Project acronym:	**Geo-Drill**		
Project title:	Development of novel and Cost-Effective drilling technology for geothermal Systems		
Activity:	LCE-07-17-Renewables		
Call:	H2020-LC-SC3-2018-RES-TwoStages		
Funding Scheme:	RIA	**Grant Agreement**	815319
WP1	**Requirement analysis and KPI**		

D1.3 Rheology testing report

Due date:	31/8/2019 (M5)	
Actual Submission Date:	22/08/2019	
Lead Beneficiary:	Gerosion EHF	
Main authors/contributors:	Gerosion EHF	
Dissemination Level[1]:	PU	
Nature:	Report	
Status of this version:		**Draft under Development**
		For Review by Coordinator
	X	**Submitted**
Version:	01	

REVISION HISTORY

Version	Date	Main Authors/Contributors	Description of changes

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No. 815319

[1] Dissemination level security:

PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /

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Document: D1.3 Rheology testing report

Version: 1

Date: 14 April 2020

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1. SUMMARY

This deliverable is part of task 1.2: *Characterization of geothermal drilling environment*, in WP1: *Requirement analysis and KPI*, of the GeoDrill project. In this part of the task, the objective is to perform rheological testing of drilling mud. The aim is to establish a baseline dataset of the rheological properties of drilling muds, as these properties will be critical to the development of the fluidic oscillator. Generally, the right parameter selection of the drilling fluid is a critical part for successful drilling jobs and this becomes especially important when the drilling mud is also being used to drive the hammer. Here, two of the most common drilling fluids are tested and reported with focus on the influence of shear rate on rheology properties.

2. OBJECTIVES MET

Rheology testing of the most common drilling muds was performed. The relationship between the fluid's shear stress and shear rate was investigated as a function of temperature and concentration of the drilling fluid. The relationship between viscosity and shear rate was also investigated. This deliverable, along with D1.2: *Characterisation report (due M5)*, serves to fulfil the following work package objective of*:*

- To characterise the geothermal drilling environment which will be used to design criteria for materials and coating and to set up the simulated laboratory geothermal.

3. INTRODUCTION

One the most important tasks during any drilling operation is to measure properties of drilling fluids to allow for optimum drilling conditions not harmful for the drilling equipment and for the properties of the reservoir formation. Rheological behaviour of drilling fluids is very complex and its properties are continuously determined and monitored during drilling jobs. American Petroleum Institute (API) provides recommended practice of standard procedures for determining the common rheological properties of drilling fluid: yield point, apparent viscosity and plastic viscosity, relationship between the fluid's shear stress and shear rate. Drilling fluid, alternatively known as drilling mud, circulates through the drill string, comes out the bit and carries cuttings to the surface. It has several purposes such as removing cuttings from well, controlling formation pressure, cooling and lubricating the bit and drill string, sealing permeable formations, maintaining wellbore stability. (e.g. Guria et al. 2013; Vajargah and van Oort 2015)

The vast majority of drilling muds are water-based. When fresh water is the liquid base, bentonite is the clay used for its excellent properties essential to meet the rheological parameters required for drilling mud. The viscosity or consistency index of a mud is a measure of flow resistance. Therefore, viscosity should be as little as possible to limit friction pressure. However, a certain amount of viscosity is necessary to improve the solids carrying capacity of the mud. If viscosity is too low, the mud might be unable to suspend drilled cuttings at the desired pump rate. This forces the pumps to be run faster to continue to circulate drilled solids out of the well. If viscosity is too high, an excessive pump pressure will be required to circulate the mud at the desired rate. Higher than necessary pump pressure is an added strain on the pumps and piping and an added pressure in the bore hole that can lead to well bore stability problems. Water-soluble polymers are also used in drilling fluids to improve the ability of muds to lift cuttings, but they are also used as fracturing fluids to improve the removal of solids after fracturing (Balhoff et al. 2011).

The Marsh Funnel was invented by Hallan N. Marsh (Marsh, 1931). It is a tool that is used to measure the time required to fill a set volume of fluid. The flow through the small tip at the end of the funnel is related to the rheological properties of the fluid being measured. The Marsh Funnel "viscosity" is

reported as seconds and used as an indicator of the relative consistency of fluids, the more viscous the fluid the longer the time to fill one quart. The Marsh Funnel provides a simple and effective tool to determine the relative viscosity of drilling mud. Conventional rheometers provide precise evaluation of the drilling parameters, however fast and simple method is often needed at the drilling site. Method to determine rheological properties of non-Newtonian fluids using a Marsh Funnel is presented in this report. The simple model presented here, based on work of Balhoff et al. (2011); Guria et al. (2013); and Schoesser and Thewes (2015) who performed Marsh Funnel testing for rheological analysis of bentonite and other suspensions, can estimate multiple parameters for a tested fluid. Using the constitutive equations of the Herschel-Bulkley flow model, which is applied to describe the flow behaviour of non-Newtonian fluids, calculations of the shear stress and the shear rate of the tested drilling fluids can be performed. Same drilling muds were measured with accurate laboratory rheometer. The geometry allows for specification of revolutions per minute (RPM), which is proportional to shear rate, and measures the resulting torque, which is proportional to shear stress. The obtained datasets from Marsh Funnel tests and rheometer were compared.
The objective of this work was to perform rheological testing of drilling mud. This report presents and provides a rheological dataset with characterization of drilling mud, commonly used bentonite and polymer-based drilling fluids, for future tasks in GeoDrill project that require such information. The data was obtained with a Marsh funnel and a rheometer which allowed for measurements at elevated temperatures.

4. MATERIALS & SETUP

The fluids used in these experiments must be mixed before testing. The fluids that are reported in this deliverable are based either on polymers or bentonite. Before addition of any solid particles or polymer to the water the temperature of water (22°C) and its pH (~9) is checked. The density of the fluid was measured using a density mud balance (OFITE). The fluid was then poured in the Marsh Funnel (OFITE) for the tests at ambient conditions. The rheological properties are measured using a HAAKE MARS rheometer at ambient and elevated temperature. The sections below describe how each fluid is prepared. The summary of all prepared drilling fluids is presented in Table 1.

4.1 Polymer based fluids

A liquid drilling fluid polymer was tested within this project. Clay Slip plus (Fischer Environmental) is a liquid co-polymer designed for fast field mixing and shale/clay stabilization in aqueous drilling fluids. Clay Slip plus can be used to inhibit clay and shale hydration, as well as an additive in bentonite drilling fluids to marginally increase viscosity and lower fluid loss by acting as a bridging agent. Drilling fluid mixes prepared were 0.1, 0.25, 0.5% wt/wt. The mixing duration of each drilling fluid was ~5 minutes before testing. The recommended typical dosage by the producer is between 0.1 and 0.2% and pH of water higher than 7.

