Oil based drilling fluids with tailor-made rheological properties: results from a multivariate analysis

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ABSTRACT

Relations between the rheological parameters of the Herschel–Bulkley model and the composition of an oil based drilling fluid were derived using multivariate analysis. Such relations may be used to optimise and tailor-make the rheological properties of drilling fluids. Molecular interpretations of some of the established relations are also presented.

INTRODUCTION

Oil based drilling fluids, also referred to as oil based muds (OBM), are complex fluids which typically may consist of ten different components. In most cases OBM are invert emulsions with oil as the continuous phase. The aqueous phase of emulsions is often droplets of brines stabilised by emulsifiers, and added lime for alkalinity. Weight materials are added to control the density of the fluids, while wetting agents may be added to increase the oil wetting of weight materials and other solids. Viscosifiers are added to increase the viscosity, and fluid loss materials are added to reduce the flow of fluids from the OBM into formations while drilling.

Drilling fluids have three main functions:

1. To transport drill cuttings out of the hole and to allow for separation of cuttings from the drilling fluids at the surface.
2. To form a thin filter cake on the walls of the wellbore to prevent inflow of drilling fluids into the formations.
3. To prevent inflow of formation fluids into the wellbore.

These main functions may, however, be divided into a number of more specialised functions[1].

Because of the complexity of the fluids, the formulation of OBM is often regarded more as an art than as a science. Very often the properties are obtained by varying "one variable at a time". A large number of tests are then needed to reach the required properties, and the final results depend often very much on the skills of the formulator.

An alternative or complementary approach may be to use multivariate analysis, a statistical method also known as experimental design or factorial design. Multivariate analysis may be used to study the effect of a number of parameters on one or several target parameters. Furthermore the method gives information about possible interactions between different variables, information which is not achieved when using the "one variable at a time"-method.

Still, even when using multivariate analysis, a large number of tests are needed to fully describe a system of ten variables. If, however, the knowledge of the experienced formulator and the statistical methods are combined, the task may be greatly reduced. The experienced formulator may know that some of the components of the drilling fluids have little or no effect on the parameters of interest. Only the remaining components may then have to be treated as variables in the analysis.

In this paper the relations between the rheological properties of OBM and five variables, related to the composition of the muds, has been studied. The established relations may be used to optimise the rheological profile of the OBM. Furthermore some of the molecular mechanisms causing these relations will be discussed.

EXPERIMENTAL

Multivariate analysis

A comprehensive treatment of the theory of multivariate analysis has been given by Box et al.[2]. To investigate the effect on a target parameter of five variables or factors, $2^5 = 32$ experiments are required. The exponent 5 describes the number of factors, while the number 2 indicates that the factors are studied at 2 levels. Such an experimental design will describe the main effects (x_1, x_2, x_3, x_4 and x_5) and all possible two-factor (x_{12}, x_{13}, x_{14}, x_{15}, x_{23}, x_{24}, x_{25}, x_{34}, x_{35}, x_{45}) and three-factor (x_{123}, x_{124}, x_{125}, x_{134}, x_{135}, x_{145}, x_{234}, x_{235}, x_{245}, x_{345}) interactions.

In this study the number of experiments has been reduced to 16 by applying a 2^{5-1} reduced factorial design. Such a system is, however, no longer fully described. Some of the two-factor and three-factor interactions will coincide as shown in Table 1. Such interactions are also referred to as aliases. The five variables chosen to describe the composition of the oil based drilling fluids, their high and low levels and their centre points are shown in Table 2. The multivariate analysis was carried out using Sirius 6.5 software[3].

Preparation of OBM

The OBM contained mineral oil and water in the volume ratio indicated in Table 2. The drilling fluids also contained two emulsifiers mixed in the volume ratio 2:1, a fluid loss additive, a wetting agent and lime in concentrations as given in Table 2. Organophilic clay (15 kg / m^3) and calcium chloride (19,9 weight % calculated on water) were added at the same level in all experiments, while weight material was

Table 1. Aliases of two-factor and three-factor interactions in a 2^{5-1} reduced factorial design.

