. 4.13 (a) and (b) show how C_a changes with YP at different hole angles. Also the combined effect of yield point on cuttings concentration at varying AVs for each hole angle can be seen in Figures C5 and C6 in the appendix. It is clear to deduce from these plots that higher values of YP will be an advantage as it will lead to a decrease in the amount of cuttings in the annulus thereby enhancing efficient hole cleaning.

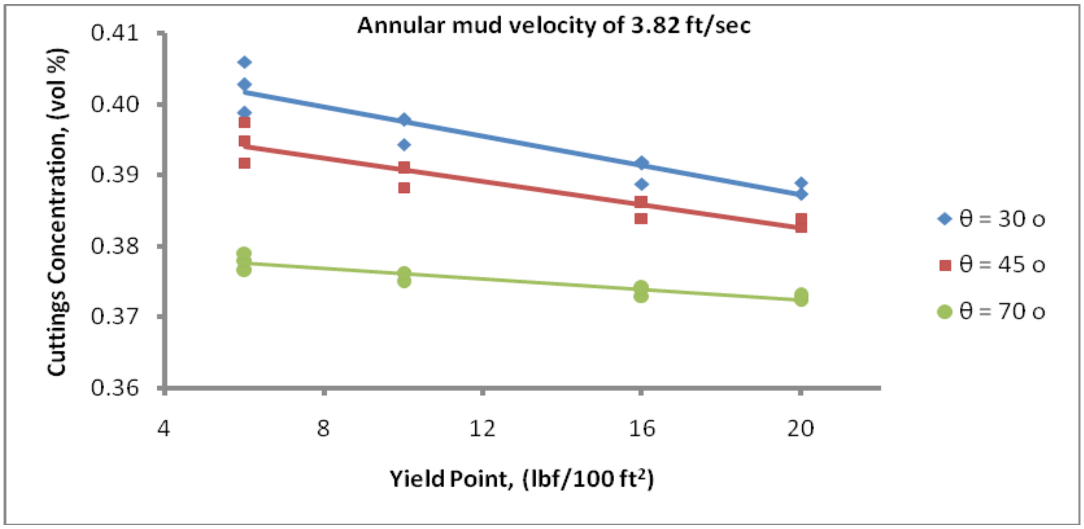

Fig. 4.13 (a): Annular cuttings concentration vs. Yield point for annular velocity of 3.82 ft/sec

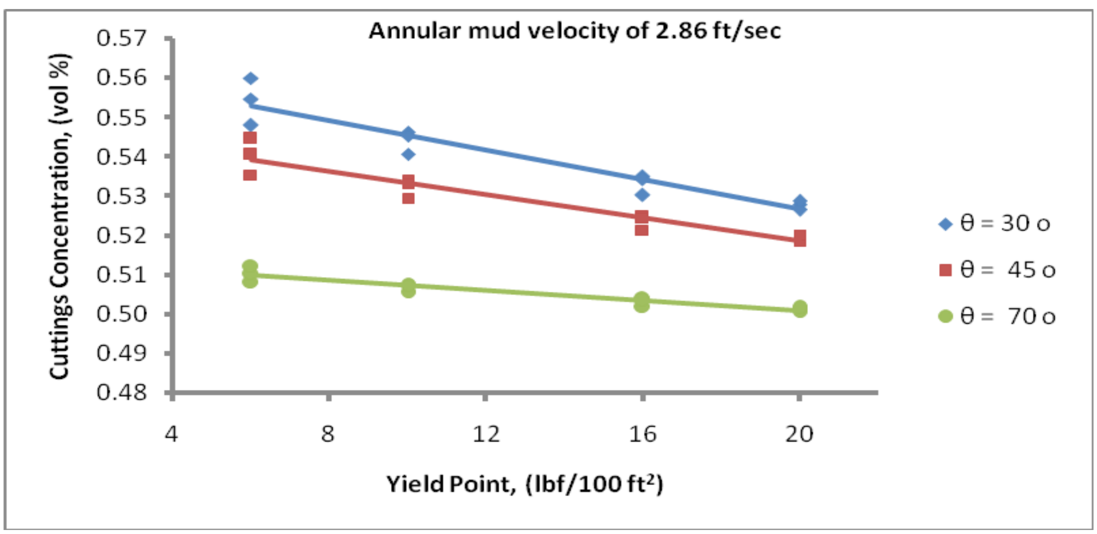

Fig. 4.13 (b): Annular cuttings concentration vs. Yield point for annular velocity of 2.86 ft/sec

