Sudan University Of Science And Technology

College of Graduate Studies

Water-Based Mud's Rheological Properties Estimation Using Marsh Funnel

تحديد الخصائص التيارية لسائل الحفر ذو الاساس المائي باستخدام قمع مارش

A thesis submitted in partial fulfillment for the degree of Master in petroleum engineering (Drilling program)

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Abstract

Marsh funnel was considered as a quick quality-control instrument in oil well drilling, it measures mud viscosity in term of time as single point which cannot provide enough evidence to credit marsh funnel as a rheometer. This work attempts to modify the recent proposed procedures of handling marsh funnel itself and its data, and provides a new procedure to indicate gel strength via marsh funnel.

In this study nine samples of water-based mud were drained through six funnel geometries, the drained volume versus associated time were recorded under many waiting categories such as drain immediately, drain after 1 minute, drain after 5 minutes, and drain after 10 minutes. The shear rate and shear stress within funnels were calculated considered them as capillary viscometer methodology, along with statistical analysis was implemented via Minitab. The study figures out two models to estimate flowing parameters and one method to indicate thixotropic property; the flowing parameters models were estimated the rheological properties in graphical and statistical manners; both models achieved high level of accuracy. In addition to, the new approach to indicate the gel strength perfectly was provided, the method was found quite precise using one proportion test.

At the lights of the study findings, the Author thought it has become common today to accept the marsh funnel as standalone rheometer.

مستخلص البحث

يُعتبر قمع مارش جهاز تحقق سريع في مجال حفر آبار النفط ، يقيس الجهاز لزوجة سائل الحفر في شكل نقطة زمنية واحدة ؛ التي لا تقدم دلالة كافية لإعتماد قمع مارش كـ(ريومير) ، حاولت الدراسة تعديل الطرق المقترحة حديثاً للتعامل مع قمع مارش والبيانات المستخرجة منه كما قدمت طريقة جديدة للاشارة الي وجود مقاومة الجل بواسطة قمع مارش.

في هذه الدراسة تم تفريغ تسع عينات لسوائل حفر ذات اساس مائي خلال ستة أقمعة مختلفة ، سُجلت بيانات الحجم المُفرغ والزمن المرافق له؛ تم تجميع البيانات بعدة فئات انتظار زمنية: التفريغ مباشرة ، التقريغ بعد دقيقة واحدة، خمس دقائق وعشر دقائق، حُسب اجهاد القص و معدل القص في الاقمعة باعتبارها مقاييس لزوجة ذات انابيب شعرية ، كما تم عمل تحليل احصائي باستخدام برنامج (Minitab). خرجت الدراسة بنموذجين لتحديد الخصائص التيارية ونموذج واحد للإشارة لوجود (thixotropic property)؛ قام نموذجا الخصائص التيارية بتحديد الخصائص التيارية بطريقتين بيانية وإحصائية ، كلا النموذجان كان علي مستوي عالي من الدقة. بالاضافة الي ذلك تم تقديم طريقة للاشارة الي وجود مقاومة الجل؛ كما وجد أن الطريقة علي قدر عالي من الدقة وذلك باستخدام اختبار الفروض (One proportion test) .

علي ضوء نتائج الدراسة يعتقد الباحث انه صار من الضرورة قبول أن قمع مارش يمكن اعتباره (ريوميتر) قائم بذاته.

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List of Symbols & abbreviations

WBM's	Water-Based Muds
OBM's	Oil-Based Muds
AV	Apparent viscosity
PV	Plastic viscosity
YP	Yield point
n	Non-Newtonian index
K	Consistency
$\dot{\gamma}$	Shear rate
τ	Shear stress
μ	Viscosity
τ_{rz}	Shear stress in r-z direction,
L	Tube length,
r	Interest radial position,
Δp	Pressure difference.
R	Tube radius.
τ_w	Shear stress at wall of tube.
ρ	Fluid density
g	Gravity constant
Z	Instantaneous fluid height inside the cone
Z_2	Orifice height
α	Slope of the marsh funnel wall
R_L	Orifice radius
R_0	Cone radius at its top
Z_1	Initial fluid height inside the cone, i.e. 11"
Q	Volumetric flow rate,
V_z	Velocity in z-direction,

	function of radius
$f(\tau_{rz})$	Unspecified function.
$\acute{n}$	Slope of line when plot log τ_w versus γ_w
V_o	Initial volume in funnel
$G.S.I$	Gel strength indicator, fraction.
$Area_{after\ (i)min}$	The area under curve when drain after waiting (i) min
$Area_{imm.}$	The area under curve when drain immediately.
i	Waiting time, i.e. 1 min, 5 min, and 10 min.
T_w	The time required to drain 1000 ml of fresh water
T_{1000}	The time required to drain 1000 ml of drilling fluid
$DivT$	Parameter reflects who mud is more viscous than water
DT	Parameter reflects who mud is more viscous than water
S%	Solid content

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Chapter 1

Introduction

CHAPTER I: INTRODUCTION

1. Introduction:

The primary drilling fluid roles are to carry out the cuttings which are drilled out from the bottom up to the surface. Also grantee sufficient hydrostatic pressure that prevent fluid within strata from flowing into wellbore in non-controlled manner then improve to blow out. To achieve the mentioned roles, drilling fluids ingredients and properties are optimized and designed to minimize and warding troubled formations. This may result of increasing the cost of drilling fluid to reach 10%-15% of the overall drilling cost, any lack of observation to ensure proper mud properties may result in sever drilling problems which costing great deal of remediation time, even may cause of abandonment of the well.

To ensure that drilling fluid functions are properly performed, many drilling fluid properties are monitored, one of the most important feature is the rheological properties. Generally, the rheological analysis plays a big role in understanding the fluids behavior at different conditions, thus preventing any problem that may happen when utilizing such fluids. The rheological analysis used to figure out the rheological properties, which have many applications in oil well drilling, for example hole cleaning and hole erosion, suspension cuttings among the mud whilst circulation operation is stopped, and hydraulic calculations. Without utilize the appropriate rheological properties one or more of the mentioned applications may not be attained, this could be result in high cost to bring the hole back to its normal situation, sometimes the circumstance may be critical and consequence in a disaster.

Mud engineers around the world manage to uphold those drilling fluids rheological properties in acceptable range to fulfillment mud functions therefore, a power full instrument is required to evaluate these suspensions. Generally, the suspensions have a very complex fluid rheological behavior. Rheometers are used to mitigate the ambiguity of suspensions behavior, also to reach more accurate estimation of rheological properties, regarding oil industry, the most common instrument to determine the rheological properties is Fann Viscometer.

In late 1930, H. Marsh invented the marsh funnel, it used to measure mud viscosity in term of time required to drain specific volume, i.e. 946 ml, Marsh hint that his device may converted into absolute viscosity, and the funnel was accepted to make a qualitative estimation of viscosity. Marsh funnel can provide only single point thus it is not fair enough to express the rheological behavior. In order to get an acceptable estimation of targeting properties, many procedures and methods have been proposed recently. Many authors refuse this aspect, even some of them conclude that marsh funnel cannot measure the rheological properties, fortunately, the majority of the recent studies proved the antipode.

This research attempts to modify the recently proposed procedures of handling marsh funnel data, therefore more accurate estimation of rheological properties can be carry out as well as rheometers. In addition to, the effect of many variables was investigated, e.g. solid content, density, marsh funnel dimensions. At top of that a new procedure to indicate the gel strength property is proposed.

1.1 Problem statement:

In oil industry, marsh funnel was described as a quick quality control test, and most of authors concluded the funnel's data cannot be converted into viscometer output. Although giant strides have been made in recent years in the field of converging marsh funnel to rheometers, marsh funnel has not reached the rheometer accuracy.

This study attempts to modify the recent proposed procedures of handling marsh funnel itself and its data, and provides a patent procedure to indicate gel strength, thus marsh funnel can be classified as standalone rheometer.

1.2 Objectives:

In order to fulfill the research problem, the following targets were managed to carry out in this research;

1) Classify the marsh funnel in the field of rheometers.
2) Estimate the rheological properties graphically.
3) Find out the influence of Marsh funnel geometry, solid percentage on rheological properties estimation.
4) Develop correlational relationships depend on March funnel to estimate rheological properties;
5) Proposed a procedure to evaluate the fluid gel strength property using marsh funnel data.

1.3 Methodology:

To classify an instrument as rheometer, it must utilize to evaluate the rheological properties. These properties classified into flowing properties and thixotropic properties; as these properties are classified, the methodology can be divided into main two parts.

The first is to figure out the flowing behavior properties, in which the flowing parameters is determined graphically; thus the instantaneous parameters that describe the fluid are estimated, in another aspects Minitab, statistical software, was used to find out the controlling relationship among some measured parameters and the targeting parameters.

The second is to obtain an indication of gel property, this can be estimated graphically, by plotting marsh funnel shear rate versus apparent viscosity for the same fluid but the fluid let to last for a while inside the funnel, then calculating the area under the curves; the difference in the area indicates the gel strength, as no change can note this a high suggestion to a fragile gel strength in such fluid.

1.4 Scope and limitation:

This experimental study focusing on utilizing marsh funnel to estimate rheological properties for water based mud at ambient temperature, the change in orifice size was taken into account, the effect of solid volume percentage also investigated. Whereas OBMs were not discussed, the effect of temperature has not ever discussed.

Some sample of the drilling fluid was too viscous to drain through the funnel, thus I did not involve such sample in the data analysis phase.

1.5 Research organization:

To obtain the ultimate benefits from the research issue, the layout of the research were spread into five chapters;

At second chapter many topics were covered, namely section about oil well drilling fluids describing their types, functions in brief, and properties. Also a concise introducing section about the rheometers covered; it contains a preface about rheology, common rheological models, reasoning of why the drilling fluids behave non-Newtonian? Finally, types of rheometers had been stated. The next section consists of reviewing of studies about marsh funnel; the ages of converging between marsh funnel and rheometers is mentioned followed by illustrating of gap in the literature and the sustainable methods and procedures among the current research efforts. Finally the shear stress and shear rate among the marsh funnel was stated.

In third chapter, the methodology to accomplish this work has been stated including the materials and instruments that have been utilized, in addition to the procedures to handle such materials and instruments. Finally the methods of analyzing the gathered data were stated in details.

After that, the fourth chapter contains the actual amounts and percentages of materials that have been equipped were mentioned as well as a clear step by step updating data. The outcome data were critically discussed professionally and linked to rheology world.

Finally, the major findings and core outputs were concluded. In addition to, the limitations that faced the researcher and variables not taken into account were recommended for further studies.

Chapter 2

Background and Literature Review

CHAPTER II: BACKGROUND AND LITERATURE REVIEW

2. Background and literature review

2.1 Oil Well Drilling Fluids:

2.1.1 Drilling fluid types

Drilling fluid is the most critical component in the rotary drilling operation (Ford, 2002), therefore, special care should be taken on choosing the mud type and properties. Generally, almost every drilling problem has a link to drilling mud either directly or indirectly; this not to say that drilling fluid is a cure or cause of a particular problem, but it is kind of tool to alleviate the problem circumstance. As a result of this reason, the first goal in mud program planning is to select the appropriate mud that will reduce the non-productive time in drilling operation (Annis and Smith, 1996).

Drilling fluid has many classification categories, the famous one which depend on continuous phase. The types are water-based mud's (WBM's), oil based mud OBM's, and aerated or gaseous mud (Ford, 2002; Rabia, 2002; Caenn et al, 2011), the two most common types of mud' are WBM's and OBM's (Ford, 2002) figure (2.1) shows various mud types.

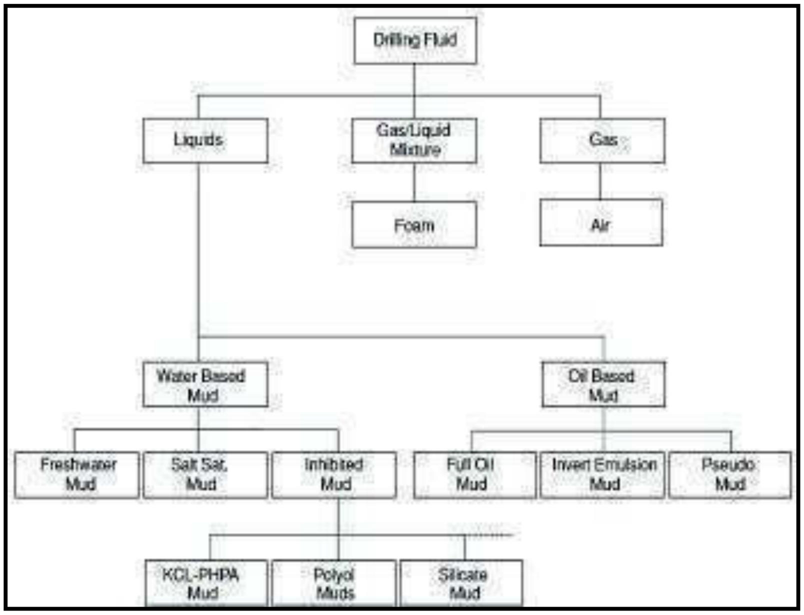


Figure (2.1): Drilling fluid types, after (Ford, 2002)

WBM's are relatively inexpensive because of the availability of the fluid, water, from which they are formed. In addition to the less environmental effect compared to other mud types, figure (2.2) shows the functional components of WBM's

2.1.2 Drilling fluid functions

Although a numerous brand names of drilling fluids exist, they are all used to achieve same functions (Chilingarian, and Vorabutr, 1981). Also the success of planned drilling program or the ability to minimize the overall drilling operation cost is a result of proper choosing and maintenance of drilling mud and the deep understanding and application of its functions (Azar and Samuel, 2008).

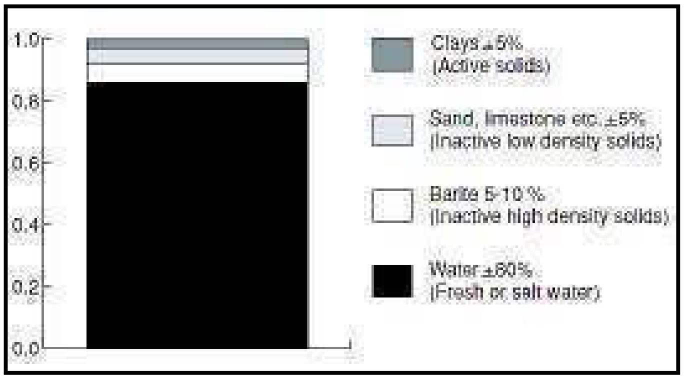


Figure (2.2): Functional composition of water based mud, after (Ford, 2002).

Drilling fluid functions arranged under two categories; primary functions, mandatory to fulfill that function at all time, and secondary functions which are not affect the drilling operation immediately, table (2.1) shows the primary drilling fluid function and the constitutive properties.

Table (2.1): Drilling fluids Functions vs. physical properties, after (Ford, 2000).

Function	Physical/chemical property
Transport cuttings from the well bore	Yield point, Apparent viscosity, Velocity, Gel strength
Prevent formation fluids flowing into well bore	Density
Maintain wellbore stability	Density, reaction with clay
Cool and lubricate the bit	Density, velocity
Transmit hydraulic horsepower to bit	Velocity, density, viscosity

The fail of drilling mud to carry out one or more of its required functions could lead to problematic and costly drilling problems, indeed most problems while drilling related somehow to the drilling fluid been used (Azar and Samuel, 2008).

2.1.3 Drilling fluid properties

The cost of drilling mud is just below 15% of the total cost of the oil well drilling; but the inadequate selection of drilling and its properties or the failure to keep mud properties within acceptable ranges may raise further drilling operation problems, therefore, a great deal of the time will be spent to fix such problems, which means an extra cost (Chilingarian, and Vorabutr, 1981; Bourgoyne et.al, 1991; Caenn et al, 2011).

To avoid such scenario, regular tests to be carried out to identify mud properties, these test are possible to identify potential problems earlier and prevent sever non-productive time (Bourgoyne et.al, 1991).

The most important drilling fluid properties for a successful drilling operation of well involve; mud weight, rheological properties, filtration loss and filter cake, and PH value (Chilingarian, and Vorabutr, 1981; Rabia, 1992). These properties are monitored on a regular basis and set around specific values all the time throughout oil well drilling operation.

Due to the scope of the thesis, only the first and second properties will be discussed in detailed.

Mud weight:

The monitoring of mud weight is very important to ensure that mud column can confine all formation fluids, i.e. water, oil, or gas, to their beds (Chilingarian, and Vorabutr, 1981), mud weight is dependent upon the fraction of solid in the liquid phase, i.e. inert solids (Rabia, 1992), therefore frequent density tests help to keep drilling condition safe by disclosing any potential changes in weight (Tschirley, 1981)

The most appropriate instrument to identify mud weight is the mud balance (Tschirley, 1981).Figure (2.3) illustrates the components of mud balance.

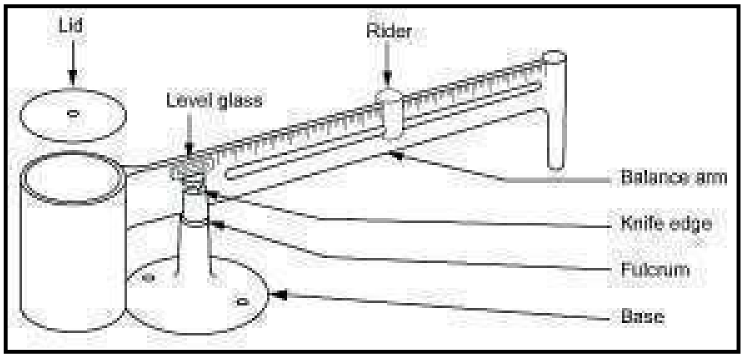


Figure (2.3): Mud balance component, after (Ford, 2002).

Rheological properties:

The rheological properties of drilling fluid must be designed carefully to carry cuttings from bit face up to the surface while drilling operation, suspend the cuttings while the circulation is stopped, and easily drop the cuttings out of the mixture at surface (Ford, 2002).

The viscosity is the measure of the friction between fluid layers, i.e. the internal fluid resistance to flow. It is very important property of drilling fluid as it related directly to the efficiency of lifting capacity (Chilingarian, and Vorabutr, 1981; Rabia, 1992). The yield point is a part of fluid flow resistance. It is caused by electro-chemical forces within fluid components, it measured by $\mathrm{lb/100\ ft^2}$ (Azar and Samuel, 2008).

Marsh funnel, see figure (2.4), is used in petroleum industry to estimate funnel viscosity.

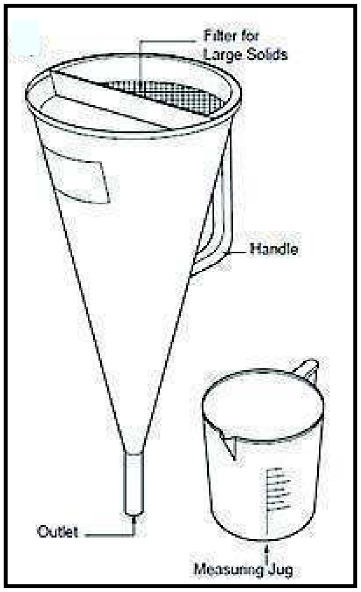


Figure (2.4): Marsh funnel Component, after (Ford, 2002).

The values of apparent viscosity (AV), plastic viscosity (PV), and yield point (YP), and gel strength are determined using rheometers(Tschirley, 1981), multi-rotational viscometer is used to quantify the rheological properties of drilling mud (Ford, 2002), figure (2.5) shows the 6-speed viscometer and its components. Also marsh funnel viscometer is used for routine viscosity determinations on almost every rig (Tschirley, 1981). Figure (2.4) illustrates the marsh funnel and its standard dimensions.

The rheological properties are determined via equations (2.1) to (2.5).

$$Apparent\ viscosity\ (AV), C.P\ = \frac{300\ \theta_N}{N} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.1)$$

$$Plastic\ viscosity\ (PV), C.P\ = \theta_{600} - \theta_{300} \ldots\ldots\ldots\ldots\ldots\ldots\ (2.2)$$

Where:

N is the rotation speed in RPM, θ_N is the dial reading at N.

$$Yield\ point\ (YP) = PV - \theta_{600} = 2\theta_{300} - \theta_{600} \ldots\ldots\ldots\ldots\ (2.3)$$

$$Non-Newtonian\ index\ (n) = 3.32\log\frac{\theta_{600}}{\theta_{300}} \ldots\ldots\ldots\ldots\ldots\ (2.4)$$

$$Consistency\ (k) = \frac{\theta_{300}}{511^n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.5)$$

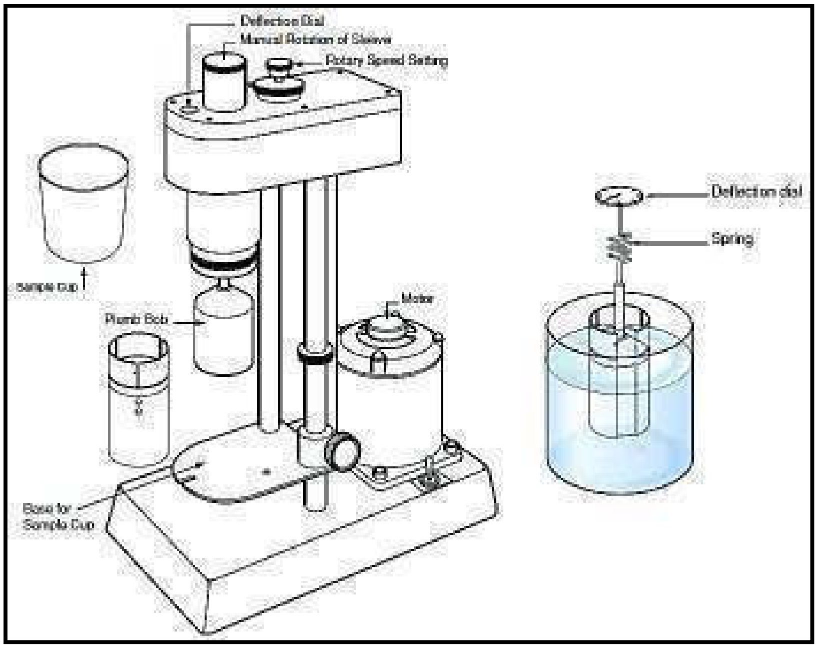


Figure (2.5): Multi-rotational viscometer, after (Ford, 2002).

Equations (2.1) through (2.5) are based on assuming the rotor speed and dial reading are the shear rate and shear stress respectively, for more accurate calculations the shear rate and shear stress can be estimated on 0.1170 cm gap from equations (2.6) and (2.7) (Tschirley, 1981).

$$\dot{\gamma}(sec^{-1}) = 1.7034 \times N \quad \text{.................................} \quad (2.6)$$

$$\tau(dynes/cm^2) = \theta_N \times 5.1 \quad \text{.................................} \quad (2.7)$$

One of the most important required properties of good mud is gel strength, i.e. the ability of mud to suspend cuttings and weighing materials when circulation is stopped; otherwise these materials could be settled down and string become stuck (Rabia, 1992).

