Viscosity of oil-based drilling fluids

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ABSTRACT

During drilling petroleum wells, drilling fluids are used to keep the well under control and to transport out drilled cuttings. Oil-based drilling fluids (OBM) are frequently used since they do not react chemically with the formation. A series of experiments has been conducted where the viscosity profile of OBMs has been measured. Clays are added to drilling fluids to create an increased drilling fluid viscosity. The experiments show how much more efficient an already chemically treated oil wet clay is to build viscosity compared to the use of a clay where the oil wetting is performed by the OBM premix chemicals. Furthermore, it is shown how an increase in OBM density gives an increase in viscosity.

In viscosity analysis mentioned above, the viscosity of drilling fluids was measured both using a freshly made fluid, and a fluid that has been hot rolled under pressure to simulate practical usage. In this paper, we showed results from tests where we have varied the testing temperature and the time spent on such hot rolling. Furthermore, the viscosity models are presented using the Herschel-Bulkley model in a dimensionless form. The latter is practical to present the drilling fluid data for digitalization purposes.

INTRODUCTION

Viscosity of oil-based drilling fluids (OBM) depends on several factors including but not limited to solid content, type of liquids and their interactions, pressure, and temperature. Viscosity of such complex liquids is the result of internal frictional forces between different layers, as they are forced to move relative to each other. These forces are caused by the cohesive forces between the particles and chemicals. When the temperature increases, the viscosity of liquids decreases. This is due to increase of kinetic energy of the molecules. As the temperature rises, the molecules oppose the cohesive forces more strongly and move more freely[1].

Oil-base drilling fluids, also known invert-emulsion fluids, are fluids whereas their continuous phase is oil, also contain typically 15-35% water. When considering the oil to water ratio (O/W) of oil-base drilling fluids, increase in water percentage leads to increase in viscosity. Although oil is more viscous than water, the water droplets interact with the solid particles and some water droplets will have to move for others to come through. Consequently, the viscosity increases.

Barite is a material added to adjust the density of drilling fluids, in order to keep the wellbore stable. Generally, added particles to the drilling fluid will increase the fluid viscosity.

To control the viscosity and some other functional aspect of drilling fluids, clay is added to the mix design. Wyoming bentonite is used for preparation of simple water-base drilling fluids. For oil-base drilling fluids, a chemically treated clay is used. These organophilic clays are treated to make as large portion as possible of their surface oleophilic. The clays are dispersed in the continuous phase of the drilling fluids and act as colloids, to increase the viscosity.

The most common viscosity model for drilling fluids with a reasonable accuracy for a wide span of shear rates is the Herschel-Bulkley model[2]. Herschel-Bulkley fluids combine a Power-law behaviour with a yield stress. Traditionally, the Herschel-Bulkley model is defined as shown in Equation (1),

$$\tau = \tau_y + k(\dot{\gamma})^n, \tag{1}$$

where k is the consistency index, n is the flow behaviour index (similar parameters to power-law model), and τ_y is the yield stress. The parameters used in this equation can be difficult to use in field application because the consistency, k, is dependent on the flow index, n, $k=k(n)$. Thus, there is no direct relation between k and viscosity. To make the model presentable with independent parameters, Saasen and Ytrehus[3] developed a model, based on a model by Nelson and Ewoldt[4], that uses dimensionless shear rates as shown in Equation (2).

$$\tau = \tau_y + \tau_s \left(\frac{\dot{\gamma}}{\dot{\gamma}_s}\right)^n. \tag{2}$$

In this equation, the term τ_s is the additional shear stress, $\tau_s = \tau - \tau_y$ at a characteristic shear rate of the flow, $\dot{\gamma}_s$. Using this type of representation of the Herschel-Bulkley model, three independent parameters for the fluids can be tabulated: the yield stress, τ_y, the surplus stress, τ_s, at a characteristic shear rate, $\dot{\gamma}_s$ (or the actual shear stress at this shear rate), and finally the flow index, n.

The yield stress is a parameter that has been debated for the last decades[5]. In drilling fluid applications, use of a yield stress is applicable because the time constants of the flow are sufficiently short. The accuracy of simple yield stress measurements using oilfield standards is more questionable[6]. Zamora and Power[7] established a method to determine the yield stress:

$$\theta_0 = (2\theta_3 - \theta_6), \tag{3}$$

$$\tau_y = 0.511 \times \theta_0 \; [Pa], \tag{4}$$

where, θ is the dial reading of the measurements conducted in accordance with oilfield standards[8].

