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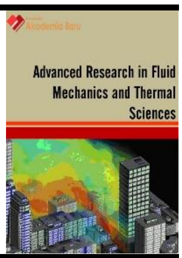

Statistical Relationship of Drilled Solid Concentration on Drilling Mud Rheology

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ABSTRACT

Drilled solid is a continuous contaminant in drilling mud during drilling operation. The purpose of this study is to evaluate the statistical correlation of drilled solid concentration on mud rheology. A Spearman's correlation was used to determine the relationship between 31 mud rheology data and the drilled solid concentration data from North Kuwait Field. Four rheological models were used to compare the rheological behaviour of the drilled solid-laden drilling fluid which were Bingham Plastic, Power Law, Herschel-Bulkley and Robertson-Stiff Model. Results showed that a positive monotonic relationship was observed between all drilled solid concentration and mud rheology parameters. An excessive relationship was observed between drilled solid concentration and mud density with a Spearman coefficient (ρ) of 0.942. Other mud rheology parameters such as plastic viscosity, yield point and gel strength show a significant (high) relationship with a spearman coefficient (ρ) in between 0.833 and 0.704. Flow curves of the drilled solid-laden drilling fluids used in this study can be well depicted by the Herschel-Bulkley and Robertson-Stiff Model. These results are not only support the justifiable attention given to address drilled solid impact to the mud rheology, but they also proposed a statistically approach in preparing data for analysis.

1. Introduction

Drilling fluid or drilling mud is characterized as shear-thinning and time dependent fluid whereby it can promote the transportation of cuttings to the surface during drilling and remain suspended when the circulation stops. Suitable rheology of the drilling fluid is important to avoid solid

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sedimentation during stops and prevent damages such as stuck pipe, loss of circulation, high overpull margin, drill bit jamming and increase in bit torque when the system restart operation [1,2]. The cuttings generated during drilling are dispersed in the mud. Cuttings are removed from the fluid using solids-control equipment at the drill site and the valuable drilling fluid is returned to the active system [3]. However, small amounts of drilled solids are occasionally unavoidable and is re-circulated back to the active system due to insufficient settling time, inefficient mechanical separation equipment, the type of formation being drilled, and the type of drilling fluid being used. Serious problems can develop if these small percentages of drilled solids are continually re-circulated and acted as contaminants. According to Lily [41], the solid particle size that is less than 5 microns could not be removed by mechanical methods, and they will stay in the mud forever and may deteriorate the mud properties over time. The degree of contaminating effect exhibited by these drilled solids depends largely on their size, shape and concentration [4,5]. A study by Du *et al.,* [6] showed that the concentration and size of the drilled solid gave combined effects to the rheology of cuttings-laden mud and the Herschel Buckley model is suitable to describe its rheological behavior [6]. Nevertheless, the shape and size of the drilled solid generated is a function of the bit types used [7]. Hence, these parameters cannot be controlled and are not being covered in this study except for the concentration of the drilled solid.

Effects of drilled solid on rheology has been studied experimentally by the previous researchers over the last decade [4,6,8]. However, the effects of drilled solid on mud rheology have been observed but not statistically proven. There are many statistical correlation methods that can justify the relationship between data such as Pearson product-moment correlation coefficient method for normal distribution data and Spearman rank correlation coefficient method for non-normal distribution data [9-14]. The decision of which method to be used for analysis was made based on the normality of the data. Spearman rank correlation coefficient method was initially proposed by Charles Spearman as a measure of the quality of a relationship between two factors and is a measure of a monotone affiliation that is utilized when the seizure of data makes Pearson's relationship coefficient undesirable or misleading [10]. It is also less sensitive to the influence of outliers [15]. Unlike Pearson's product-moment correlation coefficient, Spearman's correlation coefficient is not a measure of the linear relationship between two variables, but it assesses how well an arbitrary monotonic function can describe the relationship between two variables, without making any assumption about the frequency distribution of the variables and there is no requirement for normality [16]. A monotonic relationship is a relationship that does one of the following: (1) as the value of one variable increases, so does the value of the other variable; or (2) as the value of one variable increases, the other variable value decreases. The monotonic and non-monotonic relationships are presented in Figure 1 [17]. This research will focus on the statistical correlation between drilled solid concentration on mud rheology. The findings are noteworthy because of the limited data in literature looking at the strength of relationship between all those parameters and this outcome is significant in order to provide better rheological modelling on the drilled solid-laden drilling fluid.