Gel strength is a measurement of electro-chemical forces within fluid under static condition. It is a measure of the mud tendency to develop and retain a gel structure. It is analogous to shear strength and indicates the ability of mud to prevent solids and cuttings settle down in the mixture (Rabia, 1992), shear or gel strength of drilling fluid is scale of the minimum shearing stress required to initiate slippage movement of drilling fluid (Tschirley, 1981).

The gel strength of drilling mud can be thought as the strength of any internal structures which are formed within mud when it is static, in addition to suspension property gel strength provides another indicator of the pressure required to initiate flow after the mud has been stationary for a while (Ford, 2002).

The thixotropic proprty, which cauesing gel strength progressing tendency, is believed that it makes clay plates to align themselves in positions of minimum free energy in order to satisfy electro-statics surface charge (Caenn, et al, 1981; Azar, and Samuel, 2008; Caenn et al, 2011), therefore drilling fluids is form the electrically charged molecules and clay particles which aggregate into firm matrix when the circulation is stopped (Baker Hughes, 2006). Gel strength normally reported as $\theta_{3\ @\ 10\ sec}/\theta_{3\ @\ 10\ min}$

Gel strength is qualitatively categorized into many types depending on $10\ sec/10\ min$ gels values and the difference among them. Figure (2.6) shows different types of gel strength, the gel strength should be maintained in the range of favorable gels (Lummus, and Azar, 1986).

2.2 Rheometry:

2.2.1 Rheology

Rheology comes from Greek words " Rheo " refer to flow and "Logi " refer to science, therefore it can be defined as the science of flow and deformation of solids and fluids, i.e. liquids and gases.

Normally, fluids are characterized rheologically at given pressure and temperature as following categorizations (ChambreSyndicale de la Recherche et de la Production du Petrole et du Gaz Naturel, 1982):

A. Fluids behavior under transient circumstance, as manifested by measuring their response to various flow conditions.

B. Fluids behavior in laminar flow, the behavior is characterized by experimental curves, or rheogram. The coefficients that describe the rheogram properly called rheological properties, i.e. apparent viscosity, plastic viscosity, non-Newtonian index, consistency, and yield point.

C. Fluids behavior at rest; as exhibited by gel structure creation after a while; the fluid is classified as *thixotropic* if it forms a gel after being shearedand lift to stand, it returns to its original feature after it has been sheared again(Chilingarianand Vorabutr, 1981; ChambreSyndicale de la Recherche et de la Production du Petrole et du Gaz Naturel, 1982).

The evaluation of rheological characteristics facilities the understanding of drilling fluid role in many applications (Caenn et al, 1981) such as:

- Hole cleaning and hole erosion.
- Suspension of cuttings whilst circulation is stopped.
- Hydraulic calculations.
- Mud treatments.

It should be announced that it is too hard to meet all mentioned applications together, but the favorable practice is to meet the critical application depending on the drilling operation situation.

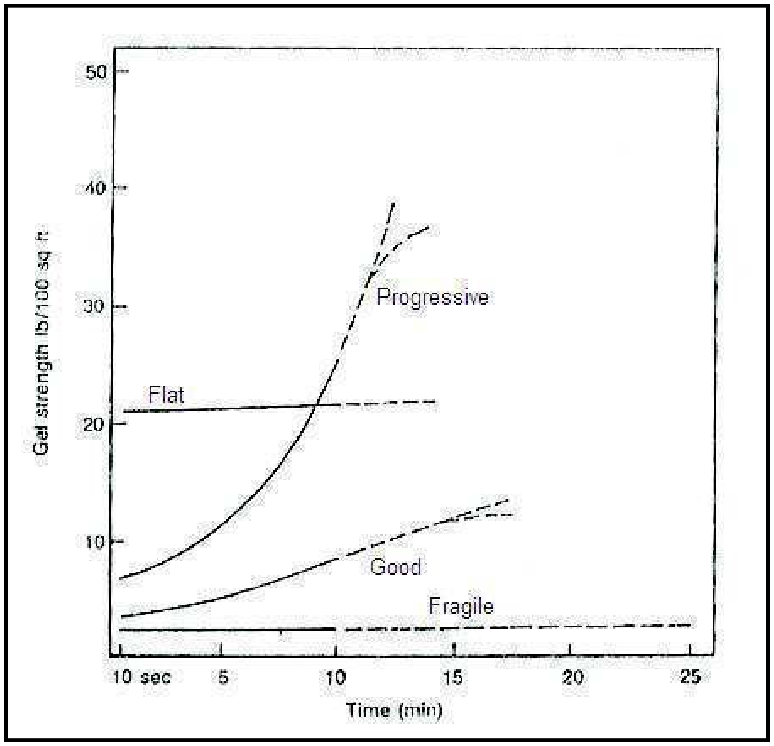


Figure (2.6): Gel strength types, after (Lummus, and Azar, 1986).

2.2.2 Rheological models

The rheological model is a mathematical description developed to indicate the viscous forces present in a fluid therefore pressure losses inside string or annuals can be estimated (Ford, 2002). One of the first attempts to develop a fluid flow model was done by Isaac S. Newton (Caenn et al, 1981), he managed to describe the shear stress thatapplied to parallel plates one was constant and the second plate was moving see figure (2.7), therefore equation (2.8) is applicable.

Newton defines the constant as the coefficient of viscosity 'μ'. Figure (2.8, a) demonstrates graphical representation of equation (2.8) as straight line has slope of 'μ', all fluids obey equation (2.8) called Newtonian fluid.

$$\tau = constant \times \dot{\gamma} \quad \text{……………………………….………} (2.8)$$

Where;

τ is the shear stress, it is defined asforce existing in the fluid that opposes the flow

$\dot{\gamma}$ is the shear rate, it is defined as the force per unit area between two layers of fluids sliding by each other.

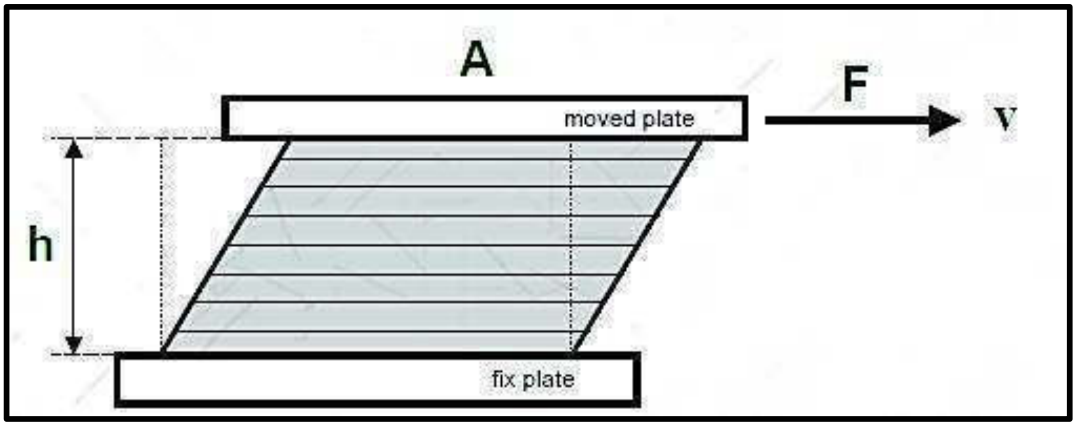
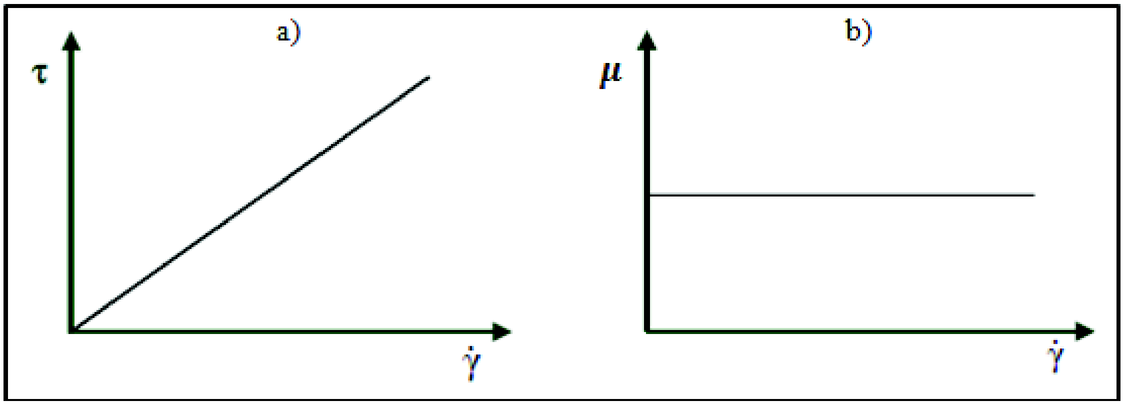


Figure (2.7): a fluid between two parallel plates, after rheotech (n. d).

The constant is the viscosity coefficient as per Bingham stated. Generally, the apparent viscosity is the slope of any point at the curve to the origin point, i.e. the shear rate divided by the shear stress, see equation (2.9); for Newtonian fluids the apparent viscosity is constant, for other fluid types the apparent viscosity is changed accordingly to the shear rate, the accurate apparent viscosity can be evaluated from equation (2.10).

$$\mu_{app} = \frac{\tau}{\dot{\gamma}} \quad \ldots\ldots (2.9)$$

$$\mu_{app}(c.P) = \frac{\tau(dynes/cm^2)}{\dot{\gamma}(sec^{-1})} \times 100 \quad \ldots\ldots (2.10)$$



a) At any value of shear stress a shear rate will be introduced linearly, b) the viscosity is constant at any shear rate value.

Figure (2.8): Newtonian Model, after rheotech (n. d)

Fluids that contain small particles percentage tend to behave as Newtonian fluid (Caenn et al, 1981), whereas suspensions and mixtures containing high particles percentage do not deform to Newton's low and classified generally as Non-Newtonian fluids (Craft et al, 1962; Caenn et al, 1981; Bourgoyne et al, 1991). Kelco (2006) had presented many mathematical models that can describe fluids behavior, due to the scope of study the most two common rheological models in oil industry are only stated.

1. Bingham plastic model:

This model is used to describe the pseudo-plastic behavior of drilling fluid and cement slurry (Bourgoyne et al, 1991), unlike Newtonian fluids, Bingham plastic fluid will not deform continuously (or flow) until the applied force, i.e. shear stress exceeds a certain minimum value, i.e. yield stress; after this point any additional shear stress will introduce an equal increment of shear rates proportion to the plastic viscosity, equation (2.11) illustrates the rational express among shear rate and shear stressfor Bingham plastic fluids (Caenn et al, 1981; Bourgoyne et al, 1991; Ford, 2002; Rabia, 2002).

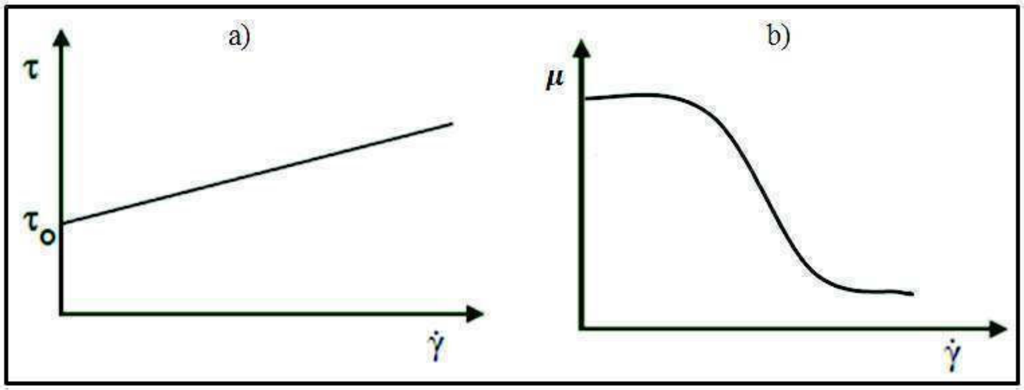
$$\tau = YP + PV\,\dot{\gamma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.11)}$$

1. Power low model:

The power low model is the most appropriate approximation for polymer based fluid behavior (Ford, 2002), the power low is expressed using equation (2.12), and figure (2.10) shows typical behavior of power low model.

$$\tau = k\dot{\gamma}^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.12)}$$

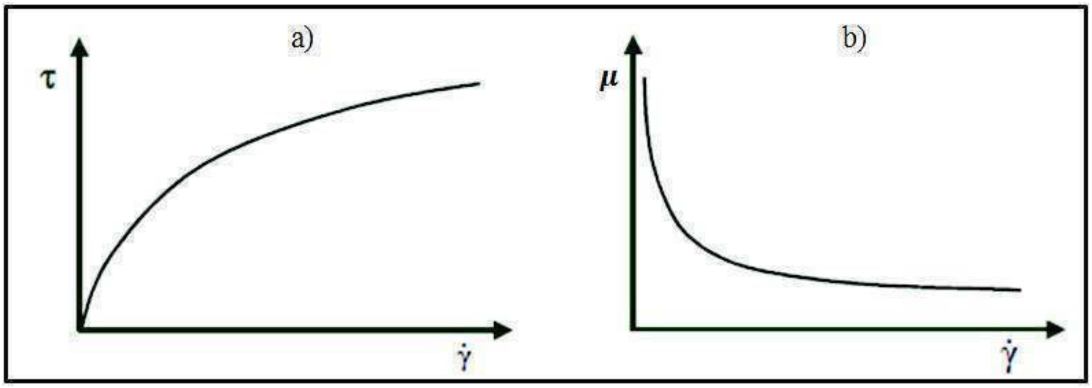
Special cases of Power low model:
$n = 1$ ⇒The fluid is Newtonian and $k = \mu$
$n < 1$ ⇒The fluid is Pseudo-plastic fluid.
$n > 1$ ⇒The fluid is dilatant fluid.



a) After critical value of shear stress (τ_o), the shear rate will be introduced, b) the viscosity is constant till shear rate reach equivalent value (τ_o), then decreases.

Figure (2.9): Bingham Model, after rheotech (n. d)

Indeed, the power low fluids deform at any announced shear stress but the shear rate does not proportional to viscosity linearly.



a) At any value of shear stress a shear rate will be introduced nonlinearly; b) the viscosity is decreases as shear rate value increases.

Figure (2.10): Power low Model, after rheotech (n. d)

2.2.3 Reasons that make drilling fluids behave Non-Newtonian:

In rheological point of view, suspensions are classified into three classes; solid particles in a liquid, liquid drop lets in another liquid, i.e. emulsions, and gas in a liquid, i.e. foam (Jan, and Macosko, 1994). drilling fluids are likely to classified under the first class, solid particles in a liquid. In order to provide viscosity for drilling fluids, Bentonite (clay minerals) is the most particles used in oil industry, behind this it plays a major role in well bore stability (Ford, 2002;Skalle, 2011). As the viscosity of mud is built up as the mud can suspend the drilling cuttings and weighing materials (Rabia, 2002).

Clay particles can be described as small crystals that have a negatively charged surface (Ford, 2002), actually Bentonite has many properties such as (Moore, 1986):

- It is a solid has an equivalent diameter of less than 2 microns.
- It can eclectically charge, particle capable of disrobe water. (Moore, 1986; Jan, and Macosko, 1994)
- It has ability to swell when adsorb water.

When clay minerals exist in aqueous media, inter-particle forces are announced, the forces can be either repulsive or attractive forces.

Repulsive force: In aqueous media the crystals have a tendency to absorb water; therefore a compensating charge is provided by the ions in solution that are elector-statically attracted to the surface (Moore, 1986; Jan, and Macosko, 1994; Ford, 2002).

Attractive force: when the volume of particle fraction grows larger than **0.01**, particles increasingly enter the neighborhood of other particles, the particles approach each other due to Brownian motion, this resulting disturbance of the flow thus viscosity is increases (Jan, and Macosko, 1994; Ford, 2002).

At top of that, the various materials within drilling fluid make it too complex to describe its flow behavior as Newtonian fluid (Caenn et al, 1981; Bourgoyne et al, 1991), the two most common rheological models to express Non-Newtonian drilling fluid are Bingham plastic and power low models (Caenn et al, 1981; Bourgoyne et al, 1991; Ford, 2002).

2.2.3 Rheometer types

The rheometers are devises used to find out rheological properties. The main concept of all rheometers is to apply a force, i.e. shear stress; this force introduces deformation on the fluid within the rheometer then measure the happened deform, i.e. shear rate. Generally shear rheometers are classified into two main groups (Macosko, 1994):

1. Drag flows: in which shear is generated between a moving and fixed surfaces.
2. Pressure-driven flows: in which shear is generated by pressure difference a long stream line.

Drag-flows rheometers (Macosko, 1994):

1. *Sliding and falling objects rheometers:*
    a. Sliding plates: perhaps the convenient method to create steady shear rate is to position a material between large fixed plate and another plate which moving at constant velocity, see figure (2.7).
    b. Falling cylinder: to eliminate some of sliding plate inaccuracy, a cylinder may slide inside a tube.
    c. Falling ball: the time required for a ball to fall down a given distance in a fluid is might be the simplest andthe oldest method to test fluid viscosity.
    d. Rolling ball: some of falling ball rheometer problems can be solved by tilting the tube and allowing the ball to roll down one side.
2. *Rotational rheometers:*
    a. Concentric cylinders rheometer (Couetterheometer): the first practical rotational viscometer was the concentric cylinders instrument of Maurice Couette (1890) utilizes a rotating outer cup and inner cylinder suspended by torsion wire. Now a day most commercial instruments, e.g. cup and pop and vane viscometers, facilitate this concept to design rotational rheometers.
    b. Cone and plate rheometer: Macosko (1994, citing Mooney and Ewart, 1934) prefer that Mooney and Ewart appear to have been the first to suggest the cone and plate geometry for viscosity measurements. Today the cone and plate with constant shear rate is the most popular rotational geometry for studying non-Newtonian fluids.
    c. Parallel disks: Macosko (1994, citing Mooney, 1934) stated that Mooney was suggested this geometry, this rheometer consists of a disk rotating inside a cylindrical cavity. The flow is similar to cone and plate geometry. However, contrasting to cone and plate rheometer the flow between the disks is not homogenous.

Figure (2.11) shows some drag-flows rheometers and their geometries and axis of flow.

Pressure-driven flows (Macosko,1994):

1. Capillary rheometer: It was the first rheometer and remains the most common method for measuring viscosity, the pressure required to initiate the flow is

generated using gravity, compressed gas or piston (Macosko,1994; Chhabraand Richardson, 2008).

2. Slit rheometer: It is a capillary rheometer with some modifications readily to forced liquids through a thin rectangular channel or slit.
3. Axial annular flow: pressure-driven axial flow through a narrow annual is essentially the same as flow through a slit, but without side wall.
4. Tangential annular flow: if fluid is pumped tangentially around an annulus stream lines are curves this curvature generates a pressure, which can be measured at different points, the observed pressure difference is related to rheological properties.
5. Squeezed flow: when a liquid is squeezed between two parallel plates, a pressure-driven flow is generated. The flow is quite complex due to the flow direction is not the same.

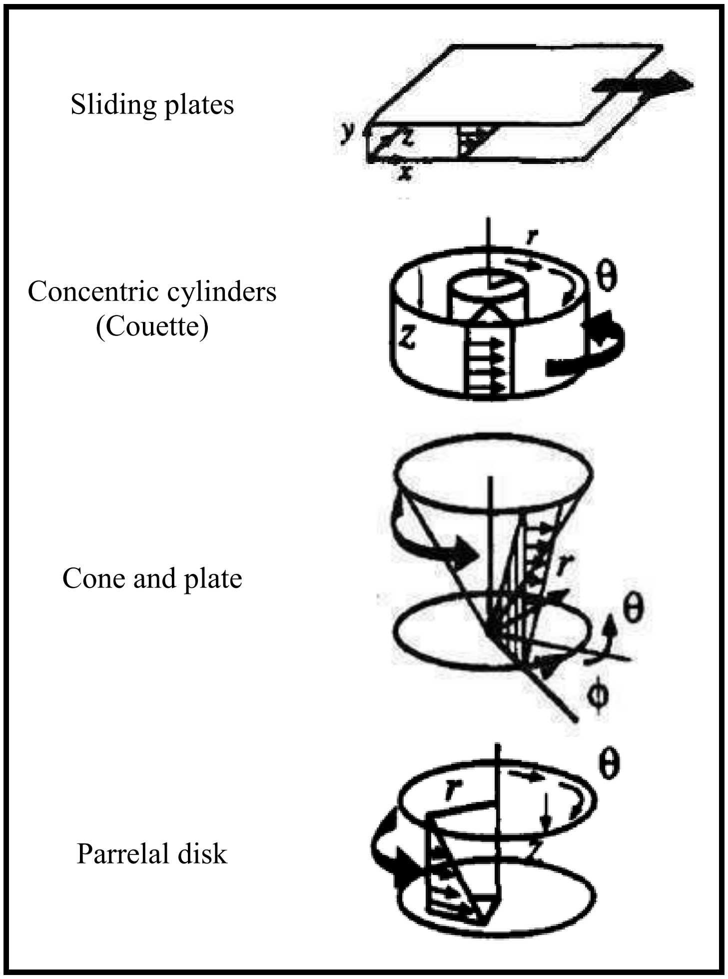


Figure (2.11): Common drag-flows rheometer geometries, after (Macosko,1994)

Figure (2.12) shows some pressure-driven flows rheometers and their geometries and axis of flow. Coussot (2014) has done an experimental review of most both types of mentioned geometries.