Riisøen et al.[9] studied the impact of Power-Law model parameters on frictional pressure loss uncertainty. They implemented the dimensionless shear rates approach[3]. They found that this method is more practical, easily computed, and suggests a robust alternative to k and n.

In the following sections, the effect of barite, oil to water ratio, clay type, hot rolling and temperature on viscous behaviour of an oil-based drilling fluid is presented. In addition, it presents application of a new approach to estimate the independent Herschel-Bulkley model parameters by the use of using dimensionless shear rates.

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials

The drilling fluid used in this study was a basic laboratory prepared oil-based drilling fluid made equal to a fluid for field application. The chemicals used in this study are tabulated in Table 1. Different mixture designs investigated in this study are presented in Appendix A.

A non-aromatic mineral oil was used as the continuous phase. A solution of fresh water with $CaCl_2$ and lime was emulsified into the oil. Normally, $CaCl_2$ is used to prevent osmosis with the formation clay water during drilling.

The main function of the emulsifier is to stabilise the emulsion. Another function is to oil-wet the solid particles. This is mainly to prevent the solid particles from having a repulsive effect from the fluid.

Table 1. Chemical used for preparation of OBM.

Mineral Oil EDC95/11
$CaCl_2$-solution
One-Mul (primary and secondary emulsifier)
Lime ($Ca(OH)_2$)
Organophilic Clay/Wyoming Bentonite
Versatrol
Barite

The main function of both Wyoming bentonite and organophilic clay is to control the viscosity. This is for maintaining weighting materials suspended and increasing the cutting transportation efficiency.

Barite is a weighting material used to adjust the density of the drilling fluid.

Equipment

The experimental equipment consisted of the following parts. All items can be used in accordance with oilfield standards[8].

- Electrical balance – A Mettler Toledo balance, with a precision of ± 0.01 g, was used for this study.
- Mixer - Hamilton Beach SCOVIL was used for mixing. The mixer has three modes: low, medium and high rotation speed.
- Mud balance – To measure the density of the designed drilling fluid, a pressurized fluid density balance (FANN model 141) was employed.
- Rotational viscometer – OFITE model 900 viscometer was used to measure the shear stresses at different shear rates. The rheometer was equipped with a heating cup to provide the heat for rheology measurements at elevated temperatures.
- Electrical Stability Tester – To measure the fluid's emulsion stability and oil-wetting capability, an electrical stability tester model 23E was hired.
- Roller oven – In order to age the drilling fluid samples at elevated temperature, a Fann roller oven was used to age the samples for 24 hours at 90°C.

Experimental Procedures

The chemical and additive mixing, and mixing time is shown in Table 2.

Table 2. Order of mixing and mixing time of the materials.

Order	Materials	Mixing Time
1	Mineral-oil	
2	$CaCl_2$ solution	2 min
3	Emulsifier	
4	$Ca(OH)_2$	2 min
5	Organophilic clay/Bentonite	5 min
6	Filter loss reducing agent (Versatrol)	2 min
7	Barite	10 min

Twelve different oil-base drilling fluids with varying content of barite, organophilic clay, Wyoming bentonite and brine-solution were studied. The base recipe has a density of 1.20 s.g., 85/15 O/W ratio and organophilic clay or Wyoming bentonite content at 5.5g.

Five recipes had varying barite content, from 1.20 s.g. to 1.60 s.g., increasing with 0.1 s.g. between measurements. Five recipes had varying brine-solution, with O/W ratios between 85/15 to 65/35, decreasing with five between measurements. Two recipes had increased organophilic clay or Wyoming bentonite content, increasing it from 5.5g in the base recipe to 8.02g.

The eight recipes with the highest density, highest organophilic clay content, highest Wyoming bentonite content, lowest O/W ratio and the base recipes were tested at temperatures from room-temperature up to approx. 70°C, increasing with 10°C between measurements. Four of these recipes were consisted of organophilic clay and four were made with Wyoming bentonite.

The roller oven was set at 90°C. The recipes were left in the oven for 24 hours, and left to cool down for another five hours before measurements were performed.

The measurements were done at ramp-down mode: 600, 300, 200, 100, 60, 30, 20, 10, 6, 3, 2 and 1 rpm. The mix-designs are listed in Appendix A. Note that there is a gear problem at 20rpm. Hence, all measurements at this shear rate show too low a shear stress.