The combined effect of both yield point (YP) and plastic viscosity (PV) on the amount of cuttings concentration was also investigated in this study. Relatively high plastic viscosities considerably reduce the YP/PV ratio. From the plots of cuttings concentration versus YP/PV ratio shown in Figures 4.14 (a) and (b), it can be shown that the higher the YP/PV ratio, the higher will be the cuttings concentration and vice versa. This is true for all the angle of inclinations considered in this study. Because of the influence that PV has on YP/PV ratio, the PV should also increase with respect to YP so as to reduce the accumulation of cuttings in the annulus. The YP/PV ratio should be low.

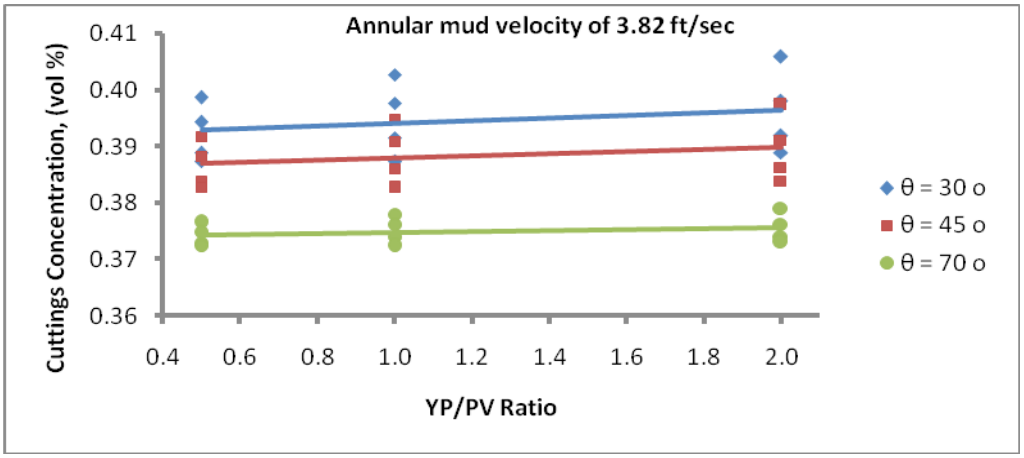

Fig. 4.14 (a): Annular cuttings concentration vs. YP/PV ratio for annular velocity of 3.82 ft/sec

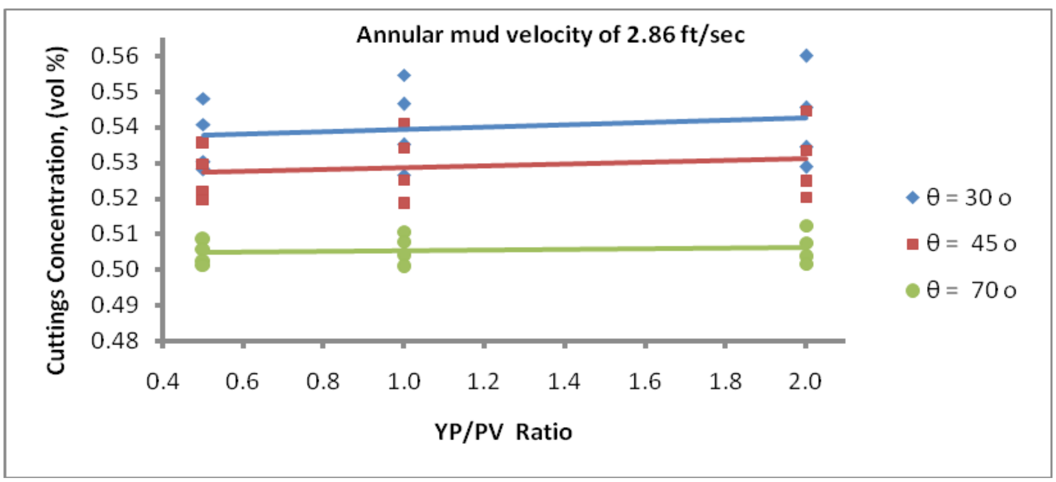

Fig. 4.14 (b): Annular cuttings concentration vs. YP/PV ratio for annular velocity of 2.86 ft/sec