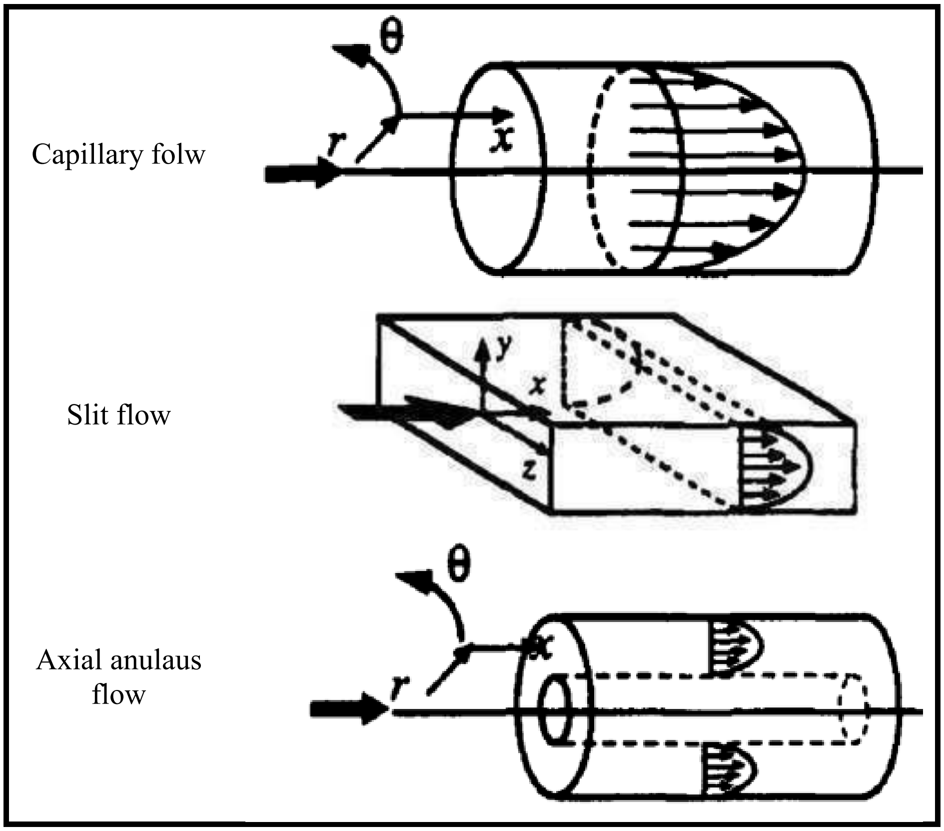


Figure (2.12): Common pressure-driven flows rheometer geometries, after (Macosko,1994)

2.3 Marsh Funnel: Review of Previous Studies

2.3.1 Marsh funnel: Rheometers and yield point

To obtain satisfy description of fluid flow behavior; the most appropriate rheological model must be chosen, thus empirical constants, e.g. n, K have to determine (Balhoff et al. 2011).

Yield stress is the vaguest property in rheological properties. This makes many kinds of rheometers cannot measure the true yield (Guria et al. 2013). Also, this gives rise to claim that there is no such thing called true yield stress (Barnes and Walters, 1985).

Fluid yield stress is hard to estimate due to many aspects, Balhoff et al. (2011) illustrate many of these aspects. Moreover a few points in rotational rheometer are available, i.e. only six points of shear rate and shear stress, all these make the most of rheometers measure the yield stress subjectively. Some of the recent studies tend to provide objective instruments and gain more accurate results (Carreau et al., 1997; Guria et al, 2013, citing Nguyen and Boger, 1983).

One of the most controversial rheometers is Marsh's funnel. It is commonly used in oil field as a quick check measurement. It is less subjectivity instruments because it relies on the fluid height itself to cause the flow (Balhoff et al., 2011).

2.3.2 Marsh funnel vs. rheometers

When it comes to the topic of marsh funnel and measuring rheology, most of us will readily agree that it is impossible to do so, where this agreement usually end, however, is one question of can the Marsh funnel builds rheograms? Whereas some are convinced that Marsh funnel may estimate the rheological properties, others maintain that marsh cannot do so.

On one side, many scientists believe that Marsh funnel is not a rheometer and it is only provided a relative measurement (Keloc, 2006). This thought is not supported by the recent studies showing that rheograms can be calculated via Marsh funnel (Pitt, 2000; Balhoff et al., 2011;Guria et al., 2013). Moreover Roussel and Roy (2004) contradict themselves, at the same time they conclude marsh is not a rheometer, they also imply that the fluid itself and cone geometry are the domain parameters on marsh funnel drain time. At top of that Roussel and Roy (2004) based their conclusions on two different procedures.

On the antithesis side other scientists advocate marsh funnel and consider it as a rheometer. This point comes from the fair agreement have been achieved amongst marsh funnel and rotational rheometer, i.e. Viscometer (Balhoff et al., 2011), even correlations have been conducted to estimate the plastic viscosity (Pitt, 2000; Almahdawi et al., 2014). However, Marsh funnel has many advantages; it is less subjective instrument, can provide many points which can be used easily to figure out fluid flow behavior parameter.

2.3.3 Review of methods, procedures and sustainable researches

In the past, marsh funnel provides a single point that cannot be used alone to get satisfy rheological analysis (Pitt, 2000). The first thing rises to mind when trying to get some convergence between rheological properties and marsh funnel data is to express the fluid model constitutive equations, in fashion of marsh funnel characteristics. To meet this converge many authors made a great deal of effort.

Ngyen et al. (2006) invent semi-analytical solution to Herschel–Bulkley model, they made a numerical model to simulate marsh funnel flow, they predicted cement velocity, accordingly the estimation of draining time was available, sometimes the built model ran for several hours' even days to estimate the time of drain in same time associated with average error about 15%.

Roussel and Roy (2004) used two different cone sizes to predict plastic viscosity and yield point of cement grouts through applying analytical solution to Bingham model. They got an average error just above 15%. This results were not satisfy for them, therefore they have made another attempt to predict the cement grouts and Glycerol viscosity from marsh funnel via analytical solution, but their attempt failed to minimize the error (Roy and Roussel, 2005).

Pitt (2004) used a numerical solution for power low model fluids, he predicted the fluid flow numerically, then used a linear regression to estimate the flow behavior index and the consistency, the study was focused on Newtonian and power low fluids. In the same trend, Almhdawi et al (2014) used nonlinear regression to correlate between apparent viscosities of Bentonite suspensions and funnel time; moreover they compared their results to Pitt (2004) equation. Almhdawi et al (2014) have a good correlation factor than Pitt (2004), at the same time Pitt (2004) provides a more versatile model than Almhdawi et al (2014).

Although Mohamed et al (2014) investigated many parameters in their study, they success to achieve a more reliable relationship, comparing to Almhdawi (2014), the correlation factor of Mohamed et al (2014) is greater than the correlation factor which have been achieved by Almhdawi (2014). In view of that, the trend of multi-variable regression is more appropriate than nonlinear regression, i.e. the accurate way to converge between marsh funnel data and rheological parameters is to find out the interrelationship of flow behavior parameters and the marsh funnel characteristics.

Recently deeper Studies have been conducted to get more converge between marsh funnel and rheological properties;

Balhoff et al (2011) built a solution based on ordinary differential equation, they never converted marsh funnel data into rheograms, also they estimated apparent viscosity and depend on the height of non-drained fluid inside the cone to estimate the yield point, they obtained good result for Newtonian and shear thinning fluids, conversely they failed to get satisfactory results for shear thickening fluids.

Guria et al (2013) made the same aspects for some Non-Newtonian fluids, they converted marsh funnel data into rheograms, they determined the equivalent shear stress to rotor speed, after that they calculated the plastic viscosity, they failed to estimate the flow behavior index, as well as Balhoff et al (2011) they relied on the height of rest fluid inside the funnel to determine the yield point, but they failed to get reasonable results for high bentonite concentration fluids.

In Addition to, Britta and Markus (2015) made another study depend on numerical solution to Herschel–Bulkley model, as well as Balhoff et al (2011) and Guria et al (2013) they depend on stagnated fluid inside the funnel to determine yield point of Bentonite suspensions.

Balhoff et al (2011) and Guria et al (2013) failed to get good prediction for the thickening fluids and high solid content fluids, this may lead to either be some limitation of marsh funnel, nor the authors have failed to find out the most appropriate relationship that reflect the rheological properties on the funnel flow data.

Guria et al. (2013) concluded that, the shear stress created by marsh funnel is greater than which calculated from 6-speed viscometer. This makes a defect on their model, consequently of the announced error on their results, Guria et al. (2013) calculate the shear stress depend on a relationship that claim the shear stress is created on the cone portion of funnel as well as the cylindrical portion, this may make them to over-estimate the values of shear stress.

Another essential point, Guria et al. (2013) claimed that yield stress has to be estimated under static condition, i.e. from the rest volume inside the funnel at the end of the experiment. The follower may has mixed thoughts about it. On one hand, it is well known that the rest volume on static condition is an indicator of the yield stress. On the other hand, the yield stress can be obtained properly based on the data in the steady range. This point is supported tacitly by Balhoff et al. (2011). In addition to, if the cone geometry is changed, obviously the rest volume will change, i.e. Guria et al. (2013) point of view is just extends of subjectivity within rheometers.

Although giant strides have been made in recent years in the field of converging marsh funnel to rheometers, there remains an open question as solid content, different cone geometries. This study attempts to fulfill the mentioned gap on knowledge.

2.4 Shear stress and shear rate inside capillary viscometer

Marsh funnel set up bears a closed resemblance to the pressure-driven flows rheometers; in marsh funnel the flow is created by pressure difference, hydrostatic pressure, between the top and the orifice outlet at the nozzle, the flow path from the top of the funnel to the end of the orifice creates the stream line. In order to carry out any rheological analysis shear rate and shear stress within marsh funnel must be estimated as the same as the capillary viscometer. Below sections illustrates the shear rate and shear stress within capillary viscometer (Chhabra, and Richardson, 2008).

2.4.1 Shear stress estimation:

As the cross section area and the geometry of the marsh funnel is seems to be like the capillary viscometers, but some differences are exist, the start of handling the shear rate and shear stress among the marsh funnel should be commenced by the capillary viscometer aspect. The fully developed, steady and laminar flow of an incompressible fluid in the tube portion of Marsh funnel is shown in figure (2.13).

The fluid element "ABCD" is balanced momentum, therefore equations (2.13) are applicable,

$$p(\pi r^2) - (p + \Delta p)(\pi r^2) = \tau_{rz}(2\pi r L) \quad \text{……………………} \quad (2.13, a)$$

i.e.

$$\tau_{rz} = \left(-\frac{\Delta p}{L}\right)\left(\frac{r}{2}\right) \quad \text{…………………………………………...} \quad (2.13, b)$$

Where,

τ_{rz} Shear stress in r-z direction,
L Tube length,
r Interest radial position,
Δp Pressure difference.

Equations (2.13) show the linear distribution of shear stress across the tube cross-section; increasing from zero at the axis of tube to a maximum value at the wall of tube.

$$\tau_w = \left(-\frac{\Delta p}{L}\right)\left(\frac{R}{2}\right) \quad \text{……………………………………………..} \quad (2.14)$$

Where,

R	Tube radius.
τ_w	Shear stress at wall of tube.

Whereas Guria et al. (2013) state that the shear stress is depend on the drag forces among the cone portion as well as the cylindrical portion, therefore the wall shear stress can be estimated using equation (2.15).

$$\tau_w = \frac{\rho g(Z+Z_2)}{(Z/(\cos\alpha\{R_L+(R_0-R_L)(Z/Z_1)\}))+(2\,Z_2/R_L)} \quad (2.15)$$

Where,

$\boldsymbol{\rho}$	Fluid density
$\boldsymbol{g}$	Gravity constant
$\boldsymbol{Z}$	Instantaneous fluid height inside the cone
$\boldsymbol{Z_2}$	Orifice height
$\boldsymbol{\alpha}$	Slope of the marsh funnel wall
$\boldsymbol{R_L}$	Orifice radius
$\boldsymbol{R_0}$	Cone radius at its top
$\boldsymbol{Z_1}$	Initial fluid height inside the cone.

2.4.2 Shear rate estimation:

The shear rate $\dot{\gamma}_w$ can be estimated from the volumetric flow rate through the annuals created between two fluid elements at the radial positions r and $r+\Delta r$ see figure (2.13, b). The volumetric flow rate can be written as equation (2.16).

$$dQ = 2\pi r V_z dr \quad (2.16)$$

Where,

Q	Volumetric flow rate,
V_z	Velocity in z-direction, function of radius

The total volumetric flow rate obtained by integrating equation (2.16) over the cross-section of the tube, therefore;

$$Q = 2\pi \int_0^R r\, V_z\, dr \quad (2.17)$$

Can be integrated by parts;

$$Q = 2\pi \left\{ \left(\frac{r^2}{2} V_z\right) + \int_0^R \frac{r^2}{2} \left(\frac{-d\,V_z}{dr}\right) dr \right\} \quad (2.18)$$

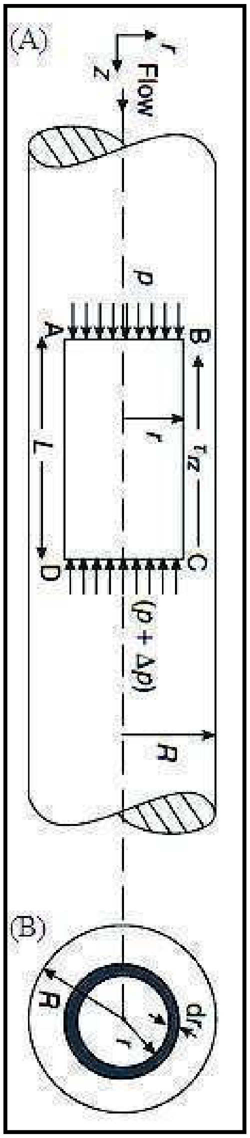


Figure (2.13) Schematic of flow in vertical flow, A) side view B) cross section of flow. After (Chhabra, and Richardson, 2008)

Assuming no slip condition at the wall of the tube, i.e. $V_z = 0$when $r = R$, from this the first component at right hand of equation (2.18) is equal to zero.

$$Q = \int_0^R \frac{r^2}{2}\left(\frac{-d\,V_z}{dr}\right) dr \quad \text{................................... (2.19)}$$

For the laminar flow of time-independent fluids, the shear rate $\left(-d\,V_z/dr\right)$ is determined only by the value of of the shear stress, i.e. the associated value of τ_{rz}, thus,

$$\frac{-d\,V_z}{dr} = \mathrm{f}(\tau_{rz}) \quad \text{.. (2.20)}$$

Where,

$\mathrm{f}(\tau_{rz})$ Unspecified function.

Combining equations (2.13), (2.14) lead to;

$$\frac{\tau_{rz}}{\tau_w} = \frac{r}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.21)}$$

$$\Rightarrow dr = \left(\frac{R}{\tau_w}\right) d\tau_{rz} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.22)}$$

Now substituting equations (2.20) through (2.22) into equation (2.19), the volumetric flow rate can be given as;

$$Q = \frac{\pi R^3}{{\tau_w}^3} \int_0^{\tau_w} {\tau_{rz}}^2 f(\tau_{rz})\, d\tau_{rz} \text{ , or } \left(\frac{Q}{\pi R^3}\right) {\tau_w}^3 = \int_0^{\tau_w} {\tau_{rz}}^2 f(\tau_{rz})\, d\tau_{rz} \ldots\ldots \text{(2.23)}$$

By applying the Leibniz rule enabling the differential of a definite integral of the form; $(d/d\acute{s})\left\{\int_0^{\acute{s}} s^2 f(s) ds\right\}$ to be written as $(\acute{s})^2 f(\acute{s})$; where s is a dummy variable of integration (τ_{rz}here) and $\acute{s}$ is naturally identified as τ_w, thus by applying Leibniz role to equation (3.10) with respect to τ_w:

$$\frac{d}{d\,\tau_w}\left\{\left(\frac{Q}{\pi R^3}\right) {\tau_w}^3\right\} = \frac{d}{d\,\tau_w}\left\{\int_0^{\tau_w} {\tau_{rz}}^2 f(\tau_{rz})\, d\tau_{rz}\right\}$$

With Leibniz simplification equation (3.10) yields to,

$$(3{\tau_w}^2)\left(\frac{Q}{\pi R^3}\right) + {\tau_w}^3 \frac{d}{d\,\tau_w}\left(\frac{Q}{\pi R^3}\right) = {\tau_w}^2 \mathrm{f}(\tau_w) \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.24)}$$

$$\Rightarrow \mathrm{f}(\tau_w) = 3\left(\frac{Q}{\pi R^3}\right) + \tau_w \frac{d}{d\,\tau_w}\left(\frac{Q}{\pi R^3}\right)$$

Introducing a factor of 4 on the right hand side and using the identity $d\, ln\, x = dx/x$, equation (2.24) may be expressed as:

$$\mathrm{f}(\tau_w) = \left(-\frac{\mathrm{d\,V_z}}{\mathrm{d\,r}}\right)_{\mathrm{w}} = \frac{4\mathrm{Q}}{\pi R^3}\left\{\frac{3}{4} + \frac{1}{4}\frac{d\ln(4Q/\pi R^3)}{d\ln\tau_w}\right\} \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.25)}$$

In terms of average velocity over the cross-section $= Q/\pi R^2$, and pipe diameter D;

$$\left(-\frac{\mathrm{d\,V_z}}{\mathrm{d\,r}}\right)_{\mathrm{w}} = \left(\frac{8\mathrm{V}}{D}\right)\left\{\frac{3}{4} + \frac{1}{4}\frac{d\ln(8\mathrm{V/D})}{d\ln\tau_w}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.26)}$$

If (τ_w) have been plot against$(8\mathrm{V/D})$, on log-log paper, thus instantaneous slope can be founded by equation (2.27),

$$\acute{n} = \frac{d\ln\tau_w}{d\ln(8\mathrm{V/D})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.27)}$$

Therefore, the corrected shear rate at the wall for non-Newtonian fluid is obtained by expressing equation (2.28) can be written in terms of the slope,$\acute{n}$, therefore;

$$\mathrm{f}(\tau_w) = \left(-\frac{\mathrm{d\,V_z}}{\mathrm{d\,r}}\right)_{\mathrm{w}} = \left(\frac{8\mathrm{V}}{D}\right)\left\{\frac{3\,\acute{n} + 1}{4\,\acute{n}}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.28)}$$

The term $(8\mathrm{V}/D)$ is the Hagen-Poiseuille relationship which determine the true shear rate at the wall for Newtonian fluids, this relation no longer describe the shear rate for non-Newtonian fluids. A correction must be added, the rest of equation (2.28) is Weissenberg-Rabinowitsch correction.

Macosko (1994) showed the appropriate use of equation (2.28) when $\acute{n}$ fall in the range of $0.2 < \acute{n} < 1.3$ and leads to error less than 2%. Another source of error when the data points be out of the laminar flow regime see figure (2.14); this can be detected as a sudden change of slope at $log\ \tau_w - log\ (8v/D)$ chart (Chhabra, and Richardson, 2008). This point help the author to set boundary for the laboratory data.

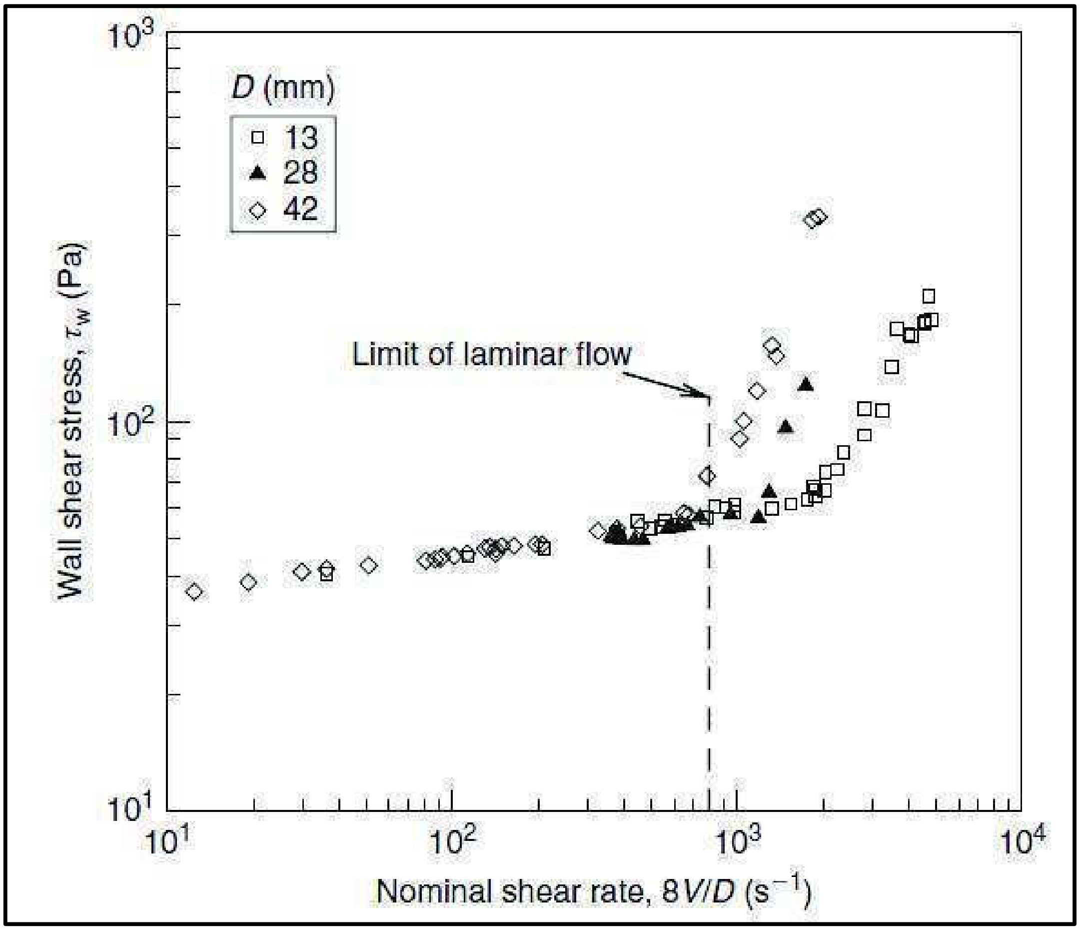


Figure (2.14) the effect of flow regime in data points, after Chhabra, and Richardson (2008)

Chapter 3

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Methodology

CHAPTER III: METHODOLOGY

3. Methodology:

Although, Marsh funnel is described as a quick quality control for rheology test, the majority of authors concluded the funnel's data cannot be rehabilitated into viscometer output; despite the fact that giant strides have been donein latest years in the field of converging marsh funnel to the rotational rheometers, i.e. Fann viscometer, marsh funnel has not improved to the rheometer accuracy level.

This work attempts to modify the recently proposed procedures of treatment marsh funnel itself and its data, also it provides a patent procedure to estimate gel strength, thus marsh funnel can be classified as standalone rheometer.

This chapter is divided into several sections addressing the research design, informants, sampling, data collection procedures, and data analysis.

3.1 Research design:

The experimental and correlational method were utilized for this study and managed to selected sample from several water-based muds' that used in the oil well drilling industry.

The tests involved measurements of mud density, solid content, 6-speed viscometer dial versus viscometer rotational speed, and drained time through marsh funnel versus associated time. Many equations were implemented to predict shear rate and shear stress I marsh funnel, along with Minitab 17 statistical software was utilized to accomplish the study goals, the software is a power full to conduct six-sigma analysis, regression analysis and hypothesis test techniques were implemented.

3.2 Data collection techniques:

3.2.1 Material:

As a result of the availability of WBMs components, they were chosen to participate as ingredients in the sample preparation. As the water is the continuous phase in WBMs, fresh water have been used to initiate the drilling fluid samples; the types of generated mud samples cover three types of water-based mud's, namely gel mud, KCL polymer mud's and KCL silicate mud's. All samples managed to fulfill the requirements of typical mud components and components percentage; many samples were generated within the same type to ensure that the mud samples cover wide range of density of the same mud type. The samples were generated at the ambient temperature as well as the tests condition.