4.2 Bentonite based fluids

Cebo Wyoming API is a high-quality sodium bentonite from Wyoming (U.S.A.). Cebo Wyoming API is used to produce drilling fluid for use in oil- and gas well drilling and in horizontal directional drilling. Bentonite muds are commonly used in oil drilling at concentrations of 5 lb/bbl (1.4 wt%) and higher. They are well known to be non-Newtonian and may exhibit a yield stress at high concentrations (Balhoff et al. 2011). Drilling fluid mixes prepared were 1.0, 2.5, 5.0 % wt/wt. The mixing duration of each fluid was ~20 minutes before testing to ensure hydration of the bentonite "powder". Recommended typical dosage for CEBO Wyoming API bentonite is between 2.5 and 5%.

Mix		Density (g/cm^3)	Temp (°C)	wt/wt (%)
pol 0.1	polymer based	0.995	22.5	0.10
pol 0.25		0.995	22.5	0.25
pol 0.5		1	22.0	0.5
ben 1	bentonite based	1.005	22.0	1.00
ben 2.5		1.015	22.5	2.50
ben 5		1.035	22.0	5.00

Table 1. List of prepared drilling fluids.

5. METHODS

To test the rheological properties of different types of drilling mud, two approaches were used; The Marsh funnel and a rheometer. Rheometers are measurement apparatus designed to measure the rheological parameters of materials capable of flow; they are most commonly used to measure yield value and plastic viscosity. Yield value is the force (or pressure) that must be overcome for flow to take place while plastic viscosity describes the relationship between force and rate of shear, or more specifically the force needed to increase the rate of shear, once the material is flowing.

5.1 Marsh Funnel tests

To use the Marsh Funnel for rheological analysis, the drainage volume was measured with the varying drainage time (Fig. 1). Suspension volume of 1500 cm^3 was used for the funnel experiments. Details of Marsh Funnel with dimensions are shown in Fig. 2. To obtain the consistent Marsh Funnel readings, experiments were duplicated with fresh suspensions. The Marsh Funnel was calibrated with water at 22°C. It was found to have a quart discharge time of 25.5 (st. dev. 0.25) seconds compared with the API specification of 26±0.5 seconds.

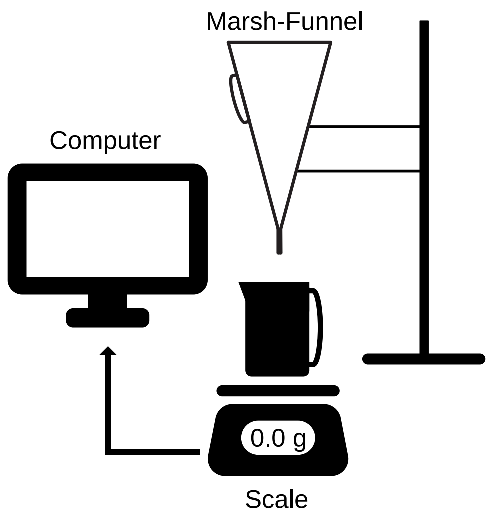


Figure 1. Arrangement of the equipment using a scale with automated data logging.

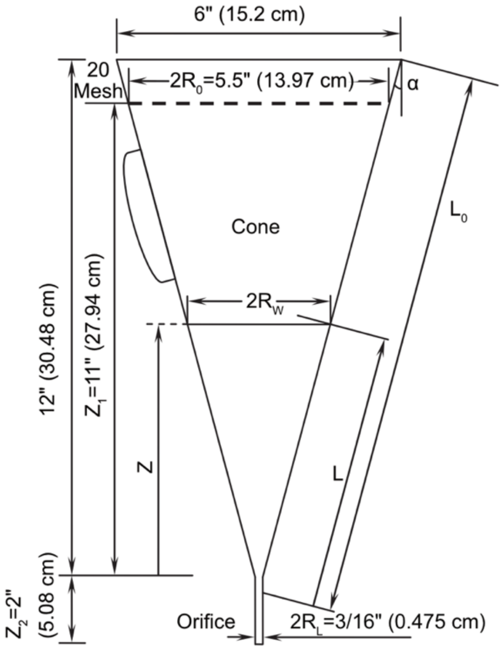


Figure 2. Schematic representation of standard Marsh-Funnel according to API 13B and DIN 4126.

5.2 Applied model

The measured data from Mars Funnel tests provide the basic information for the mathematical calculations of shear stress and shear rate. The mass M of the dripping drilling fluid is logged. Using the density of the fluid the volume V in the funnel can be calculated:

$$V = \frac{M}{\rho} \tag{1}$$

The volume of fluid in the funnel can be written as a function of height using the formula for the volume of a cone $\mathrm{V} = \pi \mathrm{r}^2\ \mathrm{h}/3$. Volume of a cone with Marsh funnel geometry, $r = R_0/Z_1$, becomes:

$$V = \frac{\pi}{3}(R_0 Z_1)^2 h^3 = \alpha h^3 \tag{2}$$

R_0 is the maximum funnel radius and Z_1 is the maximum height. The above equation has a coefficient α=0.065 using the dimensions of the funnel. A calibration curve for volume versus height has shown α=0.07 is more accurate and is used in this report. Suspension level in the Marsh funnel can be determined as:

$$Z = \sqrt[3]{V/\alpha} \tag{3}$$

Mass balance for funnel fluid can be written as:

$$\frac{\Delta V}{\Delta t} = -Q(h) \tag{4}$$

with Q as volumetric flow rate and h height of fluid in the funnel. Modelled flow rate Q_{mod} is based on the measured data for the spilling drilling mud out of the funnel. The flow rate was fitted over experimental data using the Herschel-Bulkley model (Skelland 1967) for a cylindrical tube (Eq. 5) to eliminate discontinuity of several experimental datapoints with discrete flow out of the funnel (see Figure 3).

$$Q_{mod} = \frac{\pi R^3 (\tau_w - \tau_0)^{1/n+1}}{m^{1/n} \tau_w^3} \left[\frac{(\tau_w - \tau_0)^2}{1/n + 3} + \frac{2\tau_0(\tau_w - \tau_0)}{1/n + 2} + \frac{\tau_0^2}{1/n + 1} \right] \tag{5}$$

The Herschel-Bulkley parameters flow index n, consistency index m and yield point τ_0 are estimated with data fitting.