Two-factor	Three-factor
X_{12}	x_{345}
X_{13}	x_{245}
X_{14}	x_{235}
X_{15}	x_{234}
X_{23}	x_{145}
X_{24}	x_{135}
X_{25}	x_{134}
X_{34}	x_{125}
X_{35}	x_{124}
X_{45}	x_{123}

Table 2. The experimental variables used in the multivariate analysis, their high and low values and their centre points.

Variable	High level +	Low level -	Centre point
Conc.* of emulsifiers (1)	35	25	30
The oil water ratio (2)	85:15	75:25	80:20
Conc.** of lime (3)	12,5	7,5	10
Conc.** of wetting agent (4)	5	0	2,5
Conc.** of fluid loss additive (5)	30	20	25

*Concentration in L / m^3
**Concentration in kg / m^3

added to give a final density of the OBM of 1,80 SG. The fluids were mixed in a Hamilton Beach mixer. The components were added in the order given below and mixed at low speed for the time intervals indicated: 1) mineral oil, emulsifiers, calcium chloride and organophilic clay (mixed for 5 minutes), 2) lime (5 minutes), 3) fluid loss additive (3 minutes), 4) water (10 minutes) and 5) weight material (20 minutes). Finally the wetting agent was added and the mixing continued for 10 minutes at high speed.

The OBM were filled into aging cells and hot rolled in a Fann Roller Oven for 18 hours at 150 ^{0}C. All rheological measurements were done on hot rolled fluids.

The weight material used was a tri-manganese tetraoxide (Micromax) supplied by Elkem ASA, Materials, Norway. All other chemicals were supplied by M-I Norge AS, Norway.

Rheology

A Chandler model 3500 viscometer was used for measuring the rheology of the OBM. The fluids were filled into a Fann thermo cup and heated to 65 ^{0} C while running the viscometer at 100 rpm. When 65 ^{0}C was reached, the rheology was measured as described by API[4] staring at 600 rpm and then reducing the speed stepwise down to 3 rpm.

The shear stress readings (SS) of the Chandler viscometer are recorded in the units of pounds/100 square inch and the shear rate readings as rotations per minute (rmp). The plastic viscosity (PV) and the yield point (YP) of the Bingham plastic model, and the consistency index (K) and the power law index (N) of the power law model, were calculated in SI-units from the 600 and 300 rpm readings using Eq. 1-4.

$$PV=0,511x(SS_{600}–SS_{300})/1,7x(600–300) \quad (1)$$

$$YP=0,511xSS_{300}-PVx1,7x300 \quad (2)$$

$$N=\log(SS_{600}/SS300)/\log(600/300) \quad (3)$$

$$K=0,511xSS_{600}/(1,7x600) \quad (4)$$

The shear stress τ may, according to the Herschel-Bulkley model, be expressed as a function of a yield value (τ_{YP}), a consistency index (κ), the shear rate (γ*) and the power law index (n) as shown in Eq. 5.

$$\tau=\tau_{YP}+\kappa(\gamma^*)^n \quad (5)$$

The values of τ_{YP}, κ and n were determined by fitting Eq. 5 to the experimental rheograms.

The units of the parameters in Eq. 1-5 are: PV (Pa·s), YP, τ and τ_{YP} (Pa), N and n (dimensionless), K and κ (Pa·s^N and Pa·s^n) and γ* (s^{-1}).

RESULTS

Rheological models

In Fig. 1 an experimental rheogram of an OBM is compared to the rheograms of the Bingham plastic model, the power law model and the Herschel-Bulkley model. At low shear rates the Bingham plastic model

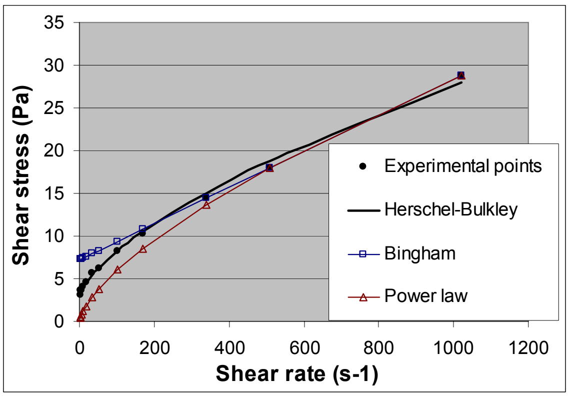

Figure 1. Comparison of an experimental rheogram of an oil based mud to rheograms predicted by the Herschel-Bulkley, the Bingham plastic and the power law models.

shows too high shear stresses compared to the experimental readings, while the power law model gives too low values. The best fit is obtained with the Herschel-Bulkley model. Several authors[5,6] have shown that the Herschel-Bulkley model may be used to describe the rheology of OBM over a wide range of temperatures and pressures. The rheological parameters of this model were therefore chosen as target parameters in the multivariate analysis.