RESULTS AND DISCUSSIONS

Effect of hot rolling on rheology

The conventional method for preparation of laboratory samples is to pour the sample into a high-pressure vessel and hot roll that at the expected down hole temperature for a certain time. The current samples were hot rolled at 90°C for 24 hours. Viscosity measurements prior to and after hot rolling showed that hot rolling caused viscosity to decrease. This is shown by for example comparing the viscosity results at different O/W ratios measured before hot rolling, Fig. 1**,** with measurements after hot rolling, Fig. 2.

When the amount of barite was increased, the viscosity increased at high shear rates and decreases at lower shear rates. The shear rates that is valid in field is typically less than 250 1/s[10,11]. Therefore, it can be said that, in practice the hot rolling also in this case lowered the viscosity. In the following, only hot rolled samples are discussed to present data anticipated to be more relevant for field applications.

Effect of oil – water ratio on viscosity

The viscosity increased with increase of brine content. This can be observed in Fig. 2 (or Fig. 1), which show the shear stress as function of the shear rate for fluids with different oil – water ratios.

An increased total brine volume can destabilise the drilling fluid when the surface-active agent affecting the emulsion is kept constant. In practice, this would have had an impact on the emulsion stability unless properly adjusted with emulsifiers.

With lowering the O/W ratio, meaning that more of the fluid is occupied with water droplets, the OBM can create emulsions that are more applicable for suspending barite and other weighting agents. However, one of the distinct effects by operating with a too low O/W ratio is its large viscosity, which is a disadvantage during circulation.

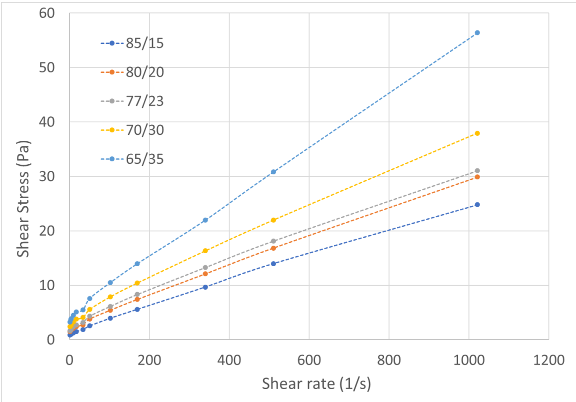

Figure 1. The effect of O/W ratio on viscosity at room temperature before hot rolling.

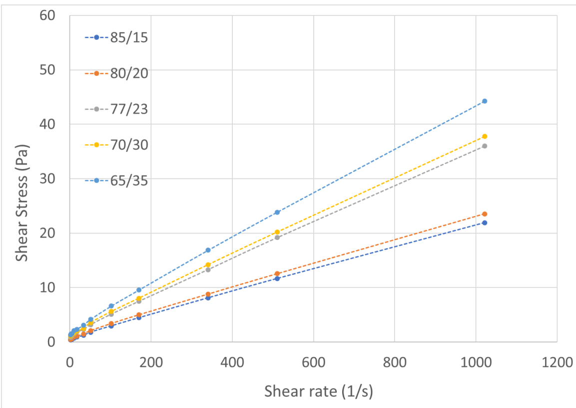

Figure 2. The effect of O/W ratio on viscosity at room temperature after 24 hours hot rolling at 90°C.

The viscosity increase with increase of brine content should be reflected on Herschel-Bulkley parameters. In Fig. 3, it is shown the effect of O/W ratio on Herschel-Bulkley parameters τ_y, τ_s and n. The yield stress is approximated following Zamora and Power[7]. The surplus stress is measured at 102.2 1/s and the exponent, n, is determined at the shear rate 170.2 1/s. It is observed that the exponent is fairly constant at a value of approximately 0.86 and that both the yield stress and the surplus stress decrease monotonically with increasing oil content.