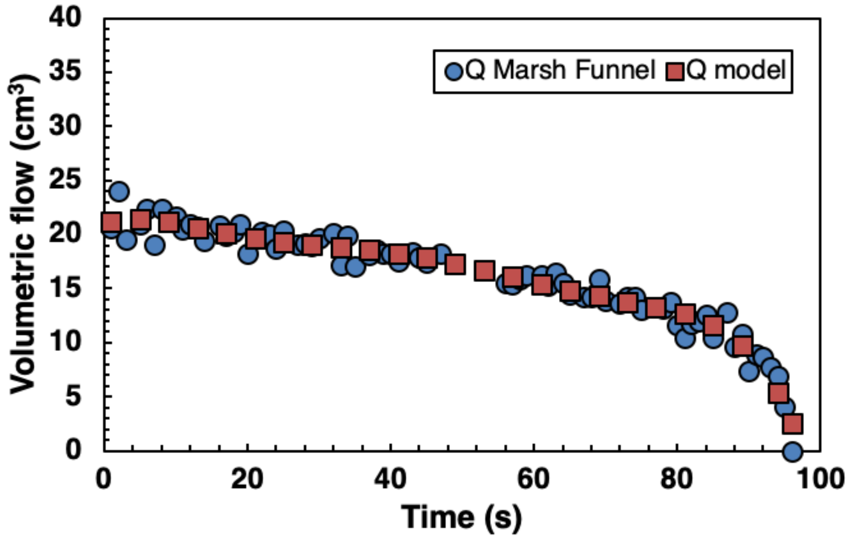


Figure 3. Measured flow rate of spilling drilling fluid (0.1 wt.% polymer based) and Herschel-Bulkley model fit.

A flow curve shows the relation between the shear stress acting in a fluid in reference to the shear rate. The wall shear stress is determined by balancing the forces acting in the cone-shaped part and the cylindrical part of the Marsh-funnel. Balancing the hydrostatic downward force and the upward acting wall shear stress only in the cone results in the following formula:

$$\pi R_w^2 \Delta P_{cone} = \pi \mathrm{R}_w \mathrm{L} \tau_w \tag{6}$$

Substituting $L = Z/\cos\alpha$ and $R_w(Z) = R_L + (R_0 - R_L)(Z/Z_1)$ in Eq. 6 provide the common from of the pressure gradient within the cone:

$$\Delta P_{cone} = \frac{\tau_w Z}{\cos\alpha (R_L + (R_0 - R_L)(Z/Z_1))} \tag{7}$$

The pressure is determined for the cylindrical part of the funnel in the same way:

$$\Delta P_{cylinder} = \frac{2\tau_w Z_2}{R_L} \tag{8}$$

The total pressure gradient ΔP within the Marsh Funnel is derived from:

$$\Delta P = \Delta P_{cone} + \Delta P_{cylinder} \tag{9}$$

By replacing ΔP with the description of the fluid height in the Marsh funnel $\Delta P = \rho g Z$ (where ρ is fluid density and g is the acceleration of gravity) the equation 9 turns after conversion to the wall shear stress τ_w to a more convenient form:

$$\tau_w = [\rho g(Z + Z_2)] / \left[\left(\frac{Z}{\cos\alpha\{R_L + (R_0 - R_L)(Z/Z_1)\}}\right) + \frac{2Z_2}{R_L}\right] \tag{10}$$

The wall shear stress can be determined now in reference to the actual fluid volume V (Eq. 1) and respectively to the fluid height (Eq. 3) in the Marsh-funnel.

Marsh Funnel wall shear rate $\dot{\gamma}_w$ is a measure of speed at which sample fluid passes through the funnel outlet. Therefore, wall shear rate is written in the following form based on funnel outlet sectional area:

$$-\dot{\gamma_w} = \frac{3}{4}\left(\frac{4Q}{\pi R_L^3}\right) + \frac{1}{4}\frac{4Q}{\pi R_L^3}\frac{d\log(4Q/\pi R_L^3)}{d\log\tau_w} \tag{14}$$

where Q is the volumetric flow rate through Marsh Funnel outlet, and n is the flow behaviour index which is related by the following equation:

$$\frac{1}{n} = \frac{d\log(4Q/\pi R_L^3)}{d\log\tau_w} \tag{14}$$

With substituting Eq. 14 in Eq. 13 the wall share rate is obtained in the following convenient form:

$$-\dot{\gamma_w} = \frac{3n+1}{4n}\frac{4Q}{\pi R_L^3} \tag{15}$$

5.3 Rheometer tests

The viscometer used in this work was a HAAKE MARS Rheometer (Figure 4). The device uses a coaxial cylinder measuring system. The stationary outer cylinder (⌀=43.4 mm), which functions as a sample holder, is filled with the sample of drilling mud (45 ml). The inner cylinder (⌀=38 mm, h=55 mm) rotates with an angular velocity that decreases in a stepwise manner (see Figure 5). The torque experienced by the inner cylinder is measured using a load cell. The outer cylinder is situated in a thermal bath controlled by a universal temperature controller, thus enabling the control over the temperature of the samples.

Each angular velocity step lasted 10 seconds during which time 100 torque measurements were taken. The 50 last measurements for each step were then averaged and that value was then used in the subsequent analysis. The angular velocity and torque were then converted to shear rate and stress respectively, using conversion factors in the HAAKE MARS software based on the geometry of the measurement setup.

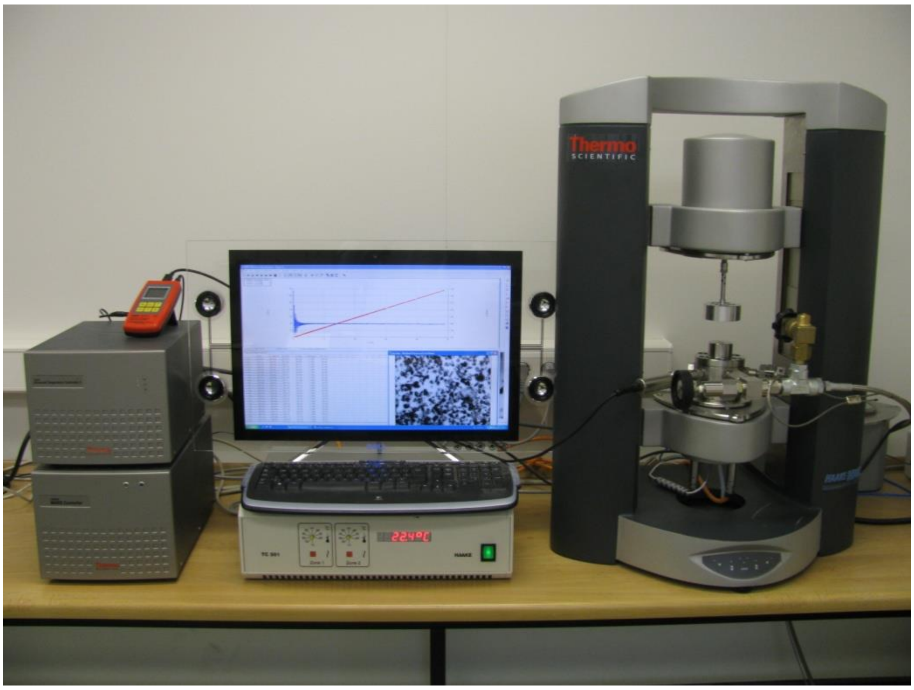


Figure 4. The HAAKE MARS (Rheomicroscope) used in this study.