Again, the effect of the YP/PV ratio on the annular cuttings concentration at the three selected mud velocities taking into account each hole angle was also considered. Figure 4.15 shows the plot for hole angle of 30° from the vertical. It can be observed from the comparison of the slopes of the curves that the effects of YP/PV ratio are more pronounced for lower annular mud velocities. In all the three plots, cuttings concentration decreases with decreasing YP/PV ratio. See Figures C7 and C8 in the appendix for similar plots for hole angle 45° and 70° from the vertical respectively.

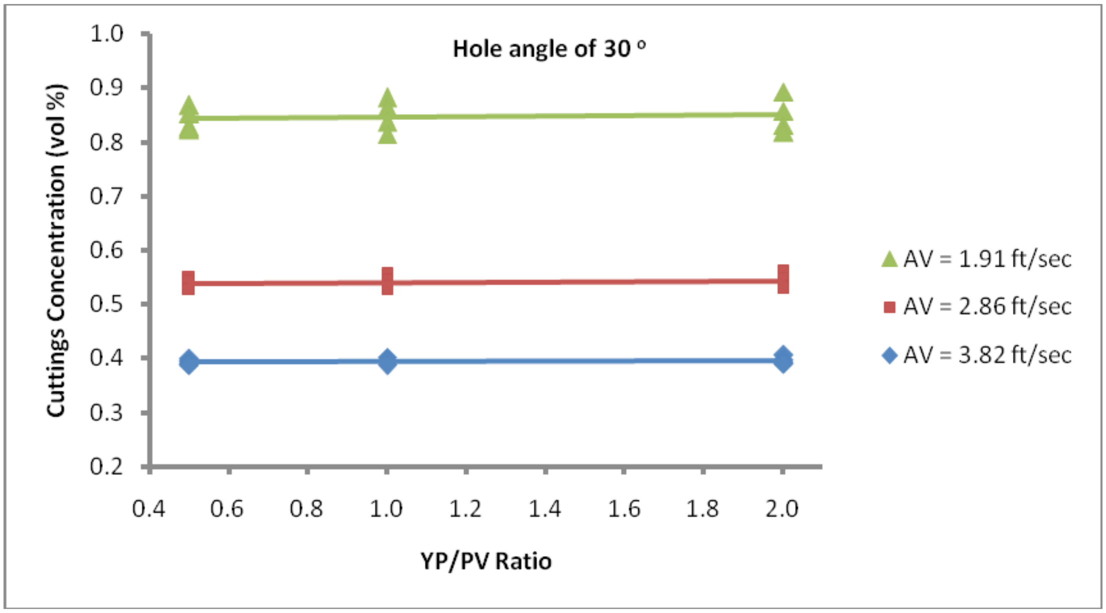

Fig. 4.15: Effect of YP/PV ratio on annular cuttings concentration

In Fig. 4.16 (a) and (b) below, we have plots of cuttings concentration versus hole inclination. From these plots, the cuttings concentration generated is highest at 30°, followed by at 45° and decreases as the angle increases. In this study, mud 1 and 12 were used to illustrate this point and they all showed a similar trend for the different annular mud velocities selected. Higher flow rates will then be needed for lower hole angles in the range of 30° – 45°.