Multivariate analysis

Multiple regression models were built for the target parameters τ_Y, κ and n of the Herschel–Bulkley model using a 2^{5-1} reduced factorial design. The variables used in the analysis are given in Table 2.

The yield value

The relation between the target parameters, τ_{yp}, and the main variables 1-5 and their two-factor interactions are given by the regression coefficients shown in Fig. 2. When the regression coefficients are positive, the target parameter increases in proportion to the regression coefficients, while negative coefficients indicate that the target parameter decreases when the variables or the interaction terms are increased.

It can be seen from Fig. 2 that the O/W–ratio is the variable having the largest effect on τ_{yp}. Higher yield values are obtained if the O/W-ratio of the fluids is decreased.

The full statistical model for the yield values of the OBM explained 99,8 % of the data, while 88,4 % were explained when interactions were excluded. This indicates that interaction terms are small and that the effects of the main variables are dominating.

The power law index

The relation between the target parameter, n, and the main variables 1-5 and their two-factor interactions are given by the regression coefficients shown in Fig. 3. It is seen that the O/W-ratio has very little effect

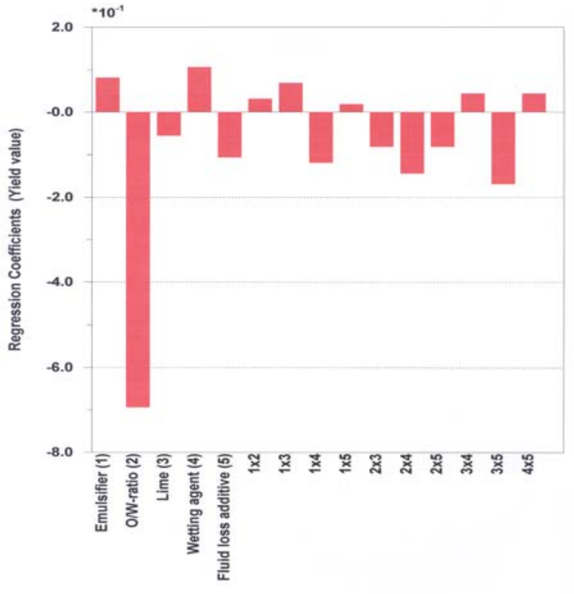

Figure 2. Regression coefficients showing the effect of the variables (1-5) and their two-factor interactions on the yield value of OBM.

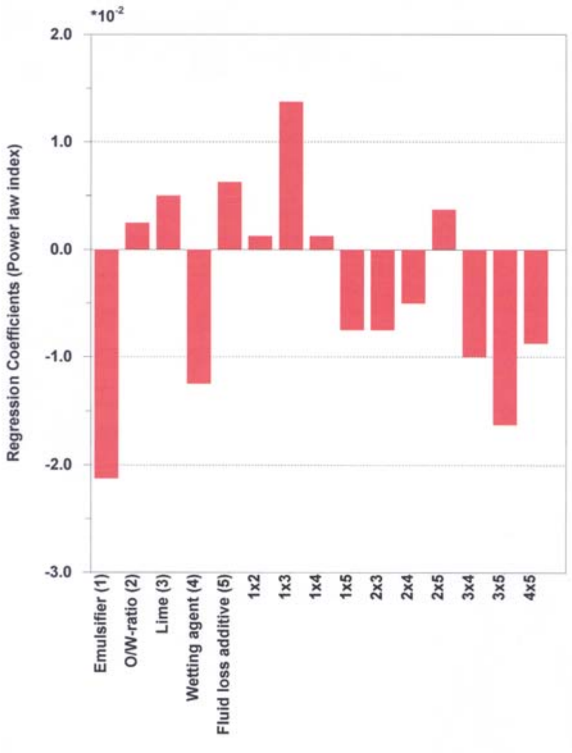

Figure 3. Regression coefficients showing the effect of the variables (1-5) and their two-factor interactions on the power law index of OBM.