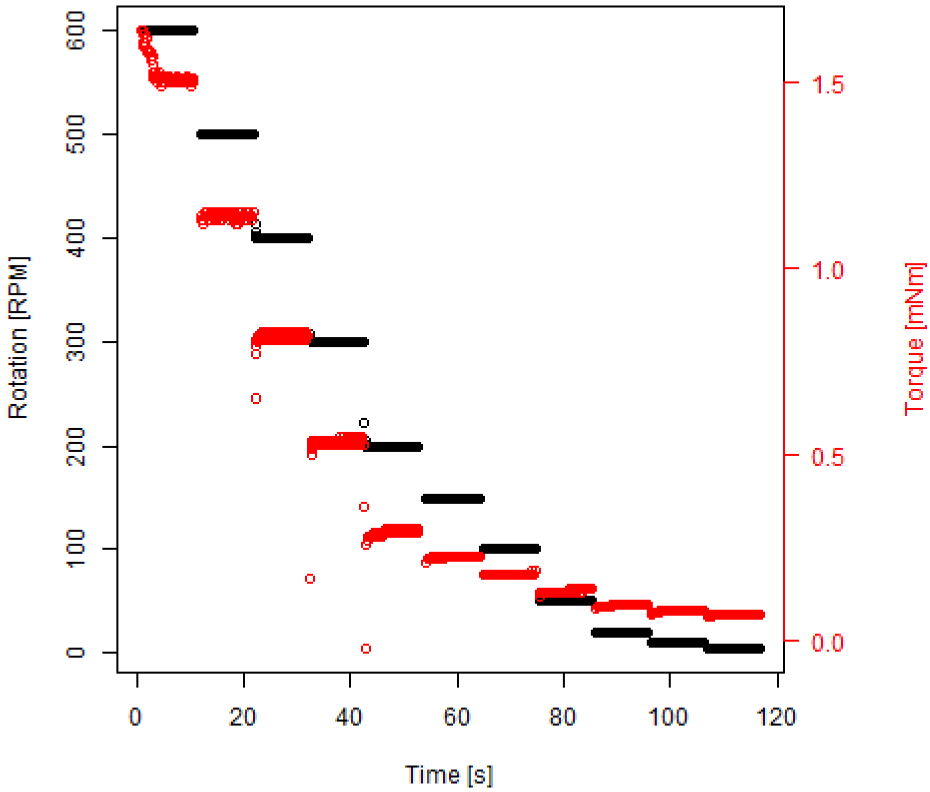


Figure 5. Angular velocity profile used by the HAAKE MARS Rheometer for this work. An example of measured torque is also displayed.

6. RESULTS AND DISCUSSION

Figure 6 shows the complete drainage time of the drilling fluids from the Marsh Funnel. With increasing concentration, for all the fluids, the time of fluid drainage from the funnel is increasing. Results of Marsh Funnel tests are summarized in the table 2.

When the values for shear stress of rheometer are compared to the values of wall shear stresses determined using the Marsh-funnel the latter are always of a higher order (Fig. 7, 10 and 11). As pointed out by Schoesser and Thewes (2015), see details therein, the values of wall shear stress represent the shear stress acting at the surface of the Marsh-funnel during drainage. These values are higher than the values for the shear stress acting within the fluid, because the friction forces between funnel wall and fluid are higher than the inner friction (= viscosity) of the fluid. With an increasing solid content, the deviation between the shear stresses of rheometer and the wall shear stress of Marsh-funnel for the same shear rate increases above average. Figures 7, 10 and 11 point out the physical limits of the measurement principle of Marsh-funnel: on case of a complete drainage, the yield point of the suspension is beyond the minimum value, that could be measured with the Marsh-funnel.

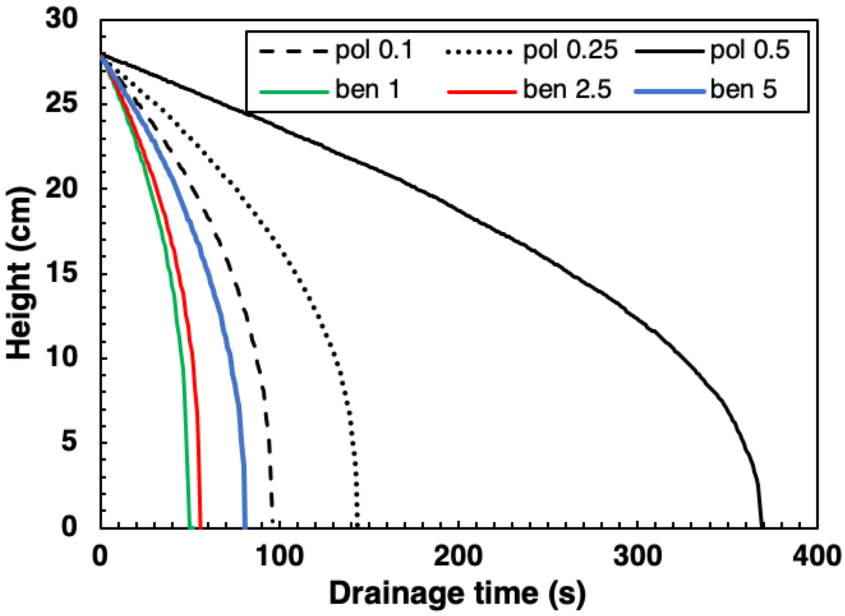


Figure 6. Drainage time for all drilling fluids tested with Marsh Funnel test as a function of fluid's height remaining in the funnel.

Mix		Density (g/cm^3)	Temp (°C)	wt/wt (%)	Marsh Funnel test (s)	Total drainage time (s)
pol 0.1	polymer based	0.995	22.5	0.10	49	96
pol 0.25		0.995	22.5	0.25	73	147
pol 0.5		1	22.0	0.5	160	370
ben 1	bentonite based	1.005	22.0	1.00	25	50
ben 2.5		1.015	22.5	2.50	30	57
ben 5		1.035	22.0	5.00	40	82

Table 2. Summary of Marsh Funnel results for all tested drilling fluids.