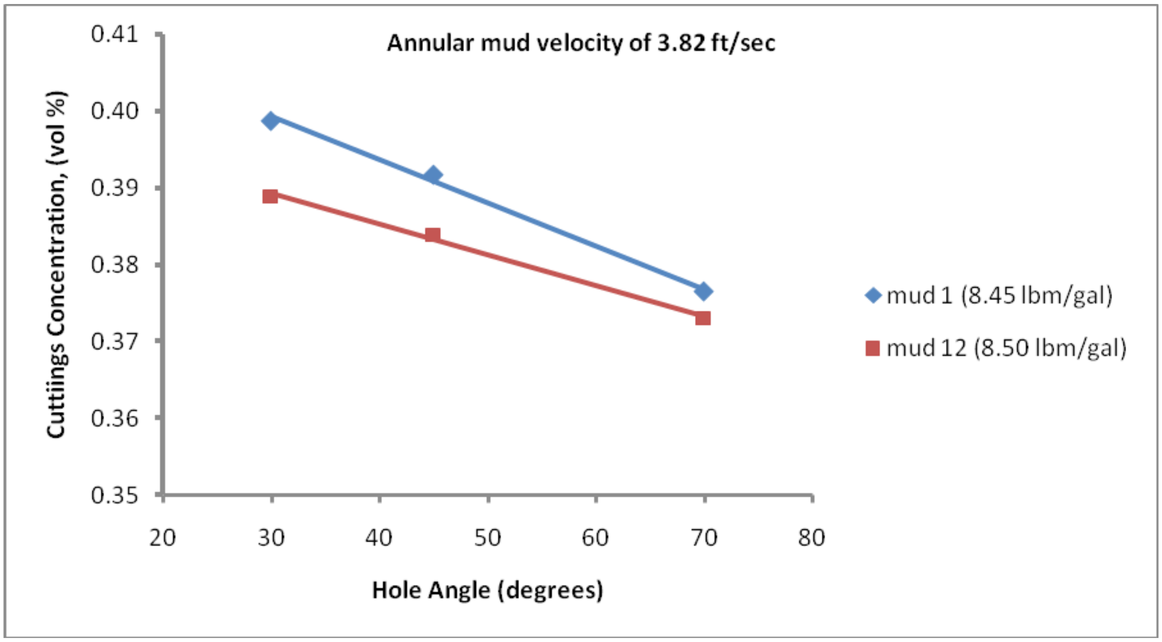

Fig. 4.16(a): Cuttings concentration vs. Hole angle for annular velocity of 3.82 ft/sec

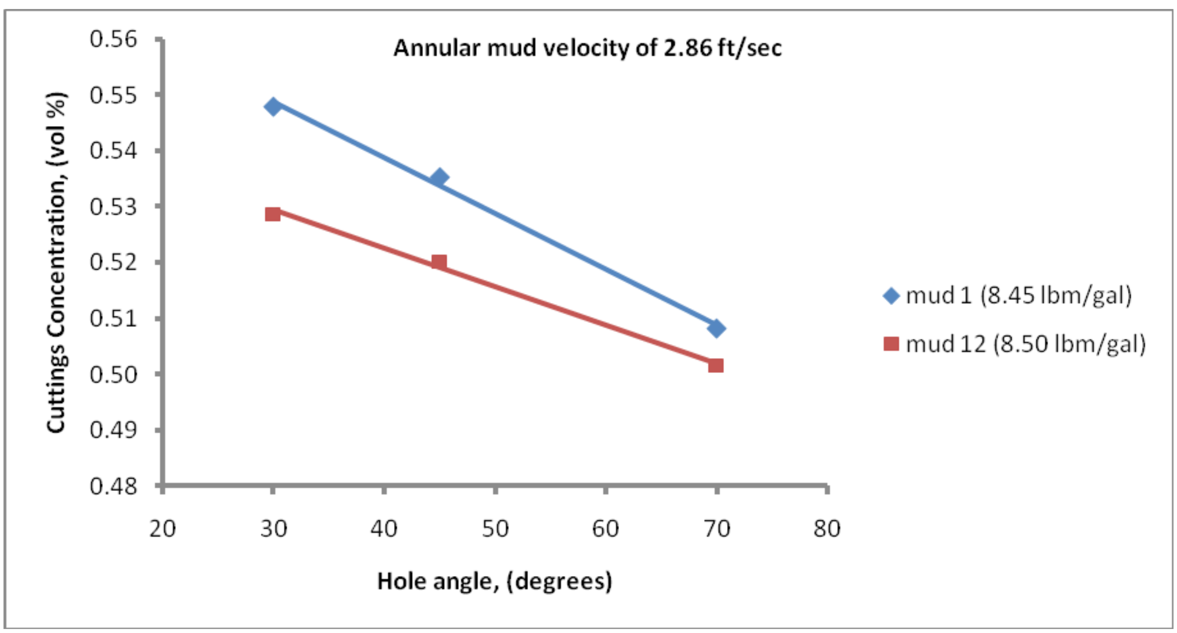

Fig. 4.16(b): Cuttings concentration vs. Hole angle for annular velocity of 2.86 ft/sec

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

From this study, it can be deduced that the rheological parameters such as flow index, consistency index, yield point, plastic viscosity, and YP/PV ratio have tremendous impact on the transportation of cuttings. Therefore in order to ensure efficient cuttings transportation, each rheological parameter is equally important and should be considered. It has been observed that, an increase in both the apparent and effective viscosities helps in better sweep of the cuttings, the power law flow index should also not be very high while the power law consistency index should be increased. The yield point and plastic viscosity values should all be high but done in such a way that they will result in low YP/PV ratios.