on n. This is in contrast to what was found for τ_{yp}. The variables having the largest effect on n are the concentrations of emulsifiers and wetting agent. An increase in both these variables resulted in lower values of n. Furthermore, several interaction terms seem to be of importance. Interactions resulting in lower n values, by increasing interaction terms, are the interactions between lime and fluid loss additive (3x5), lime and wetting agent (3x4) and wetting agent and fluid loss additive (4x5). The interaction between emulsifiers and lime (1x3) results in higher n values when the concentrations of these variables are increased.

The full model for n explains 95,3 % of the data, while only 44,2 % are explained when interactions are excluded. Interactions are clearly of much more importance for n than for τ_{yp}.

<u>The consistency index</u>

The relation between the target parameter, κ, and the main variables 1-5 and their interaction terms, are given by the regression coefficients shown in Fig. 4. The behaviour of κ seems to fall in-between that of τ_{yp} and n. It is seen from Fig. 4 that the O/W-ratio is the variable affecting κ to the greatest extent. Higher values of κ are obtained when the water-content of the OBM is increased. κ also increases with increasing concentrations of emulsifiers. Correlation analysis between κ- and τ_{yp}-values and κ- and n-values in the data-set showed correlation coefficients of 0,64 and –0,75 respectively.

The full multivariate model for κ explains 99,4 % of the data, while 72,7 % is explained when the interactions are excluded.

DISCUSSIONS

The primary result of a multivariate analysis is the relations between one or more target parameters and the variables and their interaction terms. Such relations may be useful when optimising the properties of OBM, especially if the mud should fulfil several functions simultaneously.

Furthermore, the relations from the multivariate analysis may contain information about under-lying molecular mechanisms. An attempt has been made to interpret some of these mechanisms, though, in most cases, such mechanisms are not easily revealed without additional information.

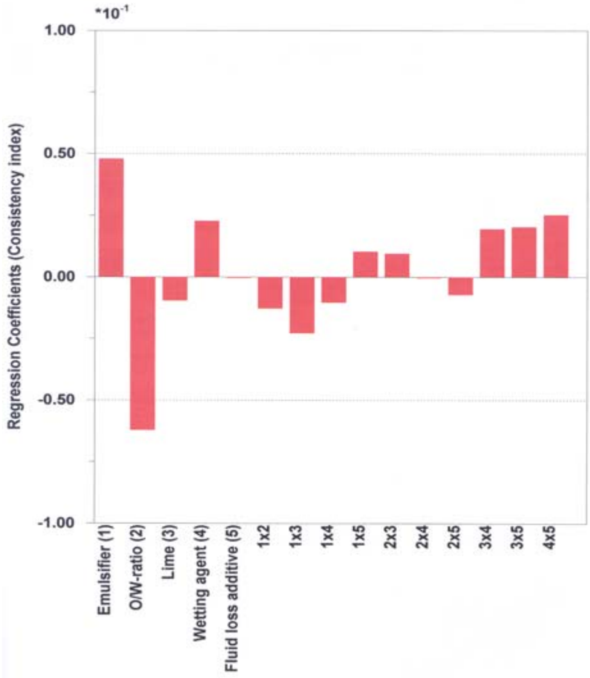

Figure 4. Regression coefficients showing the effect of the variables (1-5) and their two-factor interactions on the consistency index of OBM

<u>Tailor-making the rheological properties of OBM</u>

In this study the yield value of the OBM was found to be mostly dependent on the O/W-ratios, while the power law index depended mostly on other components of the mud. This allows the yield value and the power law index of the OBM to be manipulated independently.