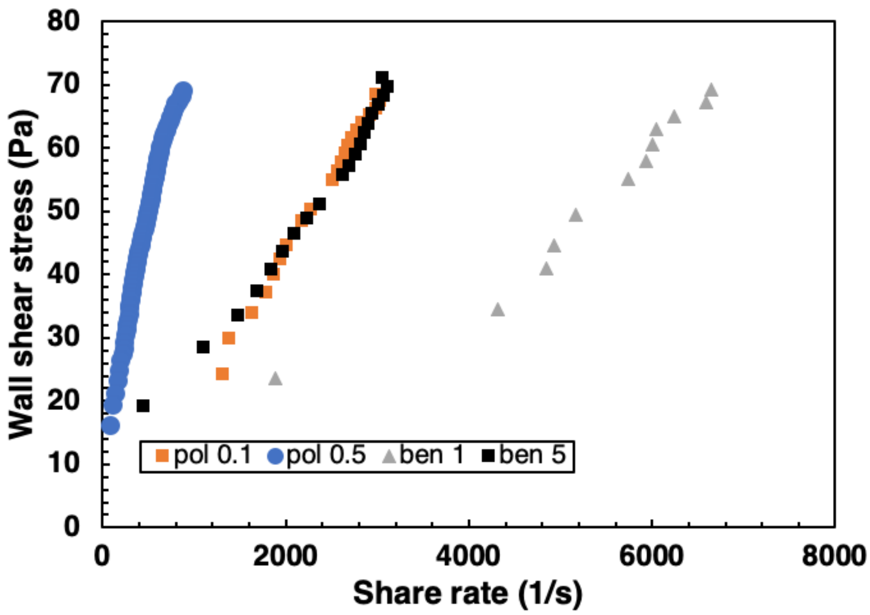
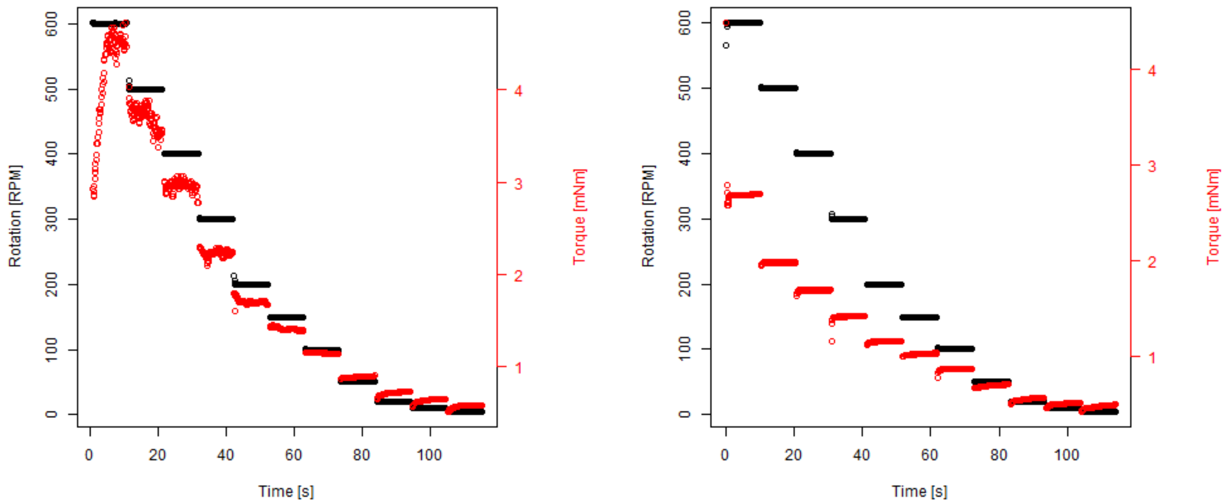


Figure 7. Shear stress as a function of shear rate for selected polymer and bentonite drilling muds determined from Marsh Funnel tests.

Figure 8 shows raw data for bentonite drilling mud and polymer drilling mud. In general, there was more noise in the raw data for the polymer drilling mud than in the raw data for the bentonite drilling mud. Originally 6 second angular velocity steps were used in the rheometer measurement setup, however this was increased to 10 seconds to ensure that the flow was closer to a steady state in the latter half of each step.



POLY_0.5%_23°C　　　BEN_5%_23°C

Figure 8. Raw data for two drilling fluids.

Figure 9 shows the results of the measurements in the viscometer at three different temperatures. The results are mostly as expected, with higher stresses measured for higher concentration drilling muds and higher temperatures resulting in lower stresses. However, for the bentonite 2.5% and 5% drill muds and the 0.5% polymer mud we do observe for low shear rates that the stress is higher for the high temperature measurements. This phenomenon is not observed for higher shear rates.

Figure 10 shows the results for the lowest and highest stress bentonite and polymer drilling muds selected for this work. The dosage of the bentonite and polymer according to the suppliers is 2.5%-5% for the bentonite and 0.1%-0.2% for the polymer drilling mud. Figure 11 shows a comparison of the bentonite and polymer drilling muds with concentrations close to the lower bounds of the supplier recommended dosage. The drilling muds behave fairly similarly at both 23°C and 80°C, although the polymer drilling mud requires more stress to induce flow at 23°C compared to the others.

The term plastic viscosity applies strictly to the Bingham model. However, for other nonlinear models, for example the Herschel Bulkley model, one can calculate the slope of the shear stress/shear rate curve, and refer to this as the “point plastic viscosity” (PPV). PPV basically describes the increase in fluid resistance when increasing the shear rate. Using the shear stress as a function of shear rate data, we can estimate the PPV at different shear rates for the drilling muds investigated in this work. Figure 12 shows the calculated PPV results. As these are water rich systems, it comes as no surprise that the PPV values are low, or below 0.1 Pa·s. After the initial drop in PPV at the lowest shear rates, the point plastic viscosity generally increases as a function of shear rate.

Apparent viscosity (shear stress / shear rate) results can be seen for the bentonite and polymer drill muds at 23°C in Figure 13. The apparent viscosity is, in general, higher for the polymer drilling muds. Figure 14 shows the effect of temperature on the different drilling muds. We see similar behaviour to the point plastic viscosity, although the effect of temperature is not as pronounced.