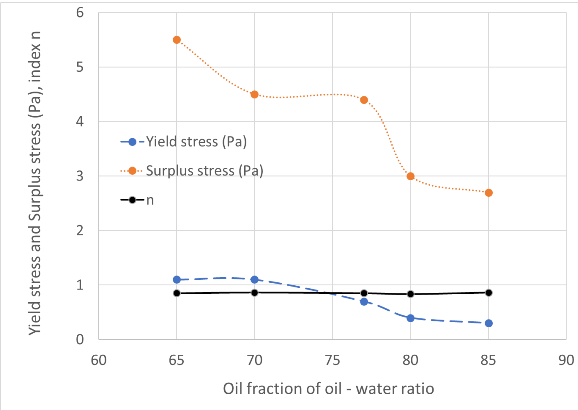

Figure 3. The effect of O/W ratio on Herschel-Bulkley parameters τ_y, τ_s and n.

<u>Effect of barite on viscosity</u>

When barite was introduced into the mixture, the shear stresses increased. Figs. 4 and 4 show the increase of shear stress as function of the shear rate. As anticipated[12, 13], the higher the barite content the higher the shear stress.

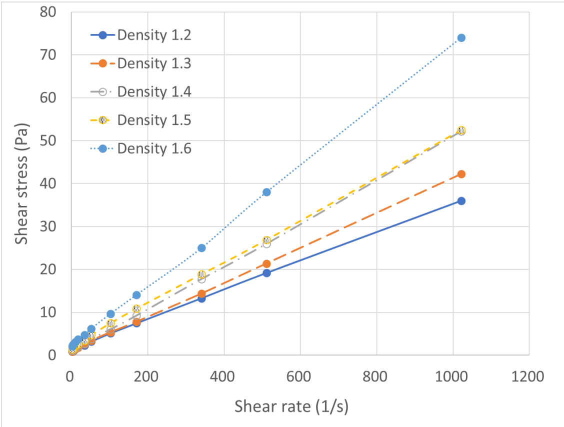

Figure 4. Shear stress plotted as a function of shear rate for five different recipes with increasing barite concentration. Measured after hot rolling.

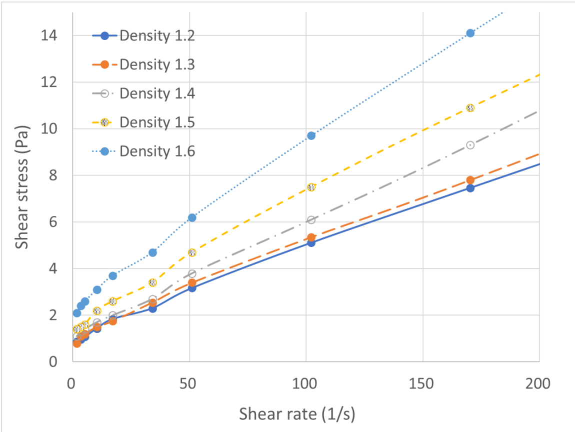

Figure 5. Low shear rate plot of data shown in Figure 5.

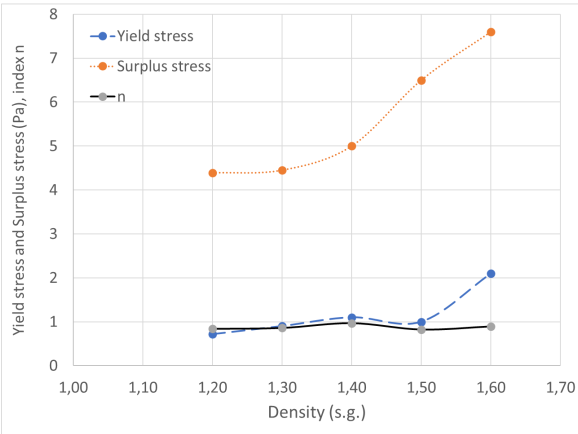

Figure 6. The effect of density on Herschel-Bulkley parameters τ_y, τ_s and n.

The viscosity of a particular drilling fluid increases with increasing density. In Fig. 6, the effect of density on Herschel-Bulkley parameters is shown. If the measurements at the densities of 1.4 and 1.5 s.g. is excluded, it is observed that the exponent is fairly constant around a value of approximately 0.85-0.89 and that both the yield stress and the surplus stress increase with increasing yield stress. The deviation from the general trend at 1.4 and 1.5 is not very large, indicating a possible measurement error.