The general samples were composed of 09 participants (03 gel mud, 03 KCL polymer mud, and 03 KCL silicate mud), table (3.1) demonstrates concentrations information about the samples, i.e. ranges of components, all materials were provided by African Drilling Fluid (ADF). The amount of these materials were added to the blend according to the pilot test see (Amoco, 1994; Chevron and BP, 2002) which is completely agreed to the typical mud components percentage.

Table (3.1): demographic information describes generated mud samples.

Material	**Soda Ash**	**Bentonite**	**Caustic Soda**	**FLC**	**Barite**	**PAC LV***	**PAL ZAN***	**Silicate**	**PAC RS***	**KCL**
Mud	PPB	PPB	PPB	PPB	PPB	PPB	PPB	GPB	PPB	PPB
GEL-01	0.01	5.0	0.1	-	-	-	-	-	-	-
GEL-02	0.01	7.5	0.1	-	-	-	0.5	-	-	-
GEL-03	0.01	12.0	0.1	-	3.50	-	1.5	-	-	-
KCL-01	0.15	-	0.15	2.87	20.0	3.9	1.0	-	0.75	18
KCL-02	0.15	-	0.15	-	20.0	3.0	0.5	-	0.75	20
KCL-03	0.15	-	0.15	-	20.0	9.0	-	-	0.75	18
Silica -01	0.15	-	0.15	-	20.0	3.0	-	6	0.50	15
Silica -02	0.15	-	0.15	-	20.0	3.0	-	8	0.75	18
Silica -03	0.15	-	0.15	-	20.0	3.0	1.0	10	0.75	18

* Type of polymer

3.2.2Instrumentations:

Most of the instruments have been provided from Drilling fluid Research Lab at college of petroleum engineering and technology, Sudan University of Science and technology, the following paragraphs briefly describe the instruments that had been used to accomplish the research variables.

Firstly, the samples have been prepared utilizing mud mixture see figure (3.1). The mixture is agitated till it was being homogeneous; the minimum time for mixing was 1.0 hrs.

Figure (3.2) illustrates the utilized mud balance, which designed to estimate the mud density, the percentage of solid content were monitored using mud retort which is shown in figure (3.3).

Figure (3.1) the used mud mixture.

Figure (3.2) the used mud balance.

Figure (3.4) demonstrates the 6-speed viscometer. It is the standard instruments in oil field to perform the rheological analysis of mud samples. Figure (3.5) shows the standard marsh funnel, and non-standard funnel. The non-standard funnel is mounted to interchangeable orifices whish are shown in figure (3.6); table (3.2) demonstrates the various dimensions of stipulated orifices and the used funnels. Figure (3.7) illustrates the typical funnel dimensions.

3.2.3Procedures:

In this experimental research, many procedures were applied to address the raw data, which extracted from generated mud samples.

At first, mud balance, mud retort, and 6-speed viscometer were utilized to measure mud density, solid content percentage, and rotor speed versus dial reading respectively.

Figure (3.3) the used mud retort.

Figure (3.4) the used 6-speed viscometer.

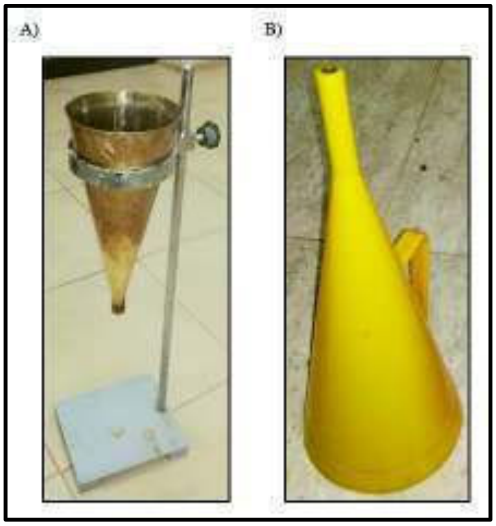


Figure (3.5) the used marsh funnels A) the Non-standard funnel, B) standard funnel.

Figure (3.6) the mounted orifices to the end of non-standard funnel.

Table (3.2): Typical dimension describe marsh funnels and orifices.

Funnel #	**Z1 , cm**	**Ro , cm**	**Z2 , cm**	**RL , cm**	**α , °**	**V_o, cm^3**	**Remarks**
1	27.94	6.985	5.08	0.238	13.611	1500	Standard marsh funnel
2	28.80	7.250	5.10	0.360	12.766	1680	
3	28.80	7.250	6.08	0.230	12.766	1680	
4	28.80	7.250	5.02	0.225	12.766	1680	
5	28.80	7.250	4.10	0.225	12.766	1680	
6	28.80	7.250	5.05	0.150	12.766	1680	

Mud balance procedure:

In order to measure the mud density, a sample of mud is poured into dry clean cup, after that the cup is covered by a cap. To ensure that no gas or air have been trapped, some of mud sample must be expelled through the lid on top of the cap. Wash and wipe the cup outside, then place the balance arm on the base fulcrum. Move the rider along the graduated balance arm till a balance is achieved. The balance is indicated when the bubble is under the centerline. The edge of rider shows the density of mud sample (API, 2009).

6-speed viscometer procedure:

The multi-speed viscometer procedure is as follow; a sample of drilling mud is placed in the instrument cup, and rotor sleeve is immersed to the scribed line exactly, after that the sample is sheared with sleeve rotating at 600 RPM, wait the viscometer dial to stabilize then read and report the dial reading, using the same criteria read and record the dial reading when the sample is sheared at 300, 200, 100, 6, and 3 RPM.

To determine the gel strength, stir the mud sample at 600 RPM for 10 second, allow the sample to stand undisturbed for 10 second, after that shear the sample at 3 RPM, record the maximum reading as initial gel strength or *10-sec gel*, denoted$\theta_{3\ @\ 10\ sec}$, Re-stir the mud sample at 600 RPM for 10 second, then allow the sample to stand undisturbed for 10 minutes, after that shear the sample at 3 RPM and record the maximum reading as *10-min gel*, denoted $\theta_{3\ @\ 10\ min}$(API, 2009).

Marsh funnel procedure:

It is measured through following procedure: cover the funnel orifice by finger, then pour fresh sample through screen until the fluid reaches the screen bottom, remove the finger and start stopwatch instantaneously, the time required to pour$946\ ml$ (1 quart) is measured and reported to the nearest second as marsh funnel viscosity (API, 2009).

The author made a little bit modification on marsh funnel procedure, as marsh funnel is used, volume drained and corresponding time to drain such volume were tabulated, also the time required to drain 1 liter of fresh water was reported. In another manner for marsh funnel handling, the mud sample was poured to funnel and enabled to last for a while, i.e. 1 minute, 5 minutes, and 10 minutes, after that it was allowed the mud to drain through the nozzle, while reporting volume drained vs. associated time.

3.2.4 Data validity:

In order to ensure high level of data accuracy, calibrated mud balance and 6-speed viscometer were used, also to mitigate the human error within marsh funnel two run were made and the average value of data points was taken.

3.3 Data Analysis:

At first, shear stress and shear rate within the 6-speed viscometer were estimated using equations (2.6) and (2.7), at the same time equation (2.15), was applied to assess the shear stress at the wall of marsh funnel, the shear ratewas estimated by following equations (2.16) through (2.28), and apparent viscosity within marsh funnel has been founded applying equation (2.10).

To figure out the rheological properties of drilling fluids that have been described at previous chapter the research follows a combination of methods. Figure (3.9) illustrates the cross linking between methods. The raw data were extracted as mentioned before. The raw data consisted of marsh funnel shear rate and shear stress and 6-speed viscometer shear rate and shear stress, apparent viscosity, and mud sample properties, i.e. mud density, solid content, time required to drain 1 liter of fresh water.

The methodology can be divided into two main parts; the parts are related to the classification of rheological parameters, i.e. parameters that describe the flowing behavior and the other describe the fluid at rest circumstance.

3.3.1 Flowing parameters estimation:

Firstly, the extracted data from 6-speed viscometer is used to determine the most appropriate rheological model that can express the data perfectly. Accordingly, the desired rheological parameter is identified and calculated.

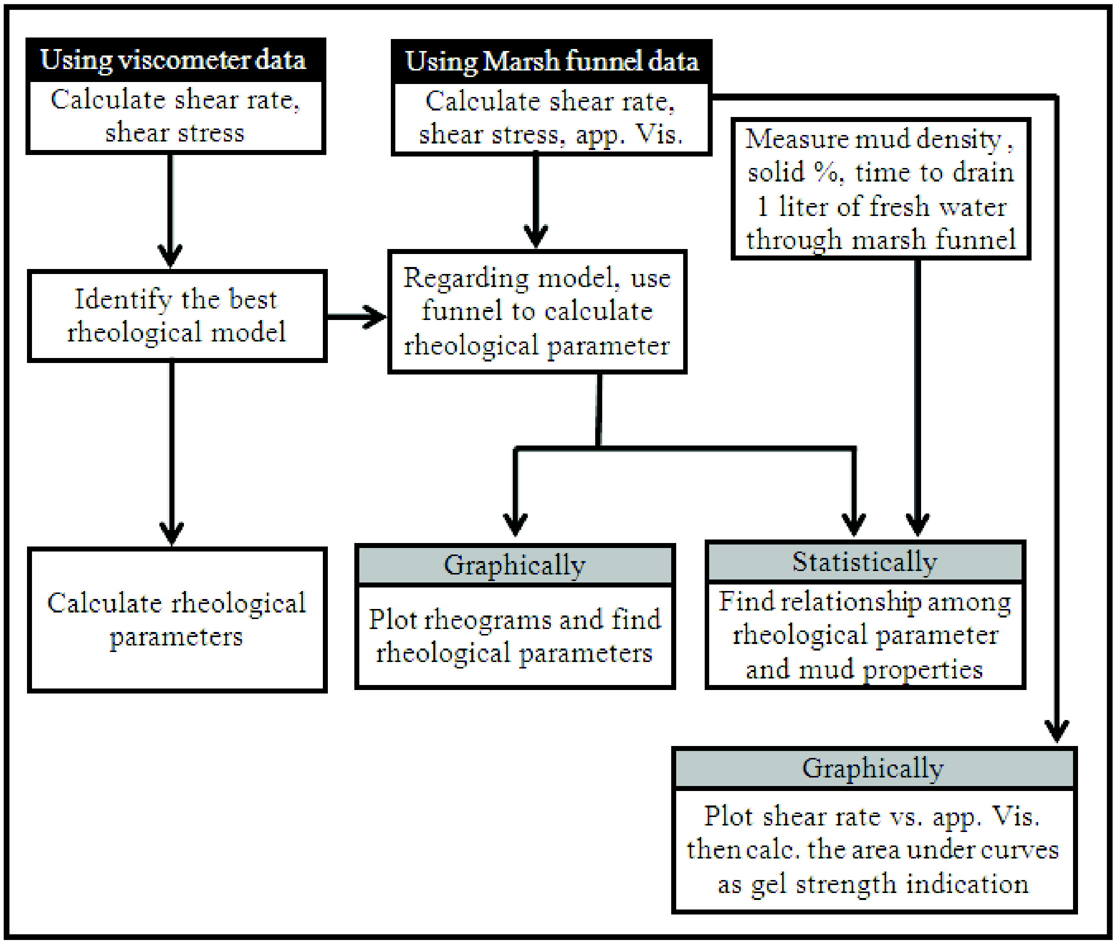


Figure (3.7) flow chart of entire methodology of the research

Taking the best model into account, the marsh funnel data is treated in two manners to find the characterized parameters:

1. The first treatment is graphical; i.e. this method is achieved by plotting the rheograms of data then extract the desired parameter, i.e. if the appropriate model that expresses the fluid behavior is Bingham plastic model, the behavior can be plotted as straight line has slope of plastic viscosity and intersect with y-axis as yield point.
2. The second treated method is achieved using statistics; i.e. this way is achieved by finding a correlational relationship among preferred parameter, which is already determined using 6-speed viscometer, and other variables which measured in the lab, the variables that investigated are: density, marsh funnel orifice dimensions, solid content, and standard time to drain standard volume of fresh water.

The statistical data analysis was performed using Minitab17 statistical software. The analysis consists of non-linear regression, and hypothesis testing; the analysis was sensitive to density, marsh funnel orifice dimensions, solid content, time to drain standard volume of fresh water, and the mud type.

3.3.2 Gel strength estimation:

As the drilling fluid lasts for a while without shearing action, it must has attraction forces that allowed the mud to suspend any cuttings or weighting material, this attraction force should progress to certain limit, then stop, the attraction force at low shear rates express the gel strength. This point makes the measuring of gel strength should be conducted associated with the time; thus attraction force can be evaluated at different time.

The soul of detection methodology is to find any change in the apparent viscosity, but the marsh funnel cannot be operated at a specific shear rate; as the fluid is poured inside the funnel and wait for a while the attraction forces are announced thus it makes the discharging through funnel orifice harder than if the fluid discharged immediately, i.e. as the fluid be inside the funnel for a while its viscosity is increase. However, the difference of area under the curves somehow indicates the increasing of fluid viscosity and the gel strength at the same time, in the same fashion, as there is no change in the area; this means the method cannot indicate the gel strength, then the key factor to identify the gel strength come from creating the chart of shear rate versus apparent viscosity and finding the area under the created curve, this curve is built at many category; i.e. immediate drain, drain after 1 min, drain after 5 min , and drain after 10 min, the immediate drain consider as the basic case and try to find any change in the area. Indeed the area of any time category had been compared to the lower time category; if any increased of area observed thus the funnel can detect the gel strength.

The author suggests equation (3.1) as indicator for gel strength within the drilling fluid using marsh funnel.

$$G.S.I = \frac{Area_{after\ (i)min} - Area_{imm.}}{Area_{imm.}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where;

$G.S.I$	Gel strength indicator, fraction.
$Area_{after\ (i)min}$	The area under curve when drain after waiting (i) min
$Area_{imm.}$	The area under curve when drain immediately.
i	Waiting time, i.e. 1 min, 5 min, and 10 min.

The area was calculated using the ⅜ -Simpson's formula, which is more reliable and accurate than the traditional formulas.

Chapter 4

Results and Discussions

CHAPTER IV: RESULT AND DISCUSSION

4 Results and discussion:

The used methodology is consisted of complicated results; the data of the methodology steps has been tabulated or illustrated in a figure depend on data feature, the figure or table consisted of step data for a sample, when draining from a funnel geometry and only for a draining category, i.e. immediate draining, drain after 1 minute, drain after 5 minutes, or drain after 10 minutes. The funnels were ordered according to table (3.2). The most important data for the same step related to the other sample have been tabulated in separated table.

4.2Estimation of flowing behavior discriminators:

The estimation of flowing parameters via marsh funnel conducted through following steps;

4.2.1 Identify the appropriate rheological model and its discriminators;

As had been demonstrated previously the rheological properties are just coefficients exist inside mathematical models that try to predict the rheograms, in this section the constants of Bingham and power low models are estimated using 6-speed dial readings, then they used to forecast the shear rate and shear stress done by fluid on the Bop as per equations (2.6) and (2.7), respectively. The R-squared was used as a key factor to identify which rheological model is appropriate; table 4.1 illustrates the calculation done on mud sample GEL-02.

Table 4.1 Calculation Rheological properties within 6-speed viscometer.

N	θ_N	γ , sec^{-1}	$\tau_{(from\ 6\ speed\ viscometer)}$, $dyne/cm^2$	$\tau_{Bingham}$, $dyne/cm^2$	$\tau_{Power\ low}$, $dyne/cm^2$
600	25	1022.04	127.50	127.50	127.50
300	19.25	511.02	98.18	98.18	98.18
200	16.5	340.68	84.15	88.40	84.26
100	12.5	170.34	63.75	78.63	64.88
6	8.5	10.22	43.35	69.44	22.46
3	6	5.11	30.60	69.14	17.29

Column #1 contains the speeds that the Fann-viscometer can operate with, Column #2 is the dial reading associated to the speed of the viscometer. Columns # 3 and #4 are the shear rate and shear stress on the viscometer. Columns #5 and #6 are the estimated shear stress on the viscometer depending on Bingham and Power low model parameters.

R-squared for Bingham model equal 0.63, whereas R-squared for Power low model equal 0.91.From the values of R-squared it is clear that the most appropriate model to present the fluid behavior for GEL-02 (mud sample) is the power low model; Table 4.2 illustrates the rheological parameter associated with R-squared values; from table 4.2 one can concluded that all mud samples are obey the power low model. This point makes the author to find out the parameters of power low model, i.e. n and k.

Table 4.2 Rheological properties associated to R-squared for mud samples.

Mud sample	Bingham Model			Power low model		
	YP	PV	R^2	n	K	R^2
GEL-01	2	1	0.999	0.737	0.154	0.854
GEL-02	5.75	13.5	0.629	0.377	9.352	0.905
GEL-03	13	48	0.481	0.279	54.607	0.896
KCL-01	31	17	0.470	0.437	16.041	0.989
KCL-02	11	12.5	0.843	0.615	2.588	0.975
KCL-03	3.5	10.25	0.928	0.804	0.466	0.997
SILICA-01	9	1	0.987	0.926	0.158	0.999
SILICA-02	12	3	0.972	0.848	0.386	0.995
SILICA-03	16	24.5	0.648	0.48	10.315	0.99

Thereforethe targeting parameters aren, and K, this can be achieved by two methods the first is calculated the exact value of property, and the second try to set a mathematical expression to predict the property;

4.2.2Estimate rheological properties graphically:

As the marsh funnel has a similarity to the capillary viscometer; therefore it can be classified as a capillary viscometer tentatively, thus set of methods related to capillary viscometers were used to find the flowing behavior parameters according to the rheograms chart. To achieve such parameters from marsh funnel the listed pullet points were applied:

- *Calculate the rheological properties using marsh funnel data;*

As the parameters are express the fluid at flowing circumstance; the data for draining immediate was only used. The value of $\log \frac{4Q}{\pi R_l^3}$was plotted versus $\log \tau_w$, see figure (4.1). After that a third order curve was used to regress the relationship, and the derivative was prepared to correct the apparent shear rate to the real shear rate as per equation (2.28), finally the rheograms is plotted and the perfect power curve was predicted then the coefficients were matched to power low model. See figure (4.2) and table (4.3).

A clear difference between expected parameters from marsh funnel and those estimated from 6 speed viscometer areobserved, this might happen due to the difference in the operating shear rate for the instruments, as the 6 speed viscometer has a lower shear rate its estimation led to higher consistency, thus the non-Newtonian index is changed accordingly to compensate the effect. Therefore the shear stress within marsh funnel were predicted at the same level of shear rates that Fann-35 viscometer can operate with, the estimated values were compared to 6-speed viscometer.

However, The forecasted parameters overestimate the shear stress more than the parameters excreted from 6 speed viscometer this point emphasized the results which delivered by Guria et. al. (2003), However the R-squared shows a good converge see table (4.3).

When mapping the R-squared values, I found that the funnel#6 (3.0 mm funnel size) had the worst expectation of shear stress; indeed the size of the marsh funnel makes a great difference, as the size be smaller as the response does not show the behavior of fluid flow, rather than that it presents another behavior may be the orifice resistance. The Most appropriate geometry was funnel#2 (7.5 mm size funnel), from this point one can conclude as the size of the orifice increases as the orifice resistance decrease as the fluid flow behavior take it’s chance to be more announced in the fluid response, vice versa.

From the values of R-squared in table (4.3) the tentative classification is approved therefore the marsh funnel can be classified as a capillary viscometer.

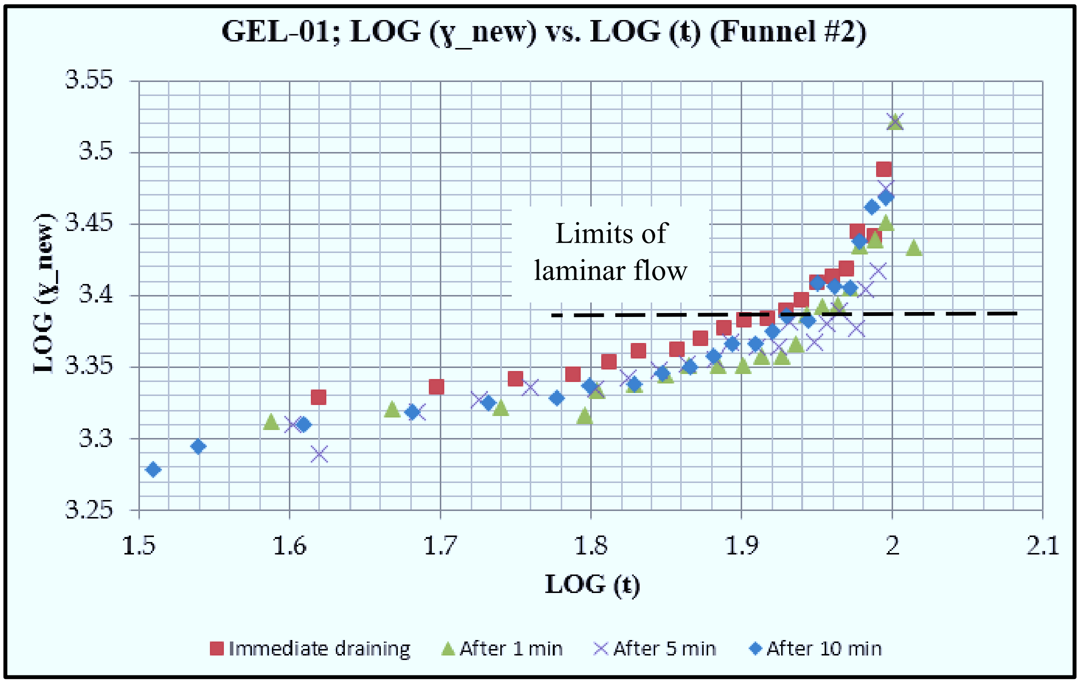


Figure (4.1) Weissenberg-Rabinowitsch correction

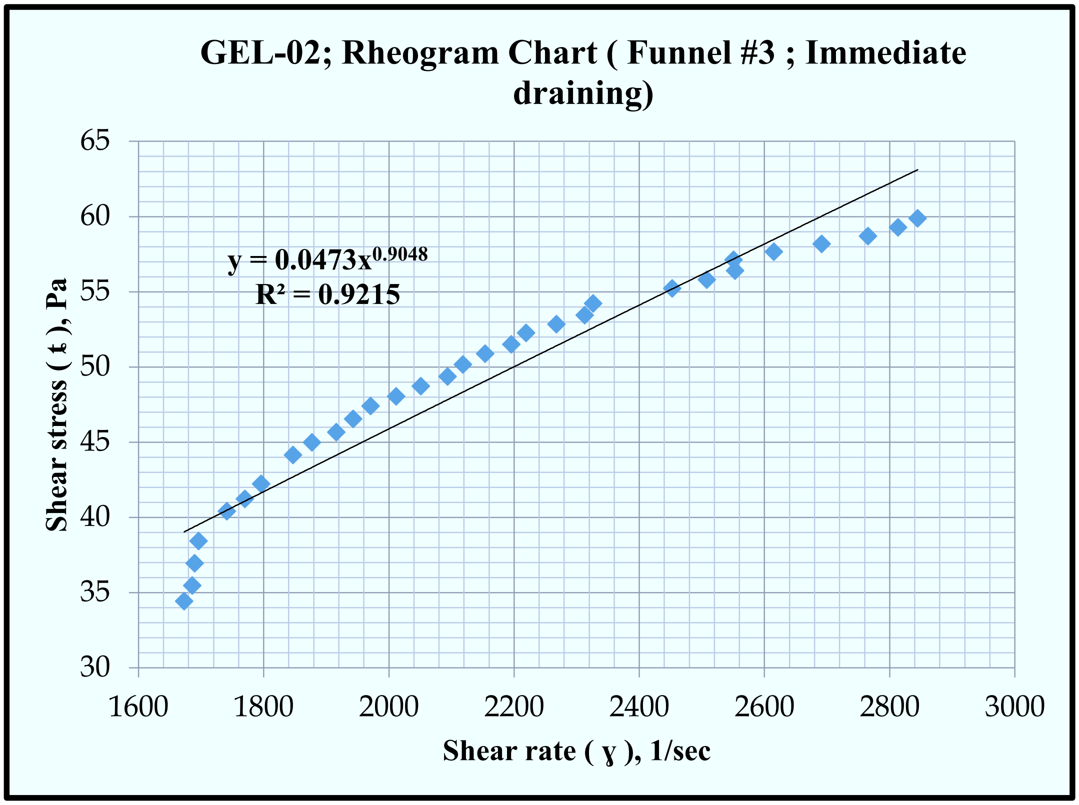


Figure (4.2) rheograms chart for data gathered from funnel#3

Table 4.3 Rheological properties for mud samples determined by funnel orifices.