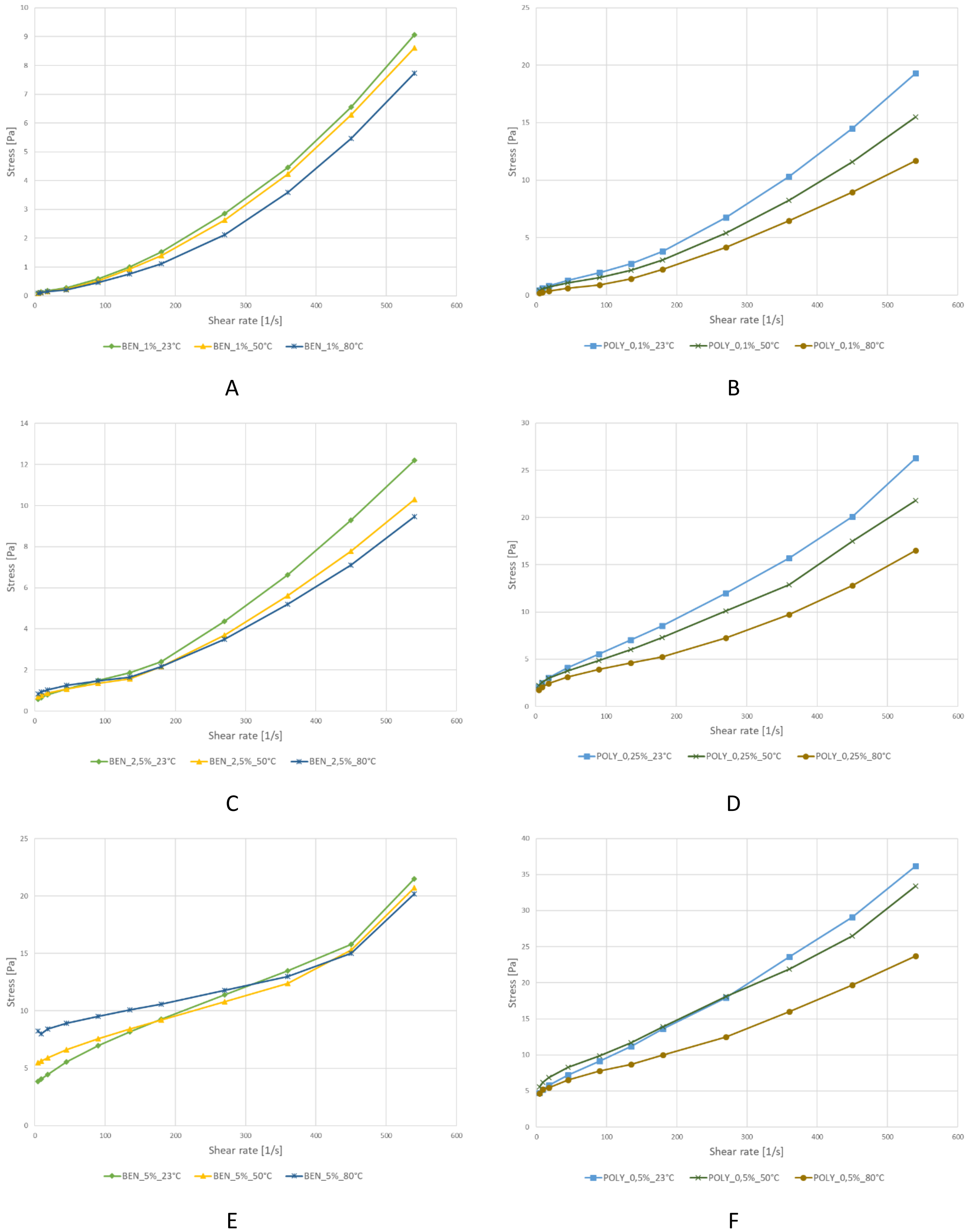


Figure 9. Shear stress as a function of shear rate for the drilling muds measured with the HAAKE MARS rheometer.

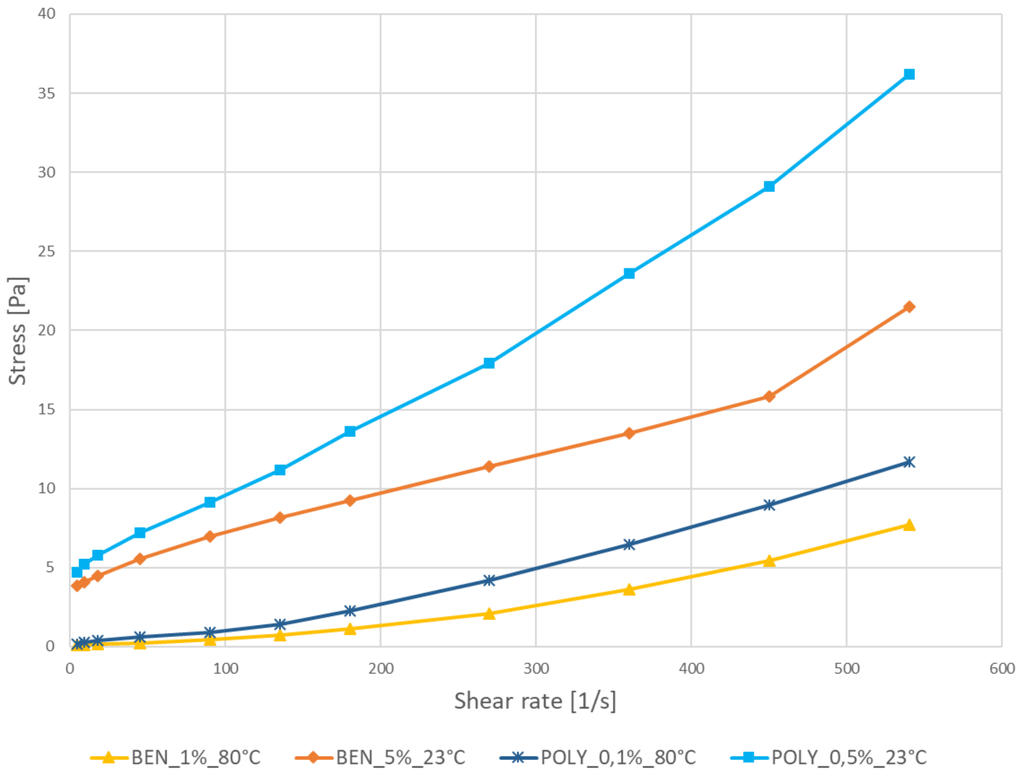


Figure 10. Shear stress as a function of shear rate for two polymer and two bentonite drilling muds measured with the HAAKE MARS rheometer.