Effect of clay type on viscous properties of OBM

An oil-based drilling fluid will contain an excess volume of emulsifiers to oil wet drill solids. A test was conducted to see if this volume was sufficient to adopt Wyoming bentonite as viscosifier in the drilling fluid. In Fig. 7 is shown the shear stress as function of the shear rate for oil-based drilling fluids with different content of Wyoming bentonite and organophilic clay. It shows that organophilic clay is more effective at increasing the viscosity of an oil-based drilling fluid compared to equal amount of Wyoming bentonite. The results show that increasing the content of organophilic clay from 5.5 (OC-1) to 8.02g (OC-2) give a significant increase in viscosity. Increasing the content of Wyoming bentonite equally does not give any distinguishable difference in viscosity.

With the use of Wyoming bentonite in OBM, the clay particles will disperse with the droplets in the water phase. As a result, the oil phase is constantly separated from the water phase and only interaction between the particle and water phase occurs. The emulsifier will have less or zero function as it will not oil-wet the bentonite. Therefore, it will be no increase in the viscosity for Wyoming bentonite compared to organophilic clay.

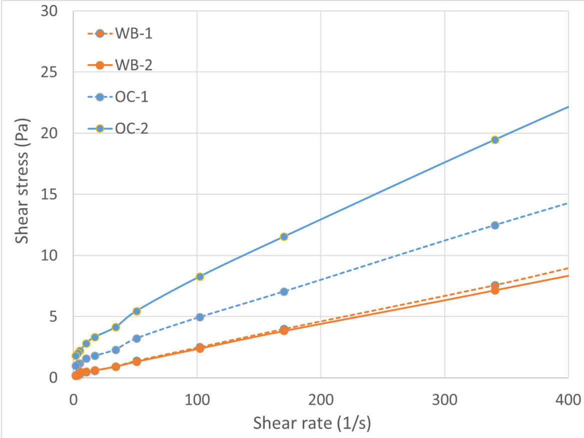

Figure 7. The shear stress as function of the shear rate for oil-based drilling fluids with different content of Wyoming bentonite and organophilic clay.

Effect of temperature on rheology

The set of experiments verified that increasing the temperature of an oil-based drilling fluid will decrease the viscosity of the fluids. This effect is observed to be the case for the all the tested recipes. The data shown in Figs. 8-11 show the viscosity of a fluid viscosified with 8.02g of an organophilic clay (Figs. 8 and 9) and a fluid densified with barite to 1.59 s.g. (Figs. 10 and 11).

The yield stress of the drilling fluid viscosified with 8.02g organophilic clay remained nearly constant for the investigated temperature span (Fig. 9). The surplus stress, however, was significantly reduced over the same temperature span. Also, the flow index was slightly reduced. This means that the fluids kept their yield stress but had a reduction in viscosity and a more curved shape as the temperature increased.

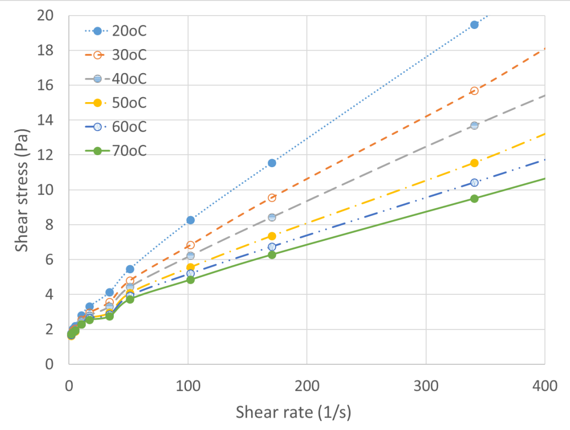

Figure 8. The shear stress as function of the shear rate for an oil-based drilling fluid viscosified with organophilic clay at different temperatures.

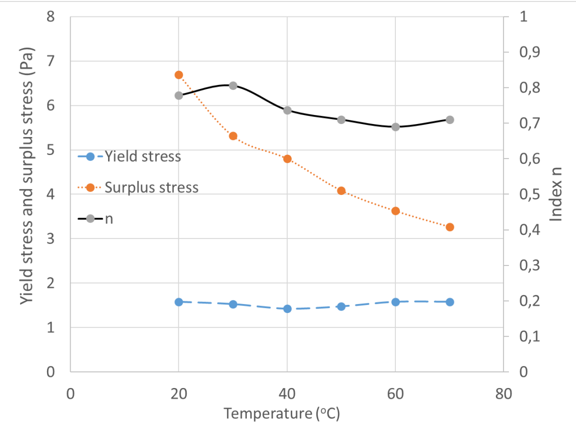

Figure 9. The effect of temperature on Herschel-Bulkley parameters τ_y, τ_s and n for the fluid shown in Figure 9.