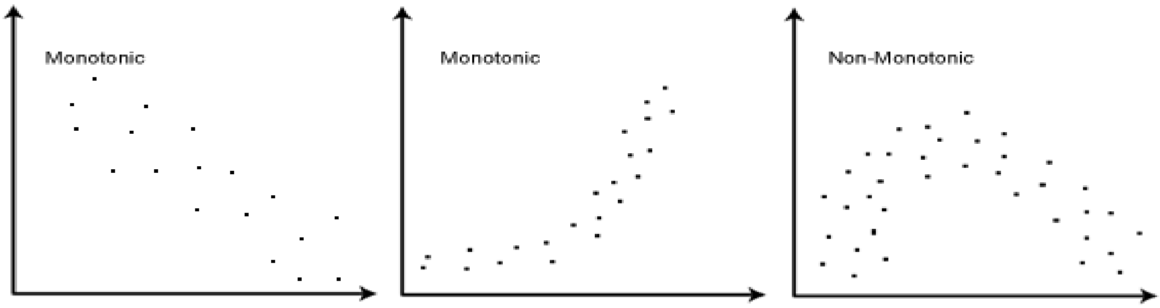


Fig. 1. Monotonic and non-monotonic data relationships for spearman correlation [17]

2. Methodology
2.1 Received Data

Mud properties data of a well drilled in North Kuwait field were gathered from daily drilling reports and daily mud reports. Data were taken at different hole sections from the depth of 1,215 ft until 8,952 ft and are summarized in Table 3 and Table 6.

2.2 Data Preparation

Data was prepared for analysis to investigate (1) the relationship between drilled solid and mud rheology such as density, plastic viscosity (PV), yield point (YP), gel strength-10 seconds (GS-10s), gel strength-10 minutes (GS-10m), gel strength-30 minutes (GS-30m) and (2) their rheological model property [11]. A boxplot graph was initiated to test for any data outliers. Then, the normal probability plot and the Anderson Darling Normality Test were used as a basic descriptive statistic test to check the normality of the data. Probability plot provides graphical method to assess normality while the Anderson Darling method provides a hypothesis test for normality. The Anderson Darling method is different from other hypothesis tests because it is used to prove the null hypothesis (H_0) rather than disprove it [18]. If the p-value is less than the 0.05, the null hypothesis will be rejected in agreement with an alternative hypothesis (H_a) that the data is not normal [19]. But if the p-value is greater than 0.05, there is a reasonable chance that the data could be normally distributed. Non-normally distributed data need to be transformed into a normal distribution depending on the skewness of the data. However, if the data cannot be transferred into a normal data, a non-parametric statistical tool can be utilized [9]. This suggests the use of Spearman Correlation method for non-normal data.

2.3 Statistical Data Correlation Analysis

Statistical correlation analysis was conducted using Spearman rank correlation coefficient method for non-normal distribution data [9,10,15–17,20–28]. This analysis was conducted using Minitab 18 Software. Spearman correlation coefficient (ρ) produces a correlation coefficient that ranges from –1 to +1. The ρ values close to either +1 or –1 constitutes strong correlation whereas values that are near to zero are likely to prove non-significant and no relationship between the variables. A negative value indicates that the relationship is negative. In other words, as one variable increases, the other variable decreases and vice versa. However, a positive value indicates a positive relationship between the variables. In other words, as one variable increases, the other variable increases as well [9]. The strength of the correlation can be categorized using the following guide in Table 1.