Mud Sample		GEL-01	GEL-02	GEL-03	KCL-01	KCL-02	KCL-03	SILICA-01	SILICA-02	SILICA-03
6-speed data	K	0.154	9.352	54.607	16.041	2.588	0.466	0.158	0.386	10.351
	n	0.737	0.377	0.279	0.437	0.615	0.804	0.926	0.848	0.48
Standard funnel	K	0.0002	0.631	4E-09	0.0009	2E-10	1E-14	7E-09	9E-09	2E-08
	n	1.8628	0.874	3.5381	1.832	3.8637	5.082	3.2662	3.2997	3.3693
	R^2	0.8543	0.6008	0.7547	0.1295	0.3459	0.4395	-0.0989	-0.1081	0.2944
Funnel#2	K	0.284	2.248	1E-09	0.488	0.575	1E-30	3.141	1.393	8E-10
	n	1.0259	0.8036	3.9832	1.0579	0.9805	10.498	0.7382	0.8713	3.9488
	R^2	0.9968	0.9690	0.8795	0.6396	0.8310	0.3092	0.9781	0.9546	0.6969
Funnel#3	K	3E-06	0.473	0.492	0.013	2E-06	N/A	1E-13	8E-07	2E-06
	n	0.284	0.9048	1.0208	1.5271	2.6585	N/A	4.8944	2.729	2.8563
	R^2	0.5720	0.4532	0.2129	-0.027	-0.2388	N/A	-0.1400	-1.0863	0.8191

Funnel#4	**K**	0.559	6E-07	1.2590	1.7512	7E-11	N/A	5E-08	7E-15	4E-05
	n	0.9479	2.7166	0.8986	0.003	4.0174	N/A	3.0276	5.2696	2.341
	R^2	0.9977	0.5279	0.3012	0.7100	0.3439	N/A	-0.5496	0.2169	0.2585
Funnel#5	**K**	0.078	5.055	0.4270	0.013	2E-07	1E-14	0.0007	2E-06	7E-06
	n	1.1323	0.6057	1.0134	1.5487	2.9292	5.2703	1.8236	2.6662	2.6519
	R^2	0.9882	0.8690	0.0454	0.2970	0.0778	-0.0002	0.5333	-0.3463	0.7180
Funnel#6	**K**	7E-10	9E-05	N/A	0.61	3E-06	N/A	5E-08	1E-06	0.0170
	n	3.3977	2.034	N/A	1.0615	2.6305	N/A	3.0141	2.6277	1.5225
	R^2	0.1887	0.3580	N/A	0.8472	-0.1250	N/A	-0.3958	-0.2633	0.6225

The N/A refer to the mud sample was too viscous thus mud sample could not pass through the marsh nozzles properly, therefore the flow response may be not fully described, this makes the author to reject the sample data.

4.2.2 Estimate rheological properties statistically:

Many drilling properties were involved in the statistical analysis, the statistical analysis was accomplished using Minitab (statistical software), and the applied analysis was multi-variable regression. In the following paragraphs the involved parameters are listed, and illustrated.

- *Time to drain 1000 ml of fresh water:*

Typical experiment of marsh funnel were performed on water. The water is poured in the funnel and then let to drain. The time required to drain 1000 ml of fresh water was recorded. The experiments conducted 20 times. Table 4.4 demonstrates the average of recorded time and the standard deviation for all funnel geometries. This time was denoted (T_w)

Table 4.4 Time required draining 1000 ml of fresh water.

Funnel No	Time to drain 1000 ml , Sec	STD. , ± Sec
1*	28	± 0.500
2	12.463	± 0.238
3	30.7	± 0.24
4	29.82	± 0.205
5	30.393	± 0.227
6	78.194	± 0.468

* The funnel is the standard funnel, thus experiments have not been conducted.

- *Time to drain 1000 ml of mud:*

The drained fluid weight and associated time data were collected, taking the mud density into account the weight was converted to drain volume, a 3rdorder polynomial equation had been used to regress the discharged volume to time data, then calculate the time required to drain 1000 ml of mud, this time is denoted (T_{1000}) . Figure (4.4) illustrates the drain volume versus associated time for GEL-02. Table 4.5 shows the time required to drain 1 liter of mud through different funnel geometry.

In order to reflect that the poured drilling fluid is more viscous than water, new parameters were generated from T_{1000}, and T_w , the parameters were $DivT$ and DT.

- *Solid content and density:*

Solid content and drilling fluid density had been investigated, in table 4.5 the second and third columns illustrates the values of density and solid content percentage of mud samples, respectively. The solid content is denoted as S%

- *Other parameters:*

Many parameters had been involved in the statistical analysis; the funnel geometries' have been illustrated in table (3.2), many combination of the geometry and funnel times were used as the absolute values and the dimensionless values i.e. percentages. As well as the mud type, mud density, and solid content were used to regress the flowing parameters. Figure (4.5) is a screen shot of the software output data for the statistical analysis of parameters.

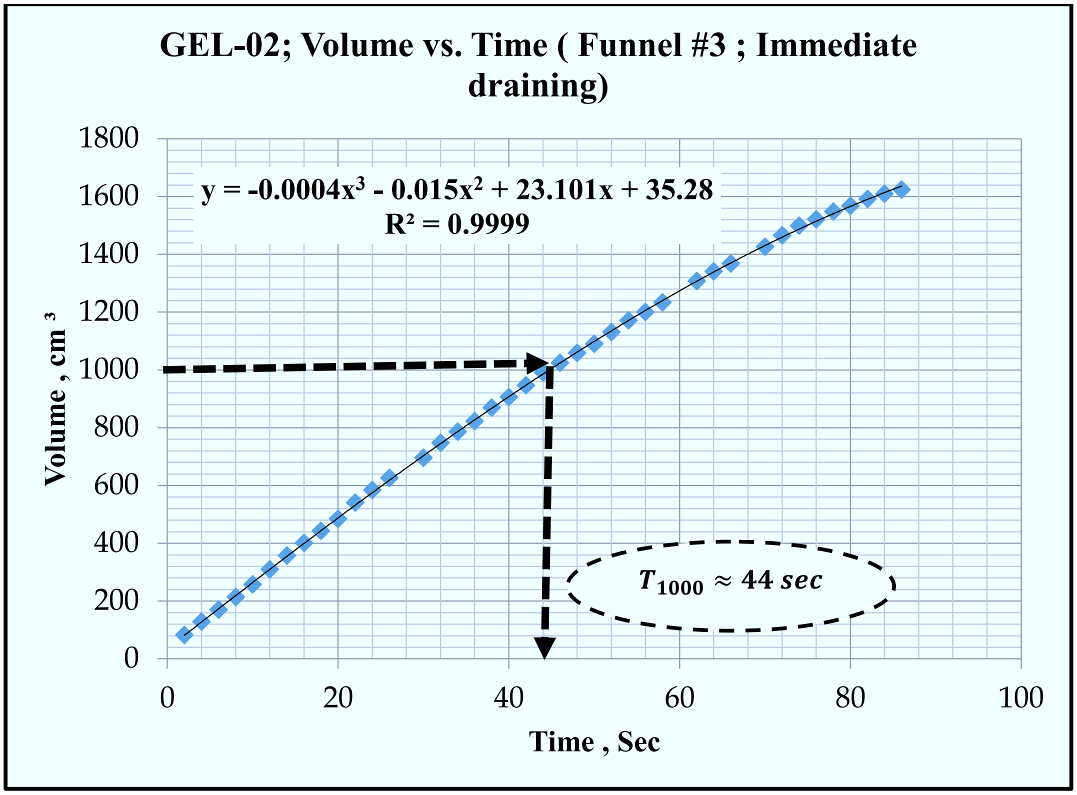
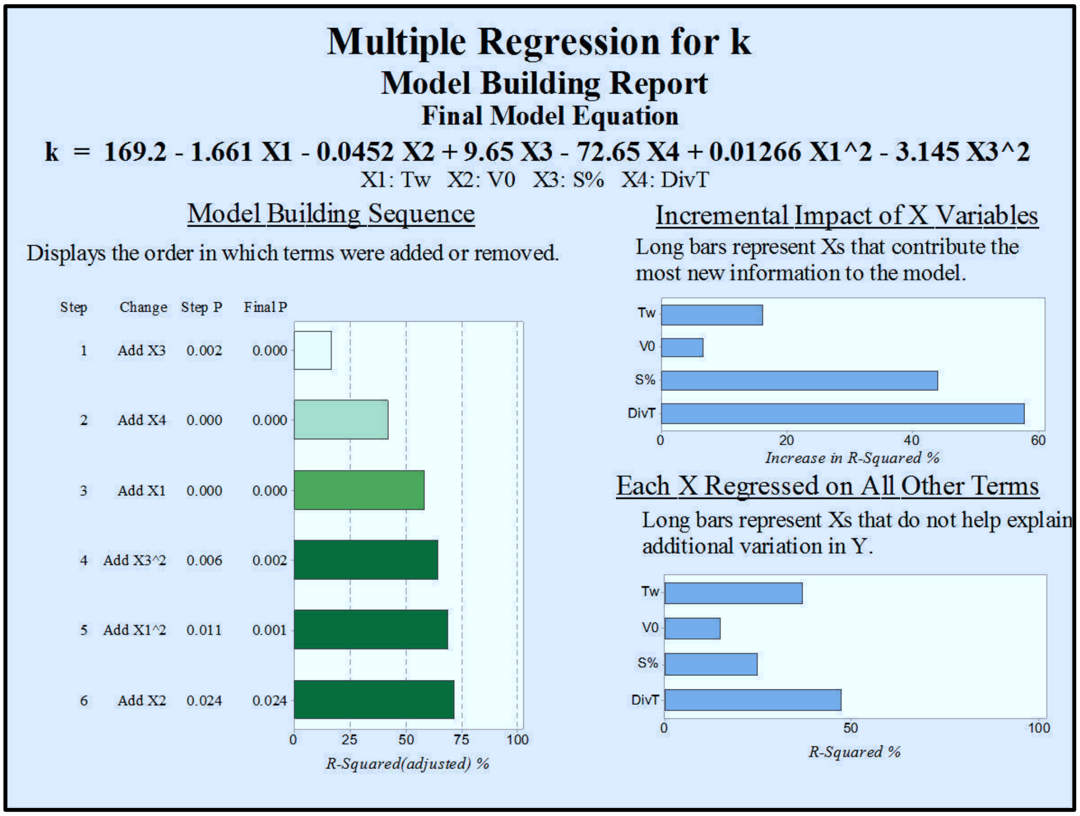


Figure (4.4) drained volume versus time associated time

Table 4.5 Time to drain 1000 ml of drilling fluid at difference funnel geometries, mud density andsolid content.

Sample	ρ gm/cm^3	S%	Time required to drain 1000 ml of mud, sec					
			Standard	Fun # **2**	Fun # **3**	Fun # **4**	Fun # **5**	Fun # **6**
GEL-01	1.007	0.5	30.17	11.26	39.29	64.41	37.48	107.69
GEL-02	1.027	1.0	37.61	16.33	44.59	73.46	41.38	182.69
GEL-03	1.041	1.0	57.44	22.49	119.39	113.35	85.13	N/A
KCL-01	1.100	4.0	57.40	20.45	93.27	109.52	91.02	777.83
KCL-02	1.086	4.0	46.17	14.83	60.41	53.34	55.32	258.72
KCL-03	1.089	4.0	40.388	15.269	N/A	N/A	55.908	N/A
SILICA -01	1.074	4.0	35.87	13.36	45.95	44.06	50.63	167.91
SILICA-02	1.077	4.0	41.62	14.80	50.75	42.56	54.66	184.60
SILICA-03	1.103	5.0	57.17	19.41	88.86	85.44	93.74	461

Correlations to forecast the flowing parameters (n, k) were tested by Minitab 17 (statistical software). The most appropriate correlation is illustrated in the figures (4.5) and (4.6) for k prediction, and figures (4.7) and (4.8) for n prediction.



Multiple Regression for k

Model Building Report

Final Model Equation

$$k = 169.2 - 1.661\,X1 - 0.0452\,X2 + 9.65\,X3 - 72.65\,X4 + 0.01266\,X1^2 - 3.145\,X3^2$$

X1: Tw X2: V0 X3: S% X4: DivT

Model Building Sequence

Displays the order in which terms were added or removed.

Step	Change	Step P	Final P
1	Add X3	0.002	0.000
2	Add X4	0.000	0.000
3	Add X1	0.000	0.000
4	Add X3^2	0.006	0.002
5	Add X1^2	0.011	0.001
6	Add X2	0.024	0.024

Incremental Impact of X Variables

Long bars represent Xs that contribute the most new information to the model.

Each X Regressed on All Other Terms

Long bars represent Xs that do not help explain additional variation in Y.

Figure (4.5) steps of building regress model for (k)

For both models, the parameters $Z_1, R_0, Z_2, R_L, alpha$ were rejected in model building phase, this finding shows the estimation of rheological properties do rational to marsh funnel geometry dimensions.

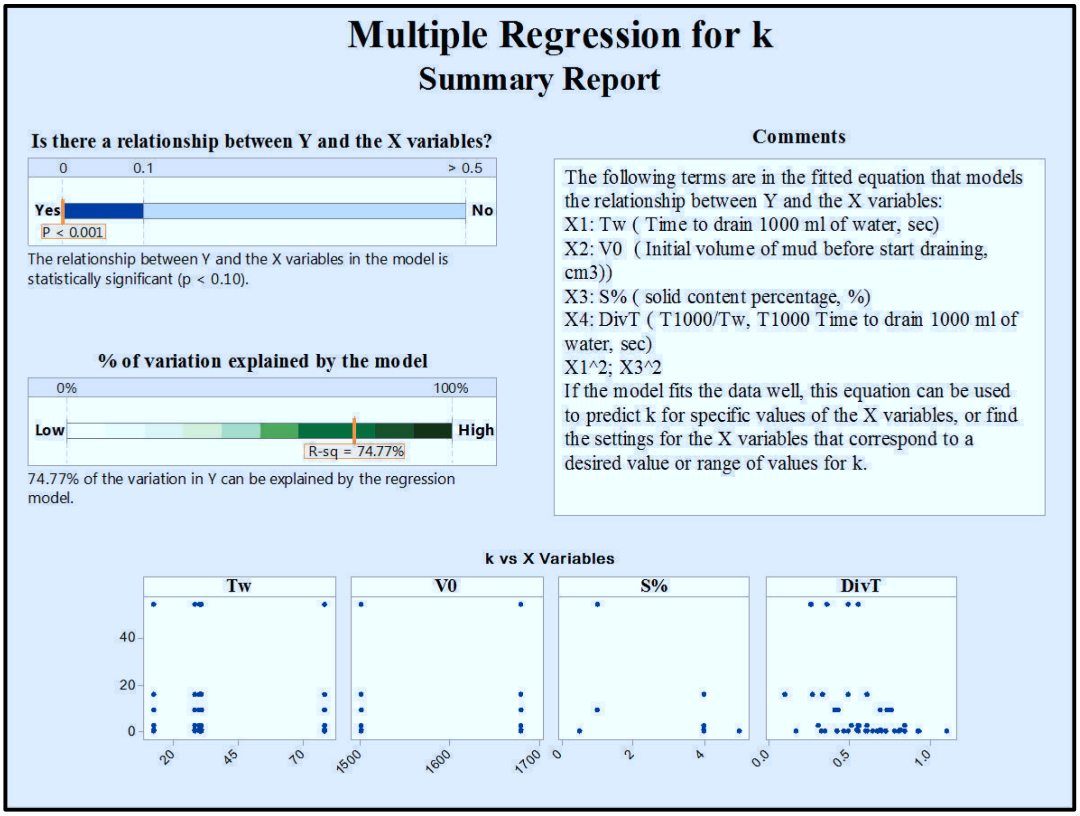
- ***K regression:***

At first step the funnel data were only regressed to (k), all alternatives fail to get fair correlation, then mud Density and solid content were added separately, the best regression come from the solid content group.

A very good amount (74.77%) and P-value of (0.024); (k) is explained by solid content, time to drain 1000 ml of fresh water and mud, initial volume of mud in the funnel, along with division of drain times of mud and water respectively. equation (4.1) is the correlation between k (consistency index) and the rest of parameters.

$$k = 9.65\,S\% - 72.65DivT - 1.66T_w + 0.01266T_w^2 - 0.0452\,V_0 - 3.145(S\%)^3 + 169.2 \qquad (4.1)$$

From figure (4.5), in section incremental impact of X variables, the most used variable was ($DivT$), when follow up the data it is the most versatile variable, where the rest predictors are the less versatile than ($DivT$), in the same time the solid content contributed as well as ($DivT$). This means that the solid content is the most contributed variable in the model.



Multiple Regression for k

Summary Report

Is there a relationship between Y and the X variables?

The relationship between Y and the X variables in the model is statistically significant (p < 0.10).

% of variation explained by the model

74.77% of the variation in Y can be explained by the regression model.

Comments

The following terms are in the fitted equation that models the relationship between Y and the X variables:
X1: Tw (Time to drain 1000 ml of water, sec)
X2: V0 (Initial volume of mud before start draining, cm3))
X3: S% (solid content percentage, %)
X4: DivT (T1000/Tw, T1000 Time to drain 1000 ml of water, sec)
X1^2; X3^2
If the model fits the data well, this equation can be used to predict k for specific values of the X variables, or find the settings for the X variables that correspond to a desired value or range of values for k.

k vs X Variables

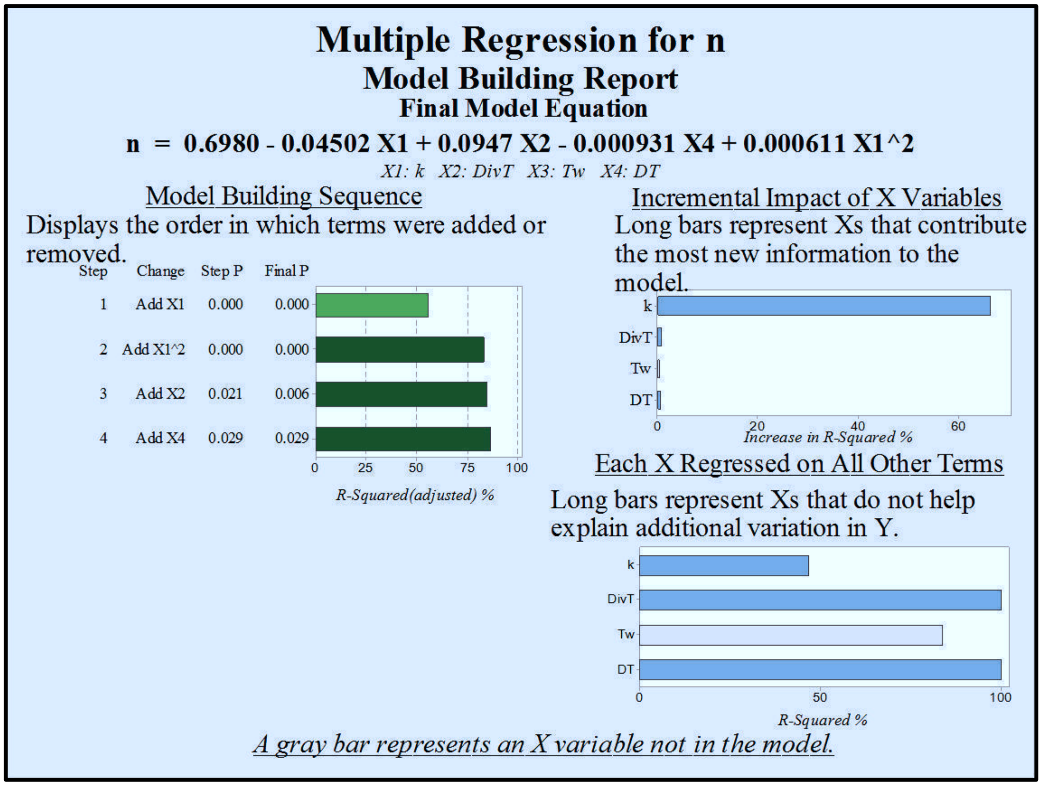
Figure (4.6) summary report for (k) regression

- ***n regression:***

As well as k regression the funnel data cannot obtain a good correlation, then solid content, density, and mud consistency were added separately, the best model was developed when adding the mud consistency. As it shown in figure (4.7) the most power full variable was (k) in the same time other parameters did not give valuable contribution for the model. This point was not appears in (k) regression this means the non-Newtonian index is harder than (K) to correlate with marsh funnel data without present of other mud properties.

An excellent degree (87.26%) and P-value of 0.029; (n) can be is expressed by mud consistency, $DivT$and DT. equation (4.2) express the multivariable regression to predict n.

$$n = 0.698 - 0.04502k + 0.0947\ DivT - 0.000931\ DT + 0.000611k^2 \qquad (4.2)$$



Multiple Regression for n

Model Building Report

Final Model Equation

$$n = 0.6980 - 0.04502\ X1 + 0.0947\ X2 - 0.000931\ X4 + 0.000611\ X1\text{^}2$$

X1: k X2: DivT X3: Tw X4: DT

Model Building Sequence

Displays the order in which terms were added or removed.