The drilling fluid weighted with barite to 1.59 s.g. demonstrated a similar behaviour as the one viscosified with organophilic clay. However, in this particular case the yield stress was also slightly reduced.

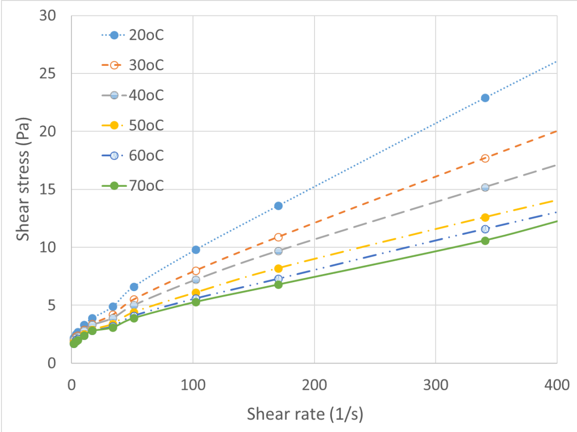

Figure 10. The shear stress as function of the shear rate for an oil-based drilling fluid weighted with barite to 1.59 s.g. at different temperatures.

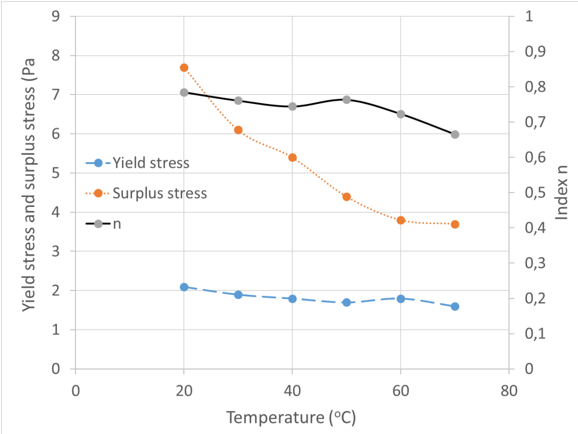

Figure 11. The effect of temperature on Herschel-Bulkley parameters τ_y, τ_s and n for the fluid shown in Figure 11.

CONCLUSION

A series of experiments verified several anticipated items:

- Hot rolling normally decreases the viscosity of the oil-base drilling fluid.
- An increase in volume of brine, barite and organophilic clay increases the viscosity. However, increasing the content of Wyoming bentonite have insignificant effect.
- Increasing the temperature decreases the viscosity. This effect was shown to be valid for all the tested fluid designs.

The Herschel-Bulkey model with dimensionless shear rates has been applied directly in this study. The Herschel-Bulkley parameters τ_y, τ_s and n have been investigated. The experiments have clearly shown the potential of using these viscosity parameters for modelling effects of:

- Changes in composition
- Changes in temperature

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APPENDIX A

Chemical	85/15 O/W			
Mineral oil (EDC95/11)	167,684	[g]	206	[ml]
Water	31,50588247	[g]		
CaCl_2	6,059	[g]	36,35294118	[ml]
Emulsifier	9,5	[g]	10	[ml]
Ca(OH)_2	8,5	[g]	3,794642857	[ml]
Organophilic Clay	5,5	[g]	3,235294118	[ml]
Filter loss reducing substance (Versatrol)	6	[g]	5,714285714	[ml]
Barite	115	[g]	27,54491018	[ml]
Sum	349,7487061	[g]	292,642074	[ml]
Density			1,1951	[g/ml]

Chemical	80/20 O/W			
Mineral oil (EDC95/11)	167,684	[g]	206	[ml]
Water	44,63333351	[g]		
CaCl_2	8,583	[g]	51,5	[ml]
Emulsifier	9,5	[g]	10	[ml]
Ca(OH)_2	8,5	[g]	3,794642857	[ml]
Organophilic Clay	5,5	[g]	3,235294118	[ml]
Filter loss reducing substance (Versatrol)	6	[g]	5,714285714	[ml]
Barite	115	[g]	27,54491018	[ml]
Sum	365,400667	[g]	307,7891329	[ml]
Density			1,1872	[g/ml]