A situation, where OBM with tailor-made rheological profiles may be needed, is when drilling horizontal wells into reservoir sections with narrow operating windows between pore and fracture pressures. In such situations the following requirements are important:

1. For optimal hole cleaning turbulent flow of the drilling fluid in the annulus is preferred[7].
2. The Equivalent Circulating Density (ECD) of the drilling fluid should be low to avoid frictional pressure build-up and fracturing of the reservoir resulting in lost circulation[8,9].
3. Sag of weight materials should be low to secure well control and to avoid kick-situations[8,9].

To avoid sag of weight materials, the OBM needs a minimum yield value. In order to pump the fluid in turbulence and to keep the ECD as low as possible, the increase in viscosity by increasing flow rates should also be low, i.e. the power law index should be low.

In this study, τ_{yp} attained values in the range 1,0 – 3,7 Pa and n values in the range 0,75 – 0,62 when the variables were varied as shown in Table 2. The data indicate that the O/W-ratio may be used to control the yield values and possibly allow the addition of organophilic clay to be reduced. The variation interval for n, however, was rather narrow. To verify if higher concentrations of emulsifiers and wetting agent than given in Table 2, allow further reduction in n, additional testing is needed.

In a situation as described above, it is also of importance to try to minimise the total build-up of solids in the system. In high pressure wells, the specific gravity of the muds is normally increased by adding more weight material. While drilling, fine cutting particles, too small to be removed by the shale shaker screens, also will accumulate in the drilling fluid. Usually it is difficult to maintain good rheological properties for muds with high solids content[8]. An interesting approach to this problem been taken by Franks and Marshall[9]. They used very fine shale shaker screens to keep the amount of drill solids in the system at a minimum and used a weight material fine enough to pass through the screens.

Molecular interpretations

When the volume fraction of water is increased the spacing between the water-droplets decreases. This will affect the colloidal forces acting between the droplets, i.e. attractive and repulsive forces. Such forces will operate even at zero shear rates and may explain the observed yield values.

As the shear rate increases, hydro-dynamic interactions increase. If the droplets carry charge, electrostatic interactions will also affect the flow. Both hydrodynamic and electrostatic interactions are expected to result in increased internal friction when the volume fraction of water-droplets increases. When the concentrations of emulsifiers and wetting agent were increased, however, the power law index decreased, indicating reduced internal friction. Furthermore, n was found to be nearly independent of the volume fraction of water. It is suggested that this is related to an improved dispersion of solids in the oil phase, i.e. the weight material, the fluid loss additive and the organophilic clay. The weight material used, trimanganese tetraoxide, has been found to be wetted by both oil and water. By the preparation of this OBM, the weight material was dispersed in the oil phase. It has been shown, by separate tests, that addition of both emulsifiers and wetting agent reduced the viscosity of a dispersion of the weight material in oil.

Interesting interactions, affecting the power law index, are found between: emulsifiers and lime (1x3), lime and fluid loss additive (3x5) and lime and wetting agent (3x4). The effect of the lime could be to increase the alkalinity of the system and thereby effecting the ionisation of some of the additives and/or to increase the charge on the surface of the water-droplets. An increase in the interaction between emulsifier and lime (1x3) results in a higher n as would be expected if electrostatic interactions became more important. The interactions between lime and fluid loss additive (3x5) and lime and wetting agent (3x4) are more difficult to explain. It should, however, also be kept in mind that the two-factor interaction alternatively may be explained as three-factor interactions as shown in Table1.

CONCLUSIONS

The Herschel-Bulkely model was found to give the best description of the rheological properties of the OBM. The relations between the rheological parameters of this model and the variables (the O/W-ratio and the concentrations of emulsifiers, fluid loss additive, wetting agent and lime) were established. The main conclusions were:

1. The yield value of the fluids was affected mostly by the O/W-ratio of the OBM. The yield value increased with increasing volume fraction of water. This is believed to be due to colloidal forces operating between the water droplets.
2. The power law indexes of the fluids were nearly independent of the O/W – ratio. The variables found to have the largest effect on the power law index, were the concentrations of emulsifiers and wetting agent. The power law index decreased as the concentrations of emulsifiers and wetting agent increased. The reduction in internal friction observed is believed to be due to an improved dispersion of solids in the oil phase.

The results above allow for tailor-making of the rheological properties of the OBM since the yield value and the power law index of the muds may be manipulated independently within the intervals studied.

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