Again, whenever there is cuttings transport problem, flow rate should be increased to its limiting value for all ranges of inclinations, particularly in the range of higher angles. But when there is the occurrence of sliding-down effect of the cuttings during drilling, then this becomes critical for lower angles (30° - 45°).

5.2 Conclusions

The following conclusions were reached from this study:

4. In the study and assessment of drilling-fluid cuttings transport in non-vertical boreholes, the annular cuttings concentration (vol %) should be considered first. Its value gives the indication of which rheological parameter to manipulate to bring about a successful cuttings removal.
5. For efficient hole cleaning process, the power-law flow index, consistency index, yield point, plastic viscosity, and YP/PV ratio should all be used in the evaluation and assessment process.

6. In laminar flow, the annular cuttings concentration is lower for higher YP/PV ratios. This is true for the entire range of hole inclinations investigated in this study.
7. In laminar flow, increasing values of mud yield value result in decreasing the annular cuttings concentration. The same situation applies to increasing plastic viscosity.
8. Very high cuttings concentrations were recorded at hole inclination in the range of 30° to 45°. This normally occurs when the annular flow rates are relatively low (0 – 90 gpm).
9. In laminar flow, the effects of mud yield value and YP/PV ratio are more pronounced for lower annular mud velocities. Thus at these velocities, higher annular cuttings concentrations were recorded.
10. The effect of mud flow rate has great influence during hole cleaning in non-vertical boreholes. Higher flow rates increases the critical annular velocity which in turn brings about decreasing cuttings concentration.

5.3 Recommendations

The following suggestions are recommended for future work:

7. Investigation should be made into the effects of temperature and pressure on the rheology of drilling fluids for cuttings transportation in the drilling of non-vertical boreholes.
8. Field data should be used to carry out this same study to make conclusive statements on the impact of the power-law flow index, consistency index, yield point, plastic viscosity, and YP/PV ratio on cuttings transportation in non-vertical boreholes.

NOMENCLATURE

AV annular velocity, ft/min

AVc critical annular velocity, ft/min

C_a annular cuttings concentration, vol %

C_h capacity of hole, bbl/ft

$D_{ens}P$ cutting density, ppg

$D_{ia}P$ cutting diameter, in.

d_h inside diameter of casing or hole size, in.

d_p outside diameter of pipe, tubing or collar, in.

E_t cuttings transport efficiency, %

GPMc critical flow rate, gpm

K power law consistency index, lbf-sec^n/ft^2

K_a power law consistency index corrected for the annulus, lbf-sec^n/ft^2

L footage drilled, ft

MW mud weight, ppg

n power-law flow index, dimensionless

n_a power-law flow index corrected for the annulus, dimensionless

P porosity, %

PO pump output, bbl/min

PV plastic viscosity, cp

Q flow rate, gal/min

R_{ea} reynolds number in the annulus

R_{ec} critical reynolds number

R_t cuttings transport ratio

SG specific gravity of cuttings

V_s cuttings slip velocity, ft/min

V_{sa} axial component of particle slip velocity, ft/min

V_{sr} radial component of particle slip velocity, ft/min

V_t cutting net rise velocity

W_{cg} solids generated, pounds

YP yield point, lbf/100 ft^2

Greek Symbols

τ shear stress, lbf/ft^2

τ_0 yield stress, lbf/ft^2

μ fluid viscosity, cp

μ_a apparent viscosity, cp

μ_{ea} annular effective viscosity, cp

μ_{eff} effective viscosity, cp

μ_p plastic viscosity, cp

γ shear rate

θ hole angle

θ_∞ dial reading at ∞ rpm

ρ fluid density, lbm/gal

ώ rotation speed, rpm

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