Step	Change	Step P	Final P
1	Add X1	0.000	0.000
2	Add X1^2	0.000	0.000
3	Add X2	0.021	0.006
4	Add X4	0.029	0.029

Incremental Impact of X Variables

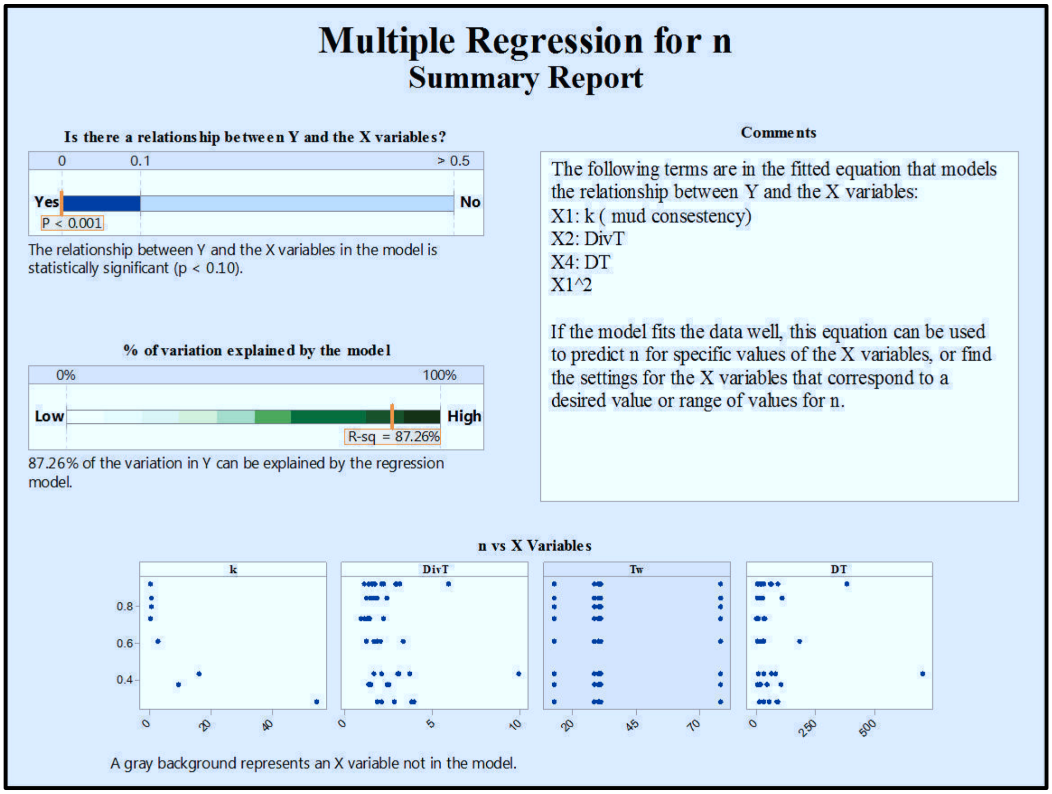
Long bars represent Xs that contribute the most new information to the model.

Each X Regressed on All Other Terms

Long bars represent Xs that do not help explain additional variation in Y.

A gray bar represents an X variable not in the model.

Figure (4.7) steps of building regress model for (n)



Multiple Regression for n
Summary Report

Is there a relationship between Y and the X variables?

The relationship between Y and the X variables in the model is statistically significant ($p < 0.10$).

% of variation explained by the model

87.26% of the variation in Y can be explained by the regression model.

Comments

The following terms are in the fitted equation that models the relationship between Y and the X variables:
X1: k (mud consestency)
X2: DivT
X4: DT
X1^2

If the model fits the data well, this equation can be used to predict n for specific values of the X variables, or find the settings for the X variables that correspond to a desired value or range of values for n.

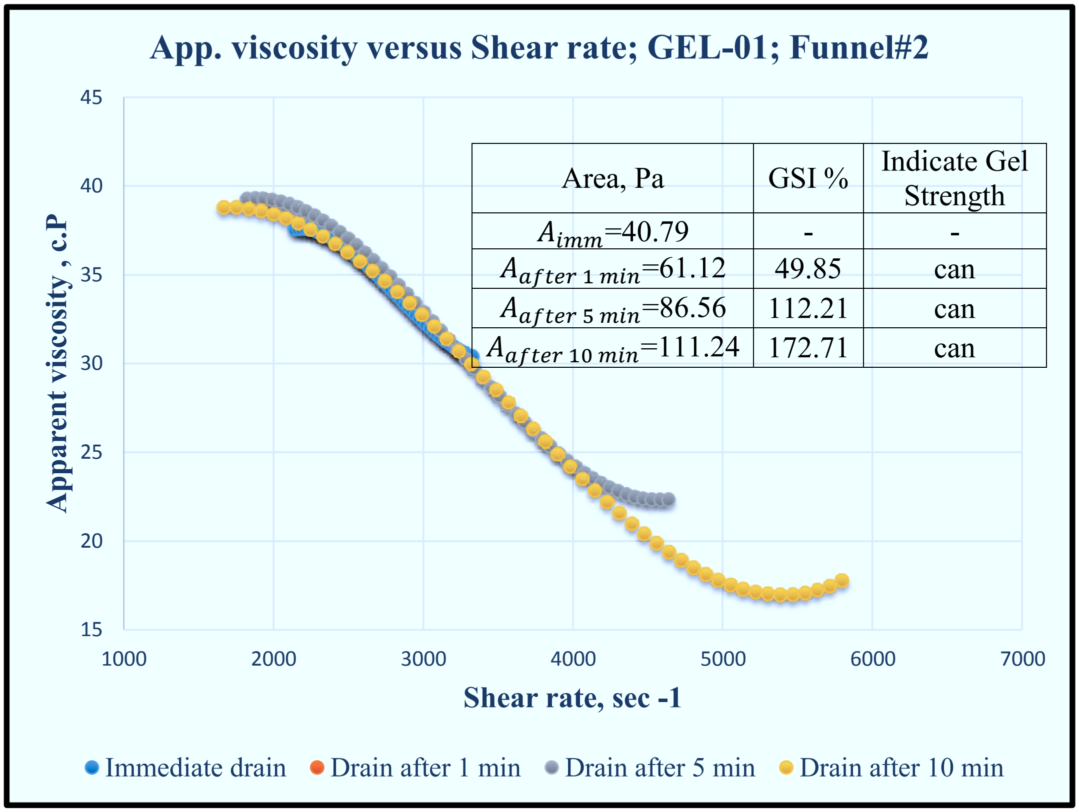
n vs X Variables

A gray background represents an X variable not in the model.

Figure (4.8) summary report for (n) regression

4.3 Indication of Gel strength:

Figure (4.9) illustrates the apparent viscosity versus shear rate for GEL-01 (mud sample) when it is discharged through funnel#2 (7.5 mm size funnel), the plotted data is already regressed and limited to the appropriate range; table 4.6 demonstrates the gel strength detection through proposed methodology, for more details see appendix A.



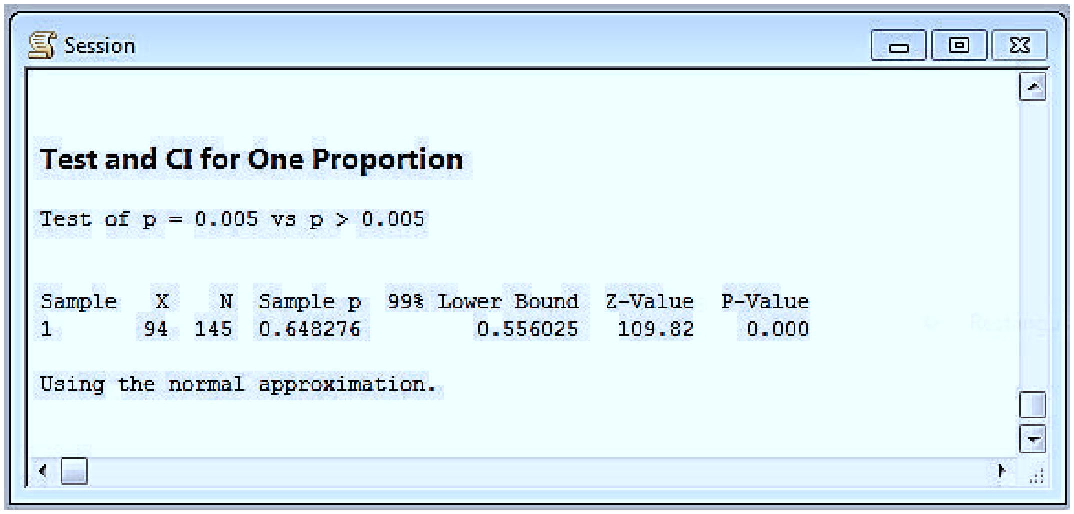
Area, Pa	GSI %	Indicate Gel Strength
A_{imm}=40.79	-	-
$A_{after\ 1\ min}$=61.12	49.85	can
$A_{after\ 5\ min}$=86.56	112.21	can
$A_{after\ 10\ min}$=111.24	172.71	can

Figure (4.9) apparent viscosity versus shear rate (marsh funnel results)

Table 4.6 summary of el strength detection.

Sample	Standard.	Fun#2	Fun#3	Fun#4	Fun#5	Fun#6
GEL-01	3(3)	3(3)	3(3)	3(3)	1(3)	3(3)
GEL-02	2(3)	1(3)	1(3)	3(3)	2(3)	2(3)
GEL-03	2(3)	2(3)	2(3)	1(3)	0(1)	0(0)
KCL-01	1(3)	1(3)	2(3)	2(3)	1(3)	0(0)
KCL-02	3(3)	2(3)	1(3)	3(3)	1(3)	3(3)
KCL-03	2(3)	3(3)	0(0)	0(0)	3(3)	0(0)
SILICA-01	2(3)	1(3)	3(3)	3(3)	2(3)	1(3)
SILICA-02	2(3)	3(3)	1(3)	2(3)	3(3)	1(3)
SILICA-03	0(3)	2(3)	3(3)	2(3)	0(3)	1(3)

The numbers of attempts were put inside brackets, whereas the numbers outside the brackets refer to succeeded attempts. The percentage of overall gel strength detection attempts was$94/145 = 65\%$, this remarkable findings was checked by Minitab17 , which is confirm this percentage is fair enough to consider that marsh funnel can indicate the gel strength. One proportion test (hypothesis test) were accomplished as per figure (4.10).



Test and CI for One Proportion

```
Test of p = 0.005 vs p > 0.005


Sample   X    N  Sample p  99% Lower Bound  Z-Value  P-Value
1       94  145  0.648276         0.556025   109.82    0.000

Using the normal approximation.
```

Figure (4.10) one proportion test for gel strength detecting

The null hypothesis was marsh funnel cannot detect the gel strength, i.e. the probability of detecting gel strength using marsh funnel is 0.0 (which cannot enter to the software therefore I have used 0.005), the alternate hypothesis was marsh funnel can indicate the gel strength, i.e. the probability of detecting gel strength using marsh funnel is greater than 0.005. The confidence level was 99%.

As the P-value is less than 0.0001 which is less than Confident Level (CL) 0.01 this means that the null hypothesis can be rejected. And the author claim that marsh funnel can indicate the gel strength has a statistical significant. Therefore marsh funnel provide enough evidence to consider as a gel strength detector.

Chapter 5

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Conclusions and Recommendations

CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS

5 Conclusions and Recommendations

5.1 Conclusions:

This research was intended to upgrade the marsh funnel accuracy to consider authorized rheometer; many methodologies had been applied to reach such position. The following conclusions can be drawn from the presented study…

The findings from this study highly indicates that marsh funnel is a rheometers that can predict the rheology along with the assistance of some drilling fluid instruments.

The findings shows that the rheograms can be predicted via marsh funnel, and the rheograms has a tendency to overestimate the shear stress rather than Fann-35 viscometer, these findings are broadly in line with those of researcher such as Guria et al. (2013). Also the funnel accuracy increases as the orifice size is increased.

The finding implies that solid content along with marsh data, e.g.$DivT$, T_{1000}, T_w have a major preceived influence on rheological properties estimations whereas funnel geometry dimensions have not affecton the rheological properties estimation.

Correlation relationships to estimate rheological parameters have been developed associated to quite good accuracy.

The study shows enough evidence that marsh funnel is a credence rheometer can indicate the gel strength.

All the above findings clearly indicate the flow of drilling fluid through marsh funnel can be affected by the funnel geometry, which offers outstanding methodologies to estimate the rheological properties either graphically or analytically, therefore the researcher thinks that, it should be become common today to dismiss believe that, marsh funnel is not a rheometer out of rheology field. At top of that findings add to a growing body of literature on universe understanding of the nature of fluid flow through marsh funnels.

5.2 Recommendations:

This work gives an important steps to correct the handling of marsh funnel, possible areas for further investigation include one at least of the following points will make the marsh funnel more appropriate rheometer to measure the rheological properties..

1. One avenue for further studies would be invent the dimensional analysis, this will come out with more versatile relationships.

2. It is important to manufacture marsh funnel mounted to heating option. This will give marsh funnel more power full assets; make sure marsh funnel relationships will not fall when high temperature is entered into account.
3. Without further investigating in the shear rate correction equation it will not be possible to eliminate the minor disturbance on funnel results.
4. Further researchesabout eliminatingtheassociatederror to pressure driven flows rheometers should usefully and pushed the developing of marsh funnel generators.

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Appendix A

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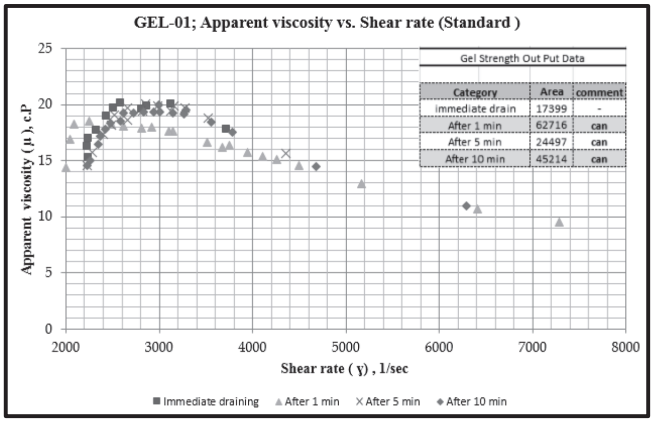
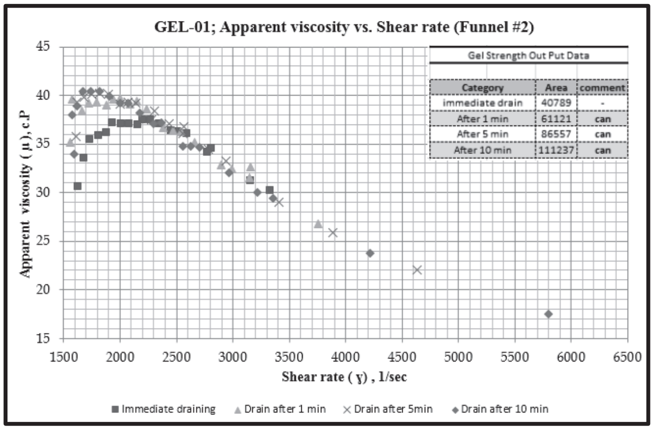
Apparent viscosity versus shear rate

Appendix A: Apparent viscosity versus shear rate



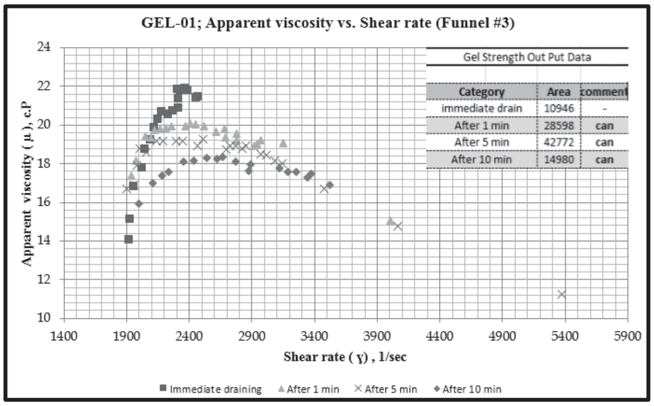
Gel Strength Out Put Data

Category	Area	comment
immediate drain	17399	-
After 1 min	62716	can
After 5 min	24497	can
After 10 min	45214	can



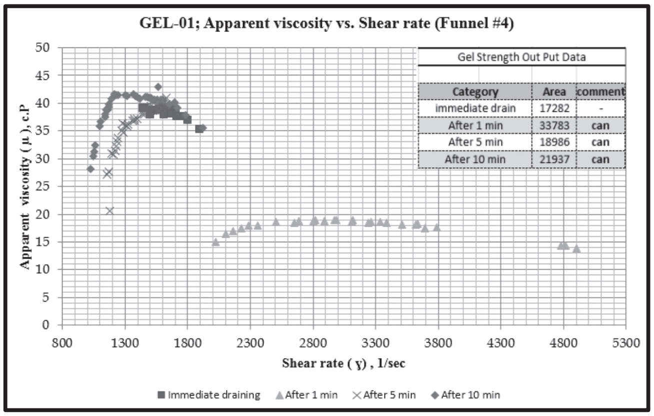
Gel Strength Out Put Data

Category	Area	comment
immediate drain	40789	-
After 1 min	61121	can
After 5 min	86557	can
After 10 min	111237	can



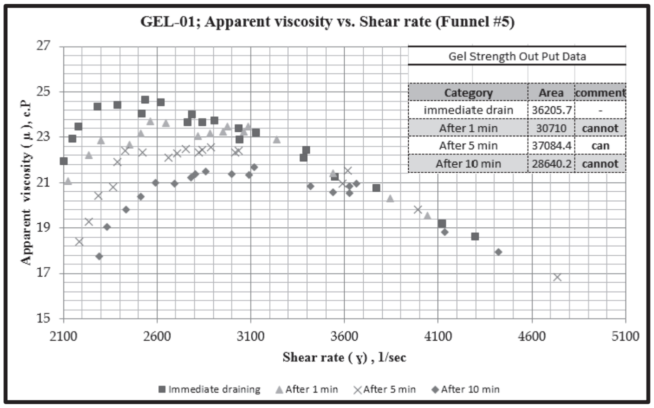
Gel Strength Out Put Data

Category	Area	comment
immediate drain	10946	-
After 1 min	28598	can
After 5 min	42772	can
After 10 min	14980	can



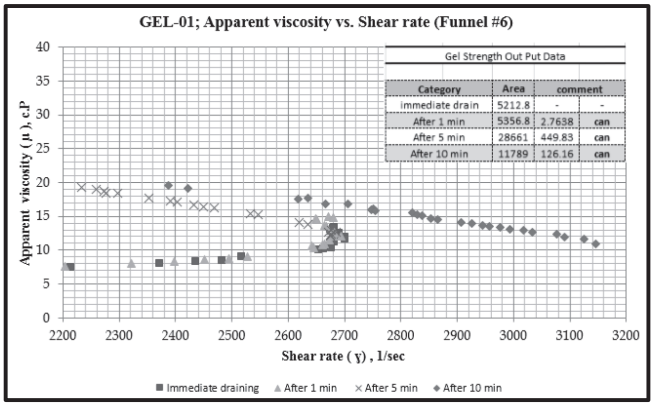
Gel Strength Out Put Data

Category	Area	comment
immediate drain	17282	-
After 1 min	33783	can
After 5 min	18986	can
After 10 min	21937	can



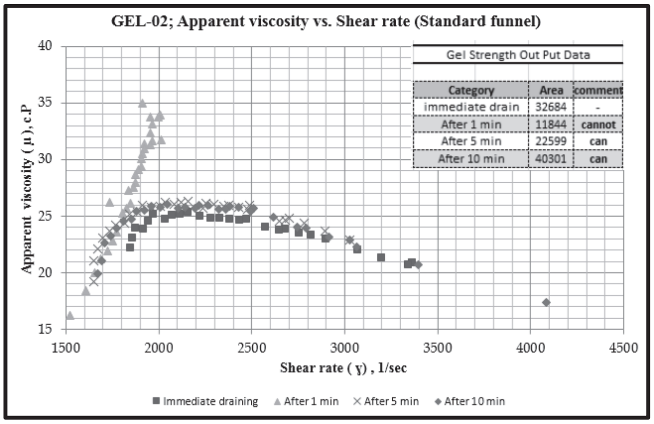
Gel Strength Out Put Data

Category	Area	comment
immediate drain	36205.7	-
After 1 min	30710	cannot
After 5 min	37084.4	can
After 10 min	28640.2	cannot



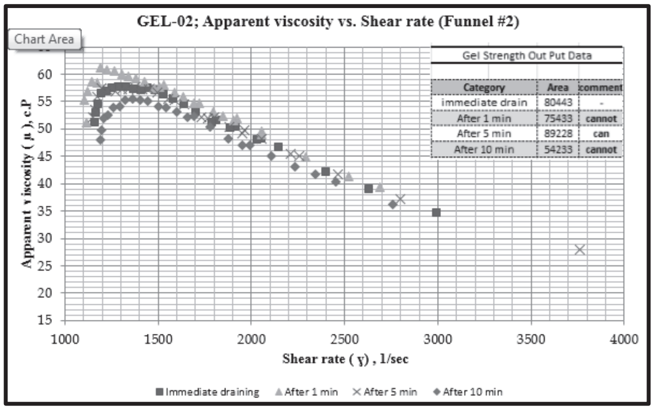
Gel Strength Out Put Data

Category	Area	comment	
immediate drain	5212.8	-	-
After 1 min	5356.8	2.7638	can
After 5 min	28661	449.83	can
After 10 min	11789	126.16	can



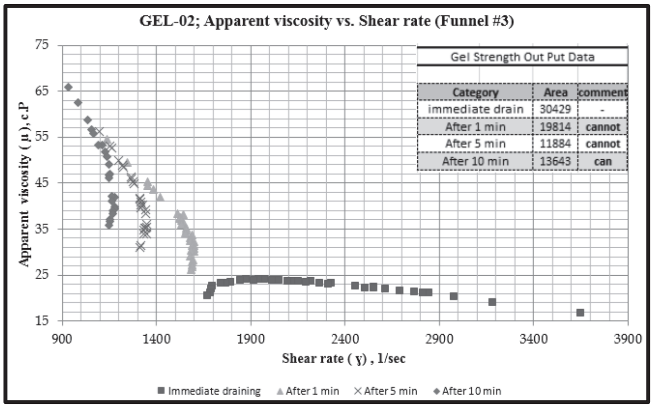
Gel Strength Out Put Data

Category	Area	comment
immediate drain	32684	-
After 1 min	11844	cannot
After 5 min	22599	can
After 10 min	40301	can