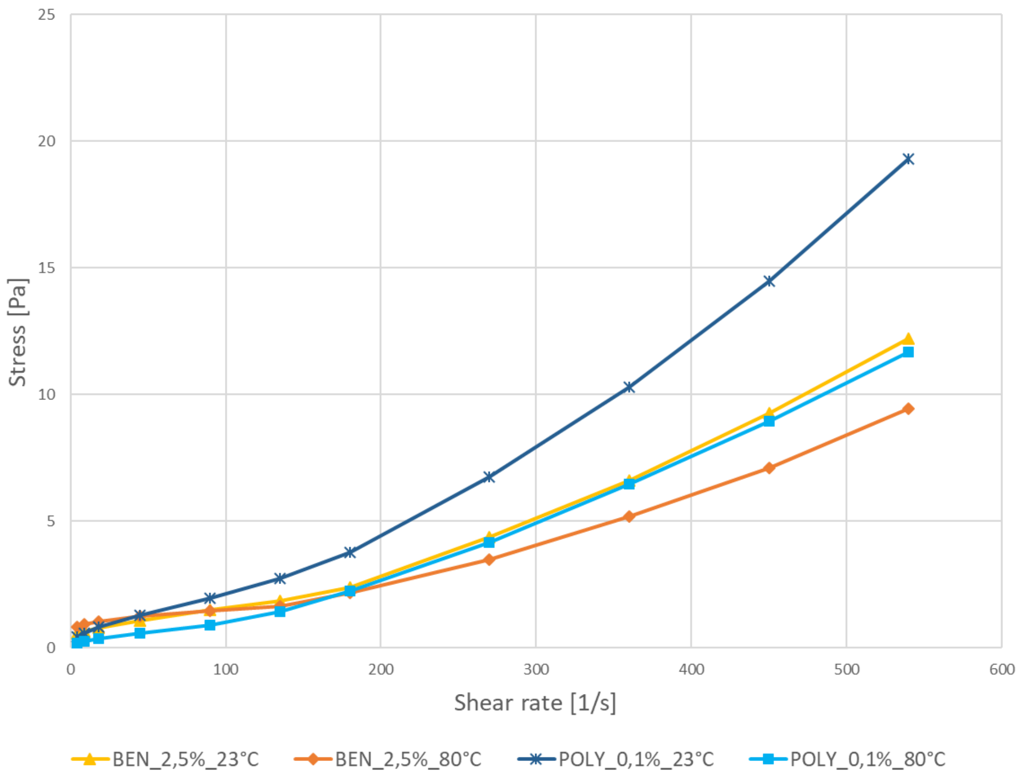


Figure 11. Shear stress as a function of shear rate for polymer and bentonite drilling muds as recommended by the supplier measured with the HAAKE MARS rheometer.

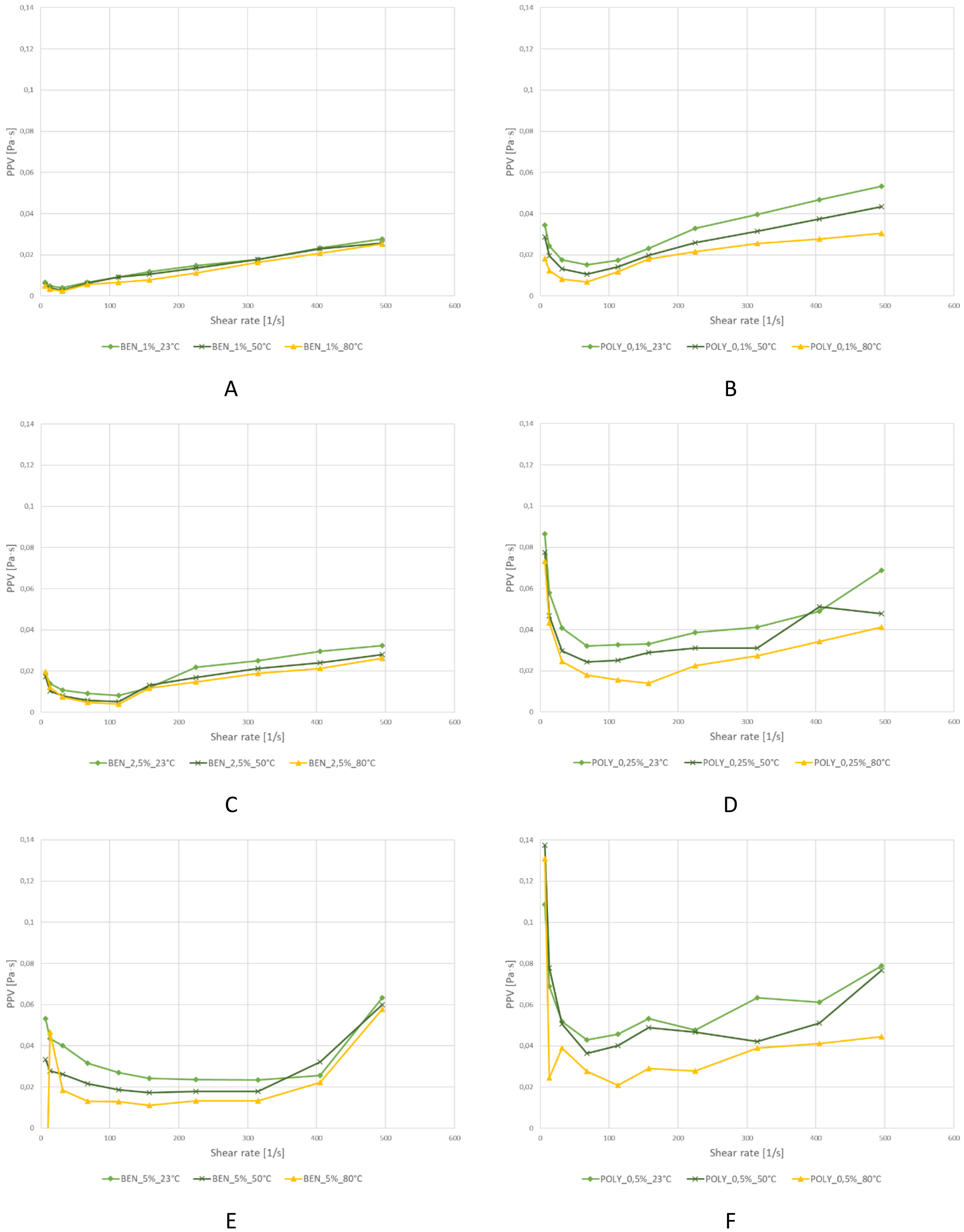


Figure 12. Point plastic viscosity as a function of shear rate for the drilling muds measured with the HAAKE MARS rheometer.

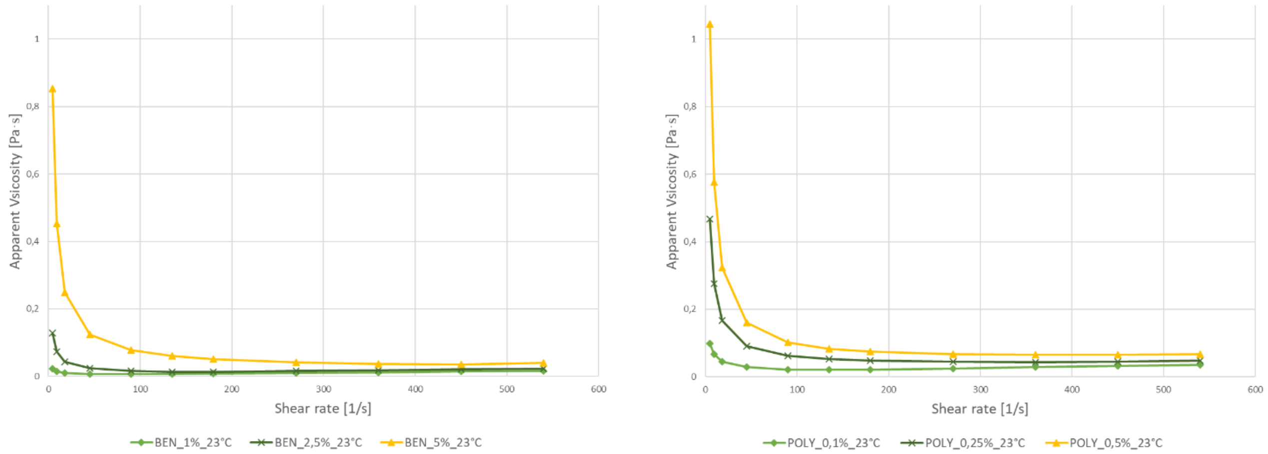


Figure 13. Apparent viscosity as a function of shear rate for bentonite and polymer drilling muds at 23°C measured with the HAAKE MARS rheometer.