Chemical	70/30 O/W			
Mineral oil (EDC95/11)	167,684	[g]	206	[ml]
Water	76,51428601	[g]		
CaCl_2	14,714	[g]	88,28571429	[ml]
Emulsifier	9,5	[g]	10	[ml]
Ca(OH)_2	8,5	[g]	3,794642857	[ml]
Organophilic Clay	5,5	[g]	3,235294118	[ml]
Filter loss reducing substance (Versatrol)	6	[g]	5,714285714	[ml]
Barite	115	[g]	27,54491018	[ml]
Sum	403,412572	[g]	344,5748472	[ml]
Density			1,1708	[g/ml]

Chemical	65/35 O/W			
Mineral oil (EDC95/11)	167,684	[g]	206	[ml]
Water	96,1333337	[g]		
CaCl_2	18,487	[g]	110,9230769	[ml]
Emulsifier	9,5	[g]	10	[ml]
Ca(OH)_2	8,5	[g]	3,794642857	[ml]
Organophilic Clay	5,5	[g]	3,235294118	[ml]
Filter loss reducing substance (Versatrol)	6	[g]	5,714285714	[ml]
Barite	115	[g]	27,54491018	[ml]
Sum	426,8045136	[g]	367,2122098	[ml]
Density			1,1623	[g/ml]

Chemical	Base Recipe		Recipe 1 Density 1,2		Recipe 2 Density 1,3		Recipe 3 Density 1,4		Recipe 4 Density 1,5		Recipe 5 Density 1,6	
Mineral oil (EDC95/11)	206	[ml]	206	[ml]	206	[ml]	206	[ml]	206	[ml]	206	[ml]
Water	52	[ml]	52	[ml]	52	[ml]	52	[ml]	52	[ml]	52	[ml]
Emulsifer	10	[ml]	10	[ml]	10	[ml]	10	[ml]	10	[ml]	10	[ml]
CaCl_2	10	[g]	10	[g]	10	[g]	10	[g]	10	[g]	10	[g]
Ca(OH)_2	8,5	[g]	8,5	[g]	8,5	[g]	8,5	[g]	8,5	[g]	8,5	[g]
Organic clay	5,5	[g]	5,5	[g]	5,5	[g]	5,5	[g]	5,5	[g]	5,5	[g]
Filter loss reducing substance (Versatrol)	6	[g]	6	[g]	6	[g]	6	[g]	6	[g]	6	[g]
Barite	115	[g]	115	[g]	161,6	[g]	210	[g]	262	[g]	318	[g]

Chemical	Recipe 1 Density 1,17		Recipe 2 Density 1,16		Recipe 3 Density 1,59		Recipe 4 Density 1,17	
	Base Recipe		O/W		Barite		Organophilic clay	
Mineral oil (EDC95/11)	206	[ml]	206	[ml]	206	[ml]	206	[ml]
Water	52	[ml]	92.2	[ml]	52	[ml]	52	[ml]
Emulsifier	10	[ml]	10	[ml]	10	[ml]	10	[ml]
$CaCl_2$	10	[g]	18.5	[g]	10	[g]	10	[g]
$Ca(OH)_2$	8.5	[g]	8.5	[g]	8.5	[g]	8.5	[g]
Organophilic clay	5.5	[g]	5.5	[g]	5.5	[g]	8.02	[g]
Filter loss reducing substance (Versatrol	6	[g]	6	[g]	6	[g]	6	[g]
Barite	115	[g]	115	[g]	317.8	[g]	115	[g]

Chemical	Recipe 5 Density 1,15		Recipe 6 Density 1,14		Recipe 7 Density 1,56		Recipe 8 Density 1,12	
	Base Recipe		O/W		Barite		Bentonite	
Mineral oil (EDC95/11)	206	[ml]	206	[ml]	206	[ml]	206	[ml]
Water	52	[ml]	92.2	[ml]	52	[ml]	52	[ml]
Emulsifier	10	[ml]	10	[ml]	10	[ml]	10	[ml]
$CaCl_2$	10	[g]	18.5	[g]	10	[g]	10	[g]
$Ca(OH)_2$	8.5	[g]	8.5	[g]	8.5	[g]	8.5	[g]
Wyoming Bentonite	5.5	[g]	5.5	[g]	5.5	[g]	8.02	[g]
Filter loss reducing substance (Versatrol	6	[g]	6	[g]	6	[g]	6	[g]
Barite	115	[g]	115	[g]	317.8	[g]	115	[g]