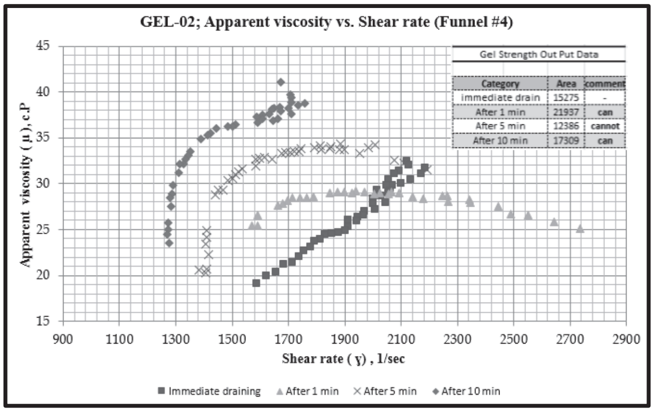
Gel Strength Out Put Data

Category	Area	comment
immediate drain	80443	-
After 1 min	75433	cannot
After 5 min	89228	can
After 10 min	54233	cannot



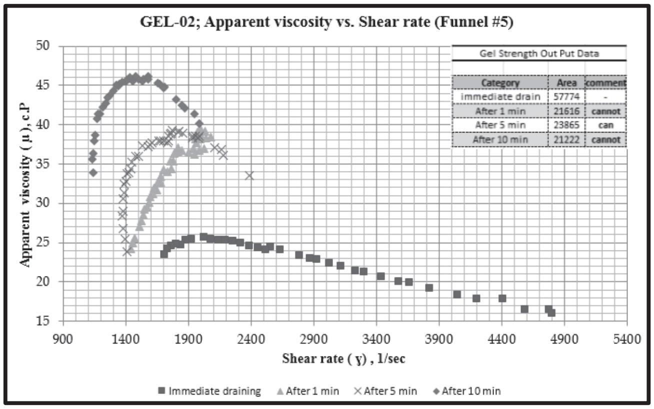
Gel Strength Out Put Data

Category	Area	comment
immediate drain	30429	-
After 1 min	19814	cannot
After 5 min	11884	cannot
After 10 min	13643	can



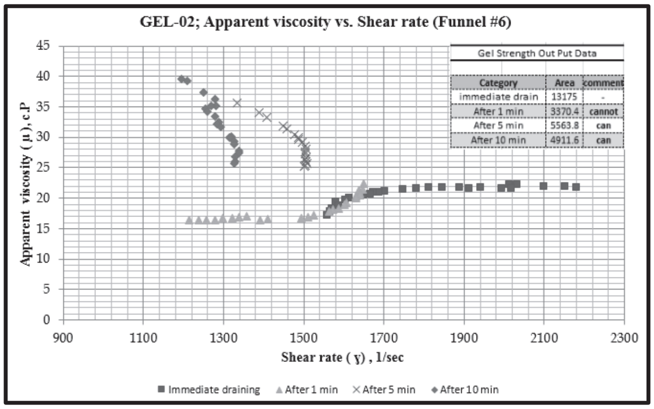
Gel Strength Out Put Data

Category	Area	comment
immediate drain	15275	-
After 1 min	21937	can
After 5 min	12386	cannot
After 10 min	17309	can



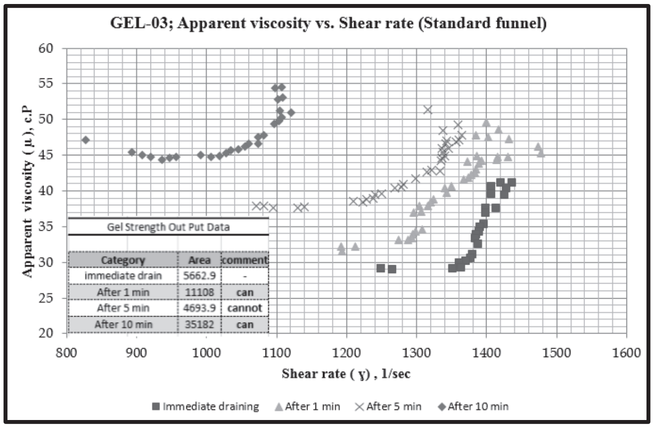
Gel Strength Out Put Data

Category	Area	comment
immediate drain	57774	-
After 1 min	21616	cannot
After 5 min	23865	can
After 10 min	21222	cannot



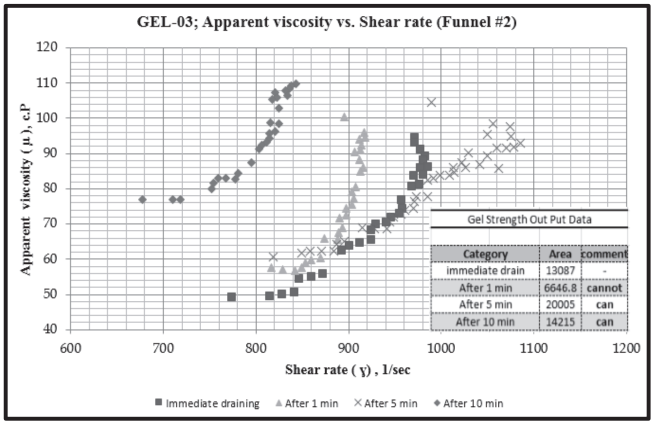
Gel Strength Out Put Data

Category	Area	comment
immediate drain	13175	-
After 1 min	3370.4	cannot
After 5 min	5563.8	can
After 10 min	4911.6	can



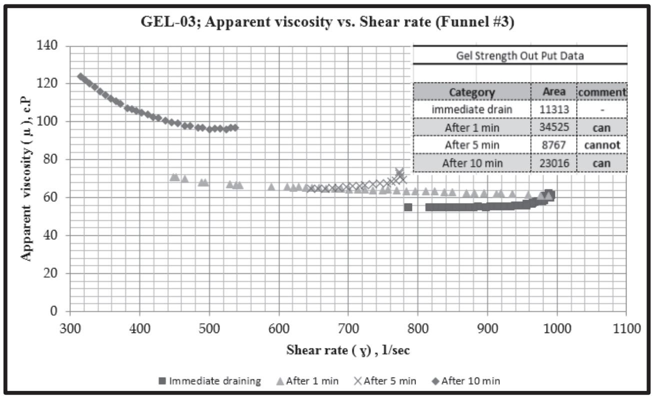
Gel Strength Out Put Data

Category	Area	comment
immediate drain	5662.9	-
After 1 min	11108	can
After 5 min	4693.9	cannot
After 10 min	35182	can



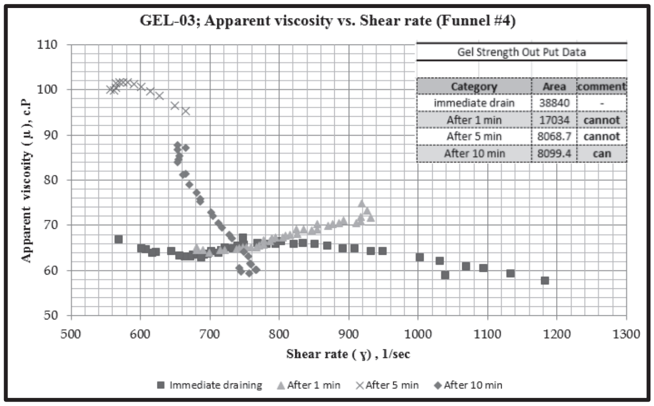
Gel Strength Out Put Data

Category	Area	comment
immediate drain	13087	-
After 1 min	6646.8	cannot
After 5 min	20005	can
After 10 min	14215	can



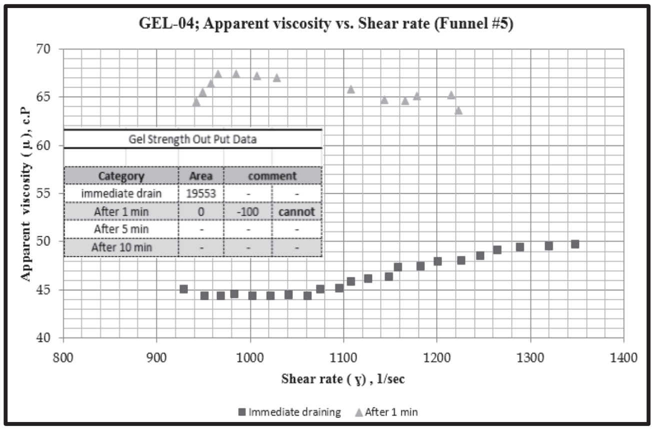
Gel Strength Out Put Data

Category	Area	comment
immediate drain	11313	-
After 1 min	34525	can
After 5 min	8767	cannot
After 10 min	23016	can



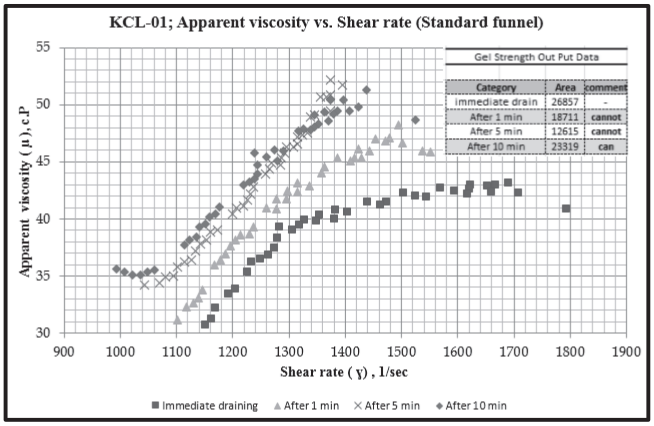
Gel Strength Out Put Data

Category	Area	comment
immediate drain	38840	-
After 1 min	17034	cannot
After 5 min	8068.7	cannot
After 10 min	8099.4	can



Gel Strength Out Put Data

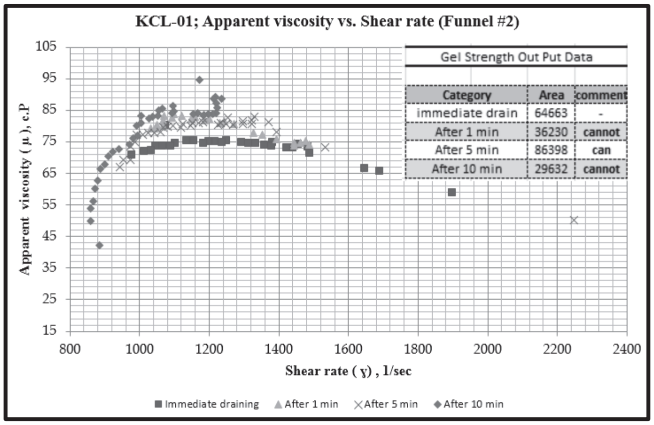
Category	Area	comment	
immediate drain	19553	-	-
After 1 min	0	-100	cannot
After 5 min	-	-	-
After 10 min	-	-	-



KCL-01; Apparent viscosity vs. Shear rate (Standard funnel)

Gel Strength Out Put Data

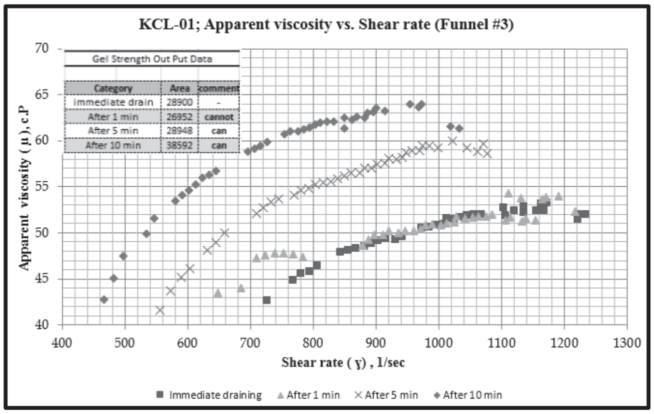
Category	Area	comment
immediate drain	26857	-
After 1 min	18711	cannot
After 5 min	12615	cannot
After 10 min	23319	can



KCL-01; Apparent viscosity vs. Shear rate (Funnel #2)

Gel Strength Out Put Data

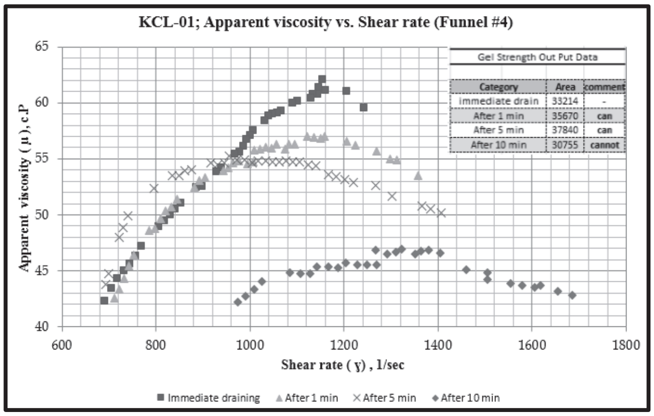
Category	Area	comment
immediate drain	64663	-
After 1 min	36230	cannot
After 5 min	86398	can
After 10 min	29632	cannot



KCL-01; Apparent viscosity vs. Shear rate (Funnel #3)

Gel Strength Out Put Data

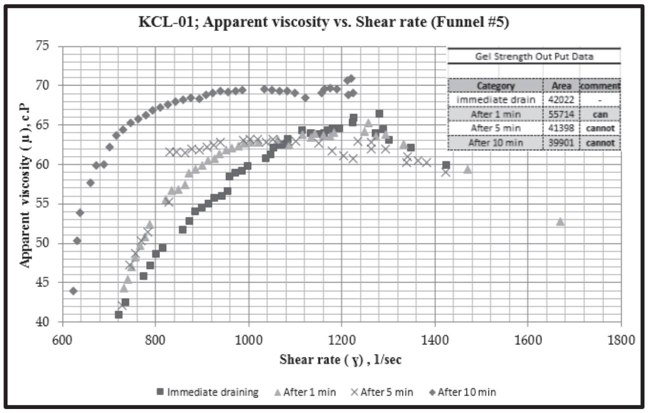
Category	Area	comment
immediate drain	28900	-
After 1 min	26952	cannot
After 5 min	28948	can
After 10 min	38592	can



KCL-01; Apparent viscosity vs. Shear rate (Funnel #4)

Gel Strength Out Put Data

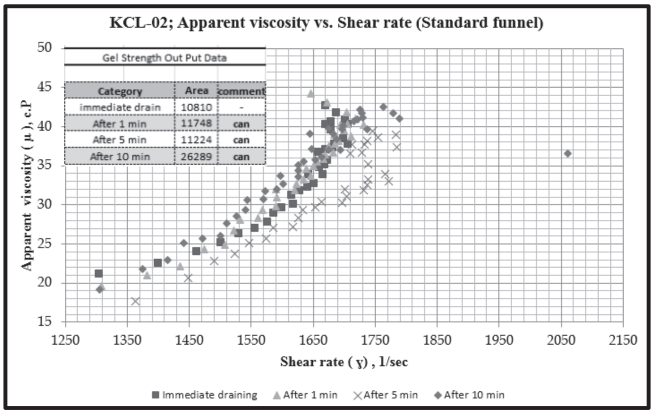
Category	Area	comment
immediate drain	33214	-
After 1 min	35670	can
After 5 min	37840	can
After 10 min	30755	cannot



KCL-01; Apparent viscosity vs. Shear rate (Funnel #5)

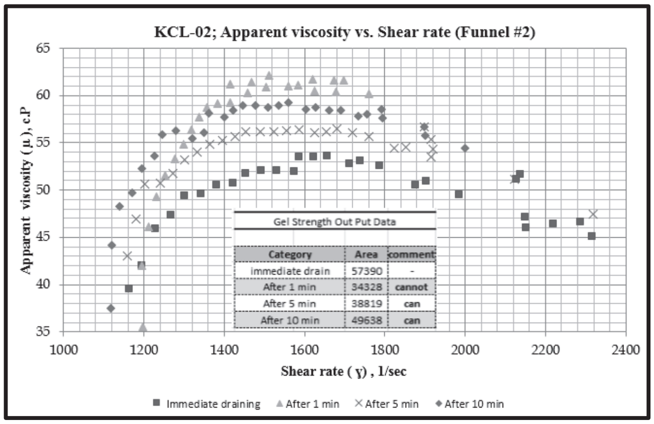
Gel Strength Out Put Data

Category	Area	comment
immediate drain	42022	-
After 1 min	55714	can
After 5 min	41398	cannot
After 10 min	39901	cannot



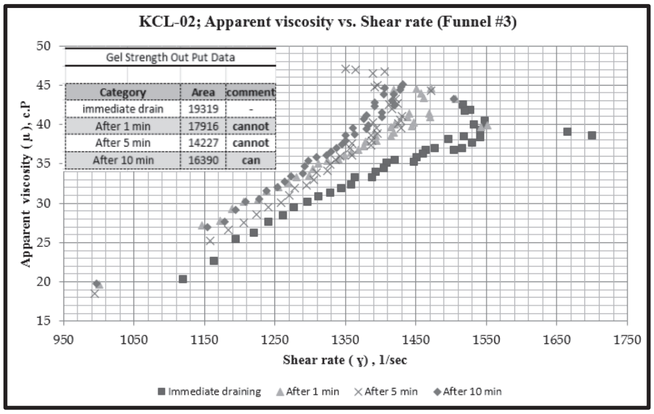
Gel Strength Out Put Data

Category	Area	comment
immediate drain	10810	-
After 1 min	11748	can
After 5 min	11224	can
After 10 min	26289	can



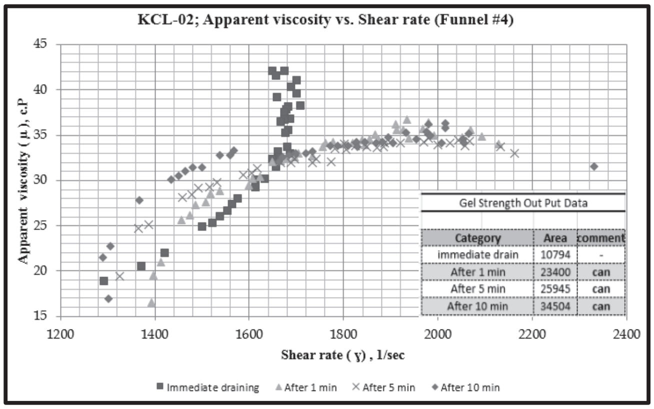
Gel Strength Out Put Data

Category	Area	comment
immediate drain	57390	-
After 1 min	34328	cannot
After 5 min	38819	can
After 10 min	49638	can



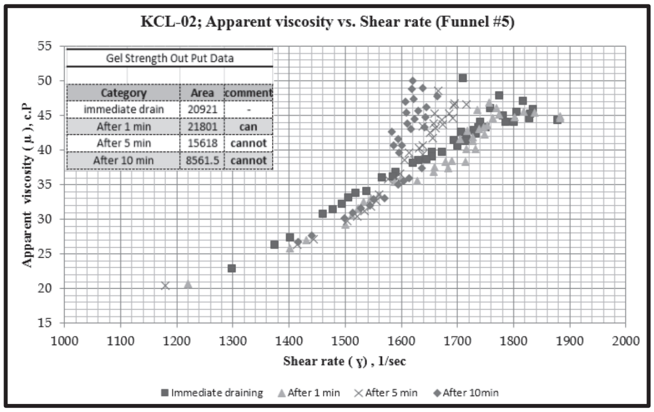
Gel Strength Out Put Data

Category	Area	comment
immediate drain	19319	-
After 1 min	17916	cannot
After 5 min	14227	cannot
After 10 min	16390	can



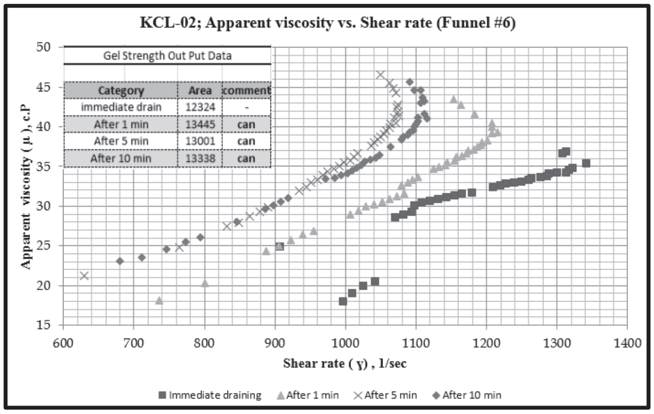
Gel Strength Out Put Data

Category	Area	comment
immediate drain	10794	-
After 1 min	23400	can
After 5 min	25945	can
After 10 min	34504	can



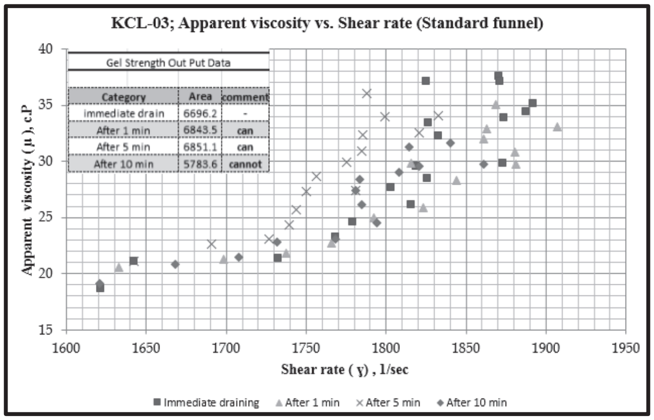
Gel Strength Out Put Data

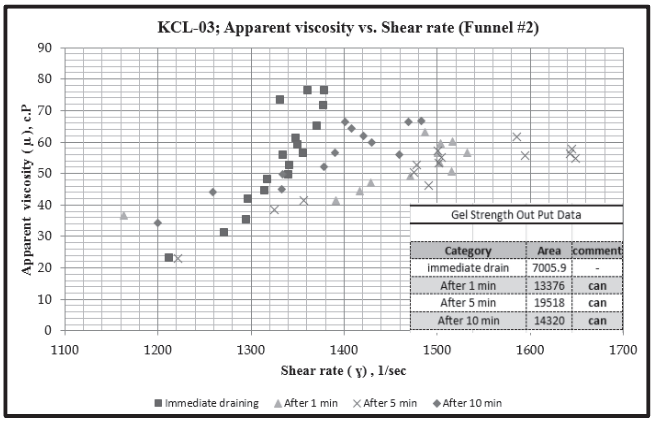
Category	Area	comment
immediate drain	20921	-
After 1 min	21801	can
After 5 min	15618	cannot
After 10 min	8561.5	cannot