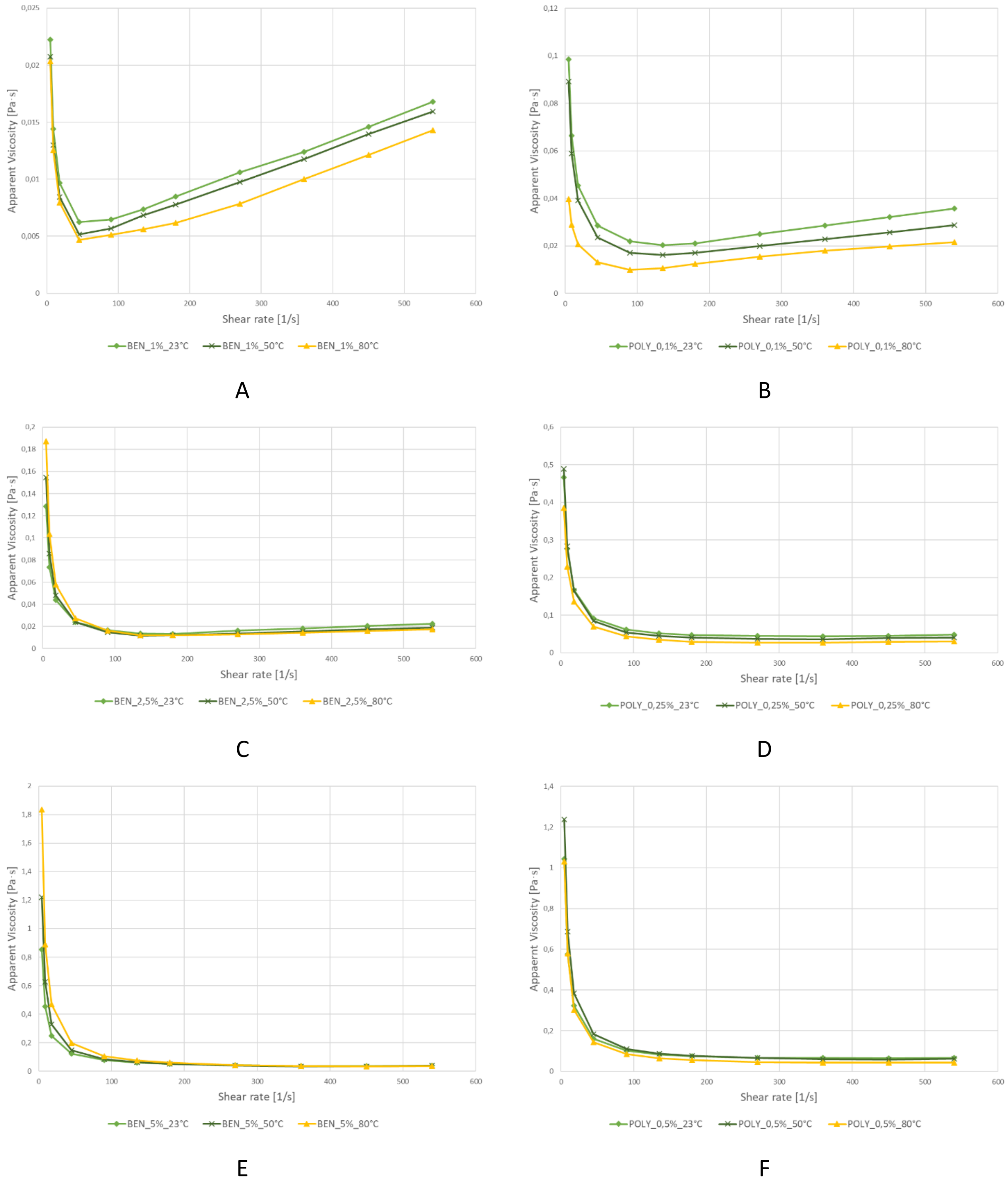


Figure 14. Apparent viscosity as a function of shear rate for the drilling muds measured with the HAAKE MARS rheometer.

In this work, the rheological properties of two types of drilling mud were investigated to give the GeoDrill team a rheological baseline for the development work yet to come. Different concentrations of the bentonite and polymer drilling mud were investigated and the effect to temperature was also included in the work. The influence of concentration and temperature were mostly as expected; increased bentonite and polymer content reduces the fluid properties of the muds (higher shear stress needed to produce the same rate of shear) and an increase in temperature results in more fluid properties (lower shear stresses and viscosities) The main result of this work that must be kept in mind in the GeoDrill project, especially in the development of the fluidic oscillator, is that elevated temperatures can influence the rheology of the drilling mud. The effect of temperature is more pronounced for the polymer drilling mud than the bentonite drilling mud and the effect is also more pronounced for higher concentration drilling muds than lower concentration drilling muds.

7. CONCLUSIONS

Rheology of common drilling fluids is reported and can be briefly described in few points:

- Marsh Funnel tests show fluids with higher concentration, for both bentonite and polymer mixes, results in higher flow resistance (viscosity) and therefore longer drainage times.
- Rheometer datasets show higher stresses are obtained for higher concentration drilling muds, in agreement with Marsh Funnel data, and higher temperatures are resulting in lower stresses.
- The drilling muds behave comparably at both 23°C and 80°C. However, the polymer-based drilling fluid requires more stress to initiate flow at room temperature compared to the others.
- Presented point plastic viscosity (PPV) defines the increase in fluid resistance when increasing the shear rate for studied drilling fluids.
- Higher temperature results in lower shear stresses and viscosities (more fluid properties), an effect greater for polymer fluids in contrast to bentonite fluids.

8. LIST OF VARIABLES

V *actual* volume *of funnel (cm^3)*
g acceleration due to gravity (m^2/s)
h height of fluid in the funnel (cm)
M mass of drilling fluid (g)
Q volumetric flow rate (cm^3/s)
ρ density (kg/m^3)
R_0 maximum radius of funnel (cm)
R_L radius of capillary (cm)
Z height of funnel during drainage (cm)
Z_1 maximum height of funnel (cm)
Z_2 length of capillary (cm)
m consistency factor of H-B model (Pa s^n)
α parameter of funnel geometry
n flow behaviour index of H-B model (-)
τ shear stress (Pa)
τ_w wall shear stress in funnel (Pa)
τ_0 yield point/yield stress (Pa)
$\dot{\gamma}_w$ wall shear rate in funnel (1/s)

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