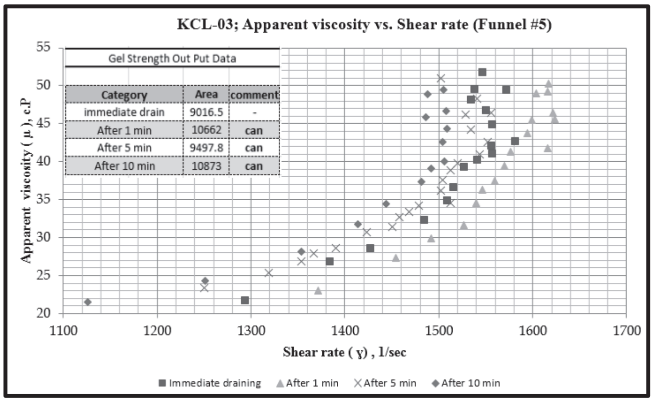


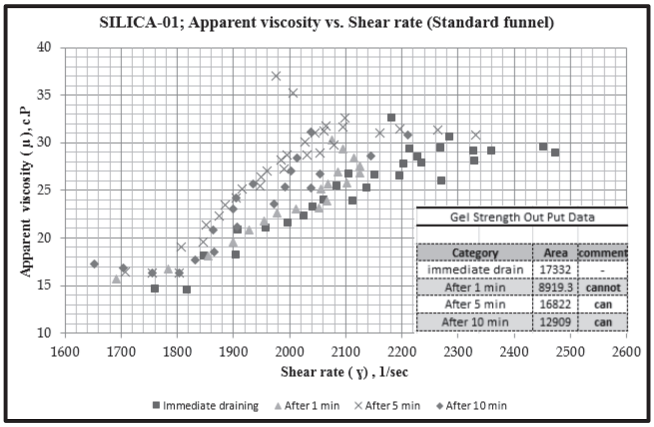
Gel Strength Out Put Data

Category	Area	comment
immediate drain	12324	-
After 1 min	13445	can
After 5 min	13001	can
After 10 min	13338	can


KCL-03; Apparent viscosity vs. Shear rate (Standard funnel)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 6696.2 | -
After 1 min | 6843.5 | can
After 5 min | 6851.1 | can
After 10 min | 5783.6 | cannot
Apparent viscosity (μ), c.P
15
20
25
30
35
40
1600
1650
1700
1750
1800
1850
1900
1950
Shear rate (γ̇) , 1/sec
■ Immediate draining
▲ After 1 min
× After 5 min
◆ After 10 min

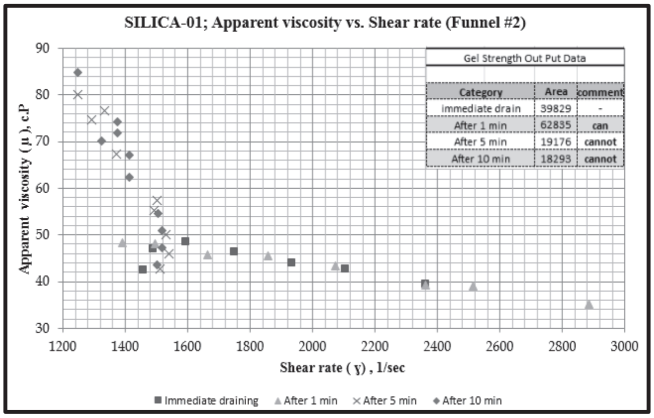

KCL-03; Apparent viscosity vs. Shear rate (Funnel #2)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 7005.9 | -
After 1 min | 13376 | can
After 5 min | 19518 | can
After 10 min | 14320 | can
Apparent viscosity (μ), c.P
0
10
20
30
40
50
60
70
80
90
1100
1200
1300
1400
1500
1600
1700
Shear rate (γ̇) , 1/sec
■ Immediate draining
▲ After 1 min
× After 5 min
◆ After 10 min


KCL-03; Apparent viscosity vs. Shear rate (Funnel #5)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 9016.5 | -
After 1 min | 10662 | can
After 5 min | 9497.8 | can
After 10 min | 10873 | can
Apparent viscosity (μ), c.P
20
25
30
35
40
45
50
55
1100
1200
1300
1400
1500
1600
1700
Shear rate (γ̇) , 1/sec
■ Immediate draining
▲ After 1 min
× After 5 min
◆ After 10 min


SILICA-01; Apparent viscosity vs. Shear rate (Standard funnel)

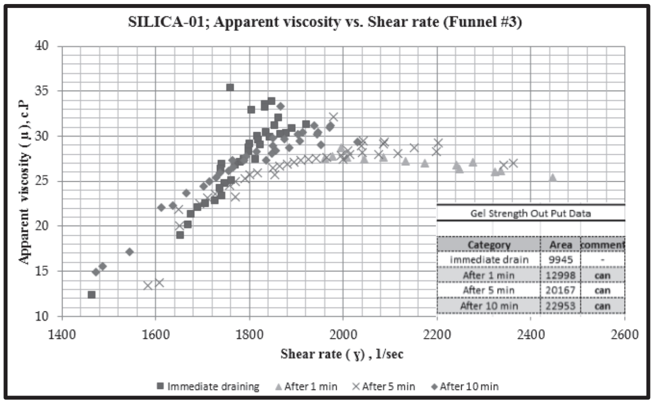
Gel Strength Out Put Data

Category	Area	comment
immediate drain	17332	-
After 1 min	8919.3	cannot
After 5 min	16822	can
After 10 min	12909	can


SILICA-01; Apparent viscosity vs. Shear rate (Funnel #2)

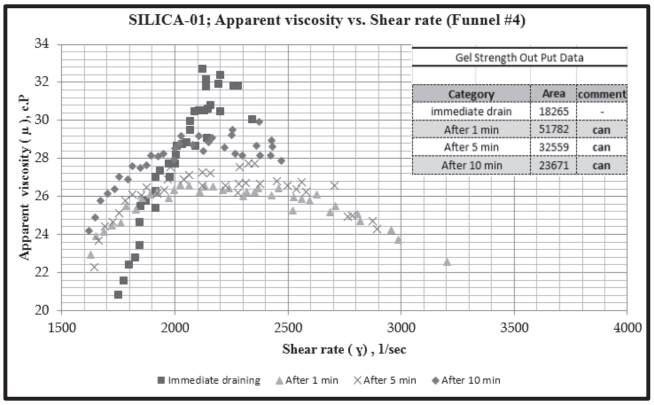
Gel Strength Out Put Data

Category	Area	comment
immediate drain	39829	-
After 1 min	62835	can
After 5 min	19176	cannot
After 10 min	18293	cannot


SILICA-01; Apparent viscosity vs. Shear rate (Funnel #3)

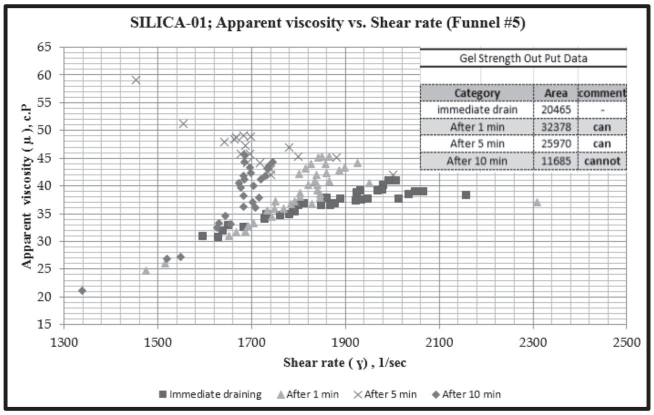
Gel Strength Out Put Data

Category	Area	comment
immediate drain	9945	-
After 1 min	12998	can
After 5 min	20167	can
After 10 min	22953	can


SILICA-01; Apparent viscosity vs. Shear rate (Funnel #4)

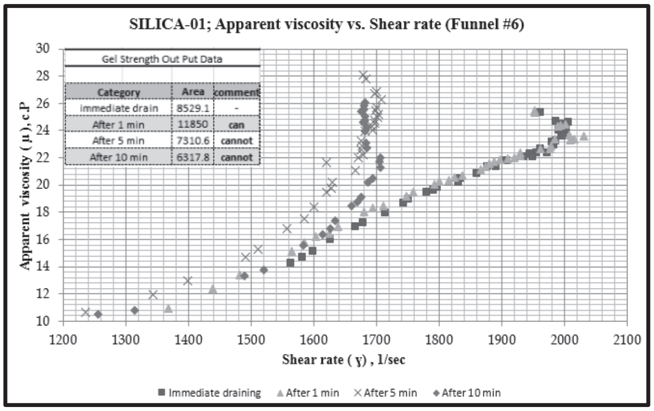
Gel Strength Out Put Data

Category	Area	comment
immediate drain	18265	-
After 1 min	51782	can
After 5 min	32559	can
After 10 min	23671	can


SILICA-01; Apparent viscosity vs. Shear rate (Funnel #5)

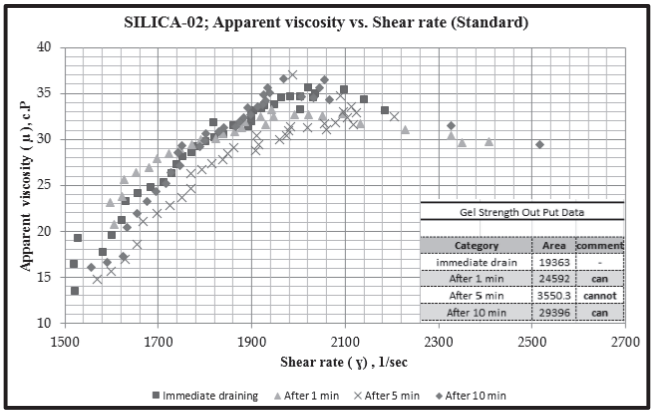
Gel Strength Out Put Data

Category	Area	comment
immediate drain	20465	-
After 1 min	32378	can
After 5 min	25970	can
After 10 min	11685	cannot


SILICA-01; Apparent viscosity vs. Shear rate (Funnel #6)

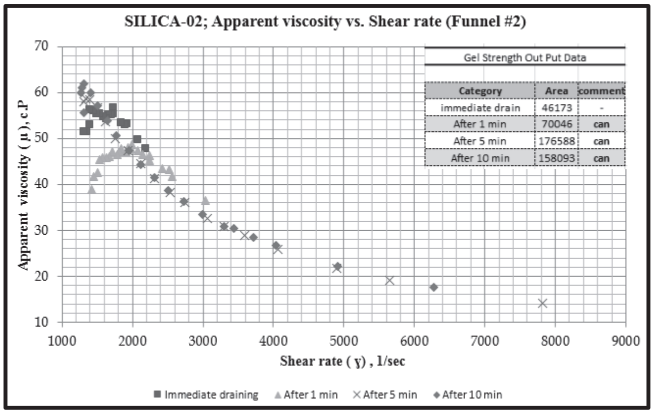
Gel Strength Out Put Data

Category	Area	comment
immediate drain	8529.1	-
After 1 min	11850	can
After 5 min	7310.6	cannot
After 10 min	6317.8	cannot


SILICA-02; Apparent viscosity vs. Shear rate (Standard)

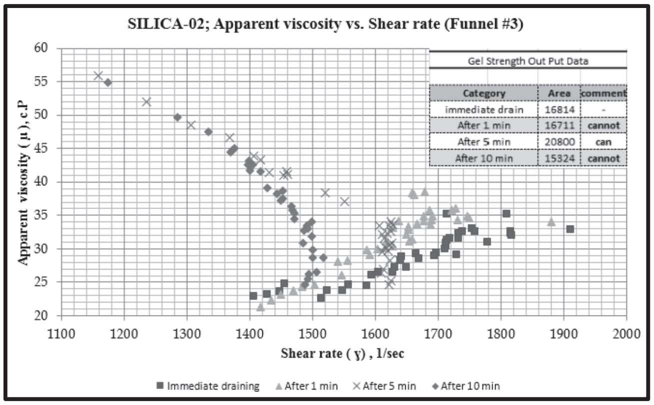
Gel Strength Out Put Data

Category	Area	comment
immediate drain	19363	-
After 1 min	24592	can
After 5 min	3550.3	cannot
After 10 min	29396	can


SILICA-02; Apparent viscosity vs. Shear rate (Funnel #2)

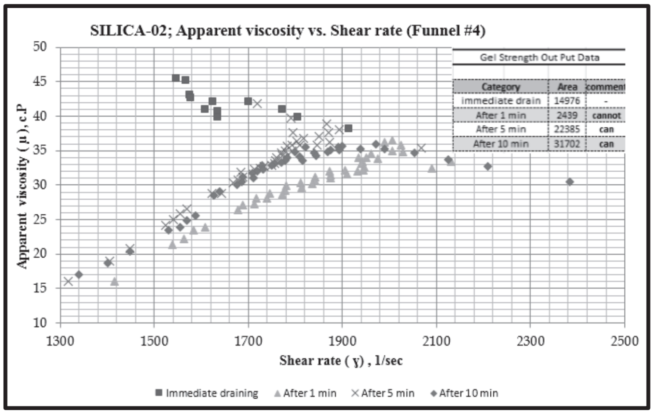
Gel Strength Out Put Data

Category	Area	comment
immediate drain	46173	-
After 1 min	70046	can
After 5 min	176588	can
After 10 min	158093	can


SILICA-02; Apparent viscosity vs. Shear rate (Funnel #3)

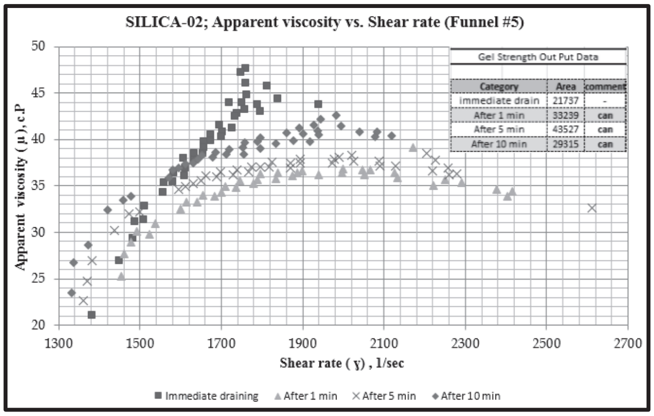
Gel Strength Out Put Data

Category	Area	comment
immediate drain	16814	-
After 1 min	16711	cannot
After 5 min	20800	can
After 10 min	15324	cannot


SILICA-02; Apparent viscosity vs. Shear rate (Funnel #4)

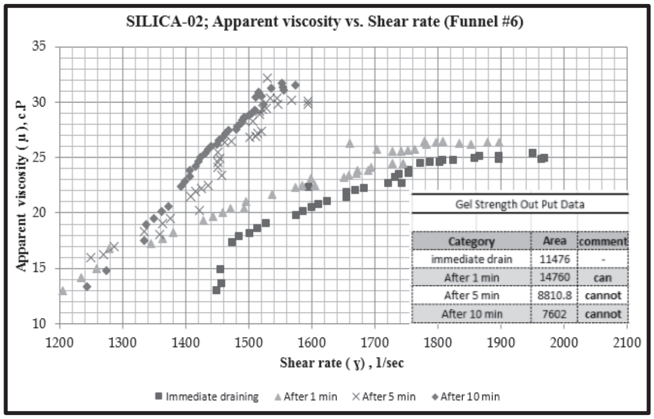
Gel Strength Out Put Data

Category	Area	comment
immediate drain	14976	-
After 1 min	2439	cannot
After 5 min	22385	can
After 10 min	31702	can


SILICA-02; Apparent viscosity vs. Shear rate (Funnel #5)

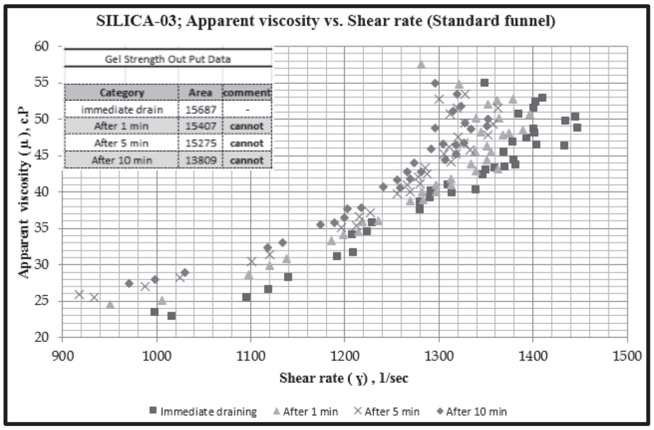
Gel Strength Out Put Data

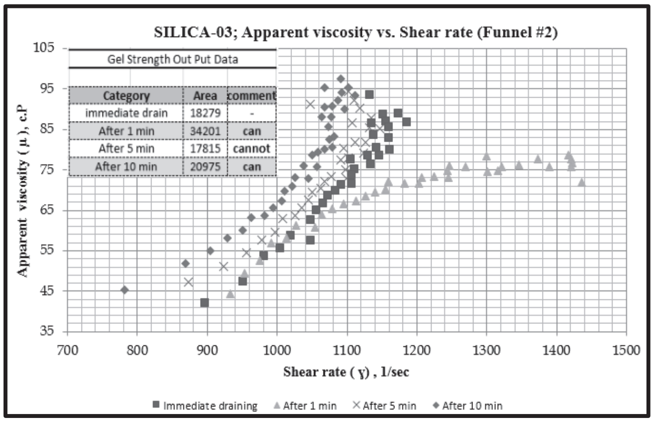
Category	Area	comment
immediate drain	21737	-
After 1 min	33239	can
After 5 min	43527	can
After 10 min	29315	can

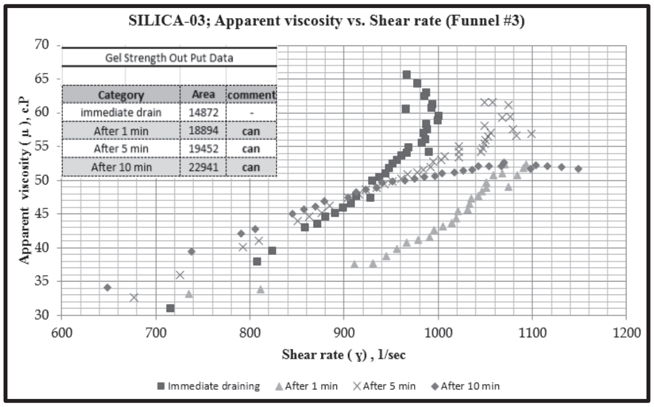

SILICA-02; Apparent viscosity vs. Shear rate (Funnel #6)

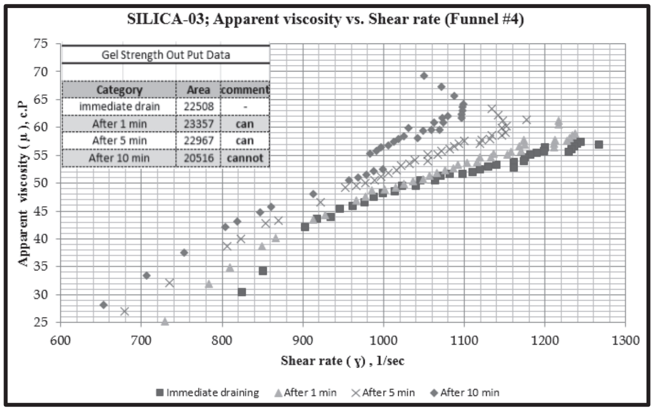
Gel Strength Out Put Data

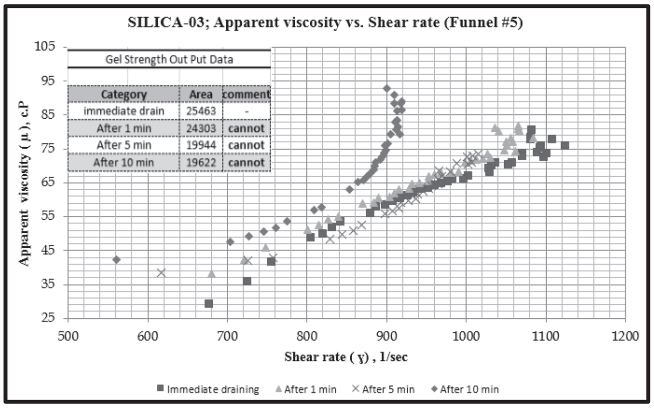
Category	Area	comment
immediate drain	11476	-
After 1 min	14760	can
After 5 min	8810.8	cannot
After 10 min	7602	cannot

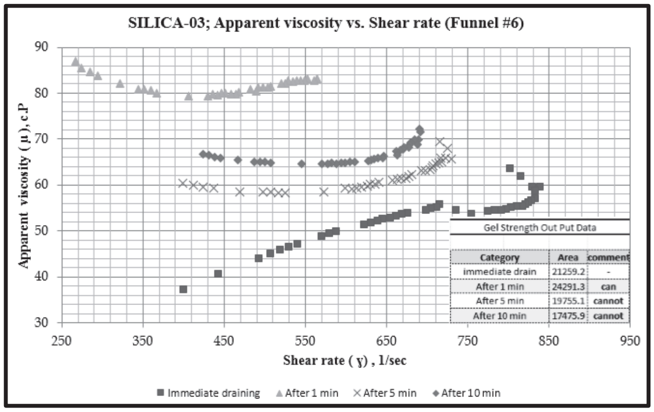

SILICA-03; Apparent viscosity vs. Shear rate (Standard funnel)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 15687 | -
After 1 min | 15407 | cannot
After 5 min | 15275 | cannot
After 10 min | 13809 | cannot
Apparent viscosity (μ), c.P
20 25 30 35 40 45 50 55 60
900 1000 1100 1200 1300 1400 1500
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min


SILICA-03; Apparent viscosity vs. Shear rate (Funnel #2)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 18279 | -
After 1 min | 34201 | can
After 5 min | 17815 | cannot
After 10 min | 20975 | can
Apparent viscosity (μ), c.P
35 45 55 65 75 85 95 105
700 800 900 1000 1100 1200 1300 1400 1500
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min


SILICA-03; Apparent viscosity vs. Shear rate (Funnel #3)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 14872 | -
After 1 min | 18894 | can
After 5 min | 19452 | can
After 10 min | 22941 | can
Apparent viscosity (μ), c.P
30 35 40 45 50 55 60 65 70
600 700 800 900 1000 1100 1200
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min


SILICA-03; Apparent viscosity vs. Shear rate (Funnel #4)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 22508 | -
After 1 min | 23357 | can
After 5 min | 22967 | can
After 10 min | 20516 | cannot
Apparent viscosity (μ), c.P
25 30 35 40 45 50 55 60 65 70 75
600 700 800 900 1000 1100 1200 1300
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min


SILICA-03; Apparent viscosity vs. Shear rate (Funnel #5)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 25463 | -
After 1 min | 24303 | cannot
After 5 min | 19944 | cannot
After 10 min | 19622 | cannot
Apparent viscosity (μ), c.P
25 35 45 55 65 75 85 95 105
500 600 700 800 900 1000 1100 1200
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min


SILICA-03; Apparent viscosity vs. Shear rate (Funnel #6)
Gel Strength Out Put Data
Category | Area | comment
immediate drain | 21259.2 | -
After 1 min | 24291.3 | can
After 5 min | 19755.1 | cannot
After 10 min | 17475.9 | cannot
Apparent viscosity (μ), c.P
30 40 50 60 70 80 90
250 350 450 550 650 750 850 950
Shear rate (γ̇) , 1/sec
Immediate draining
After 1 min
After 5 min
After 10 min