Table 1
Spearman's correlation coefficient: Strength indicator [28,29]

Correlation Coefficient	Strength indicator
0.90 – 1.00 (-0.90 to -1.00)	Very high positive (negative) correlation
0.70 – 0.90 (-0.70 to -0.90)	High positive (negative) correlation
0.50 – 0.70 (-0.50 to -0.70)	Moderate positive (negative) correlation
0.30 – 0.50 (-0.30 to -0.50)	Low positive (negative) correlation
0.00 – 0.30 (-0.00 to -0.30)	Negligible correlation

A scatterplot was used to represent the correlation coefficient that exists between two factors. However, it is possible for a scatter plot to suggest a correlation between two factors when in fact none exists especially when a random and small sample size data are taken [18]. As such, it is necessary to evaluate its statistical significance as to whether the data is real or not. The statistical significance was determined based on Null hypothesis where a correlation exists when p-value is less than 0.05. If the p-value is more than 0.05, it indicates that no correlation exists [18]. Spearman correlation was done using the rank of data. The original data had to be converted into rank prior to Spearman correlation analysis [10]. The data with the highest value was ranked as "1" and the lowest data value was ranked according to the number of cases available.

2.4 Determination of Rheological Model Parameters

There are four established rheological models used to describe the rheological behavior of field measured data parameters which are Bingham plastic model, Power law Model, Hershel-Buckley model and Robertson-Stiff model. The summary of the rheology models is shown in Table 2.

Table 2
Summary of rheological models used [28-30]

Rheological model	Equation	Legend
Bingham plastic	$\tau = \tau_0 + \mu_p$ $\tau_0 = \theta_{300} - \mu_p$ $\mu_p = \theta_{600} - \theta_{300}$	τ_o = yield point (lb/100ft^2); μ_p = plastic viscosity (cP)
Power Law	$\tau = k\gamma^n$ $n = 3.32log\left(\frac{\theta_{600}}{\theta_{300}}\right)$ $k = \frac{\tau}{\gamma^n} = \frac{\theta_{600}}{1022^n}$	n = fluid flow behaviour index and dimensionless; k = consistency coefficient (lb/100ft^2) which can be converted to Pa by multiplying with a factor of 0.51 [31].
Herschel-Bulkley	$\tau = \tau_{0H} + k_H\gamma^{n_H}$	γ = shear rate (s^{-1}); τ= shear stress (Pa); n_H = flow behaviour index (dimensionless); k_H= Herschel-Bulkley consistency index (Pa.s^n); τ_{oH} = Herschel-Bulkley yield stress (Pa). The parameters of k_H and n_H can be determined by linearizing the equation with a plot of log ($\tau - \tau_{oH}$) versus log (γ). This plot will result in a straight line with intercept (log k_H) and slope (n_H) respectively.
Robertson-Stiff	$\tau = A(\gamma + C)^B$ $C = \frac{\gamma_{min}\gamma_{max} - \gamma^{*2}}{2\gamma^* - \gamma_{min} - \gamma_{max}}$ $\tau^* = (\tau_{min} \times \tau_{max})^{\frac{1}{2}}$	A, B, and C are model parameters. A and B can be considered similar to the parameters k and n of the Power-law model. The third parameter C is a correction factor to the shear rate, and the term (γ+C) is considered effective shear rate. γ* is the shear rate value corresponding to the geometric mean of the shear stress, τ*.

All these models are categorized under non-Newtonian fluid model whereby the fluid viscosity is not constant but as a function of the shear stress and/or the dominant shear rate [32,33]. Prior to this analysis, the viscometry data from Table 3 was converted into shear stress-shear rate data.

Table 3
Viscometer reading at different concentrations of drilled solid

MD check (ft)	Hole Section	Mud Type	Mud Weight	DS (Vol%)	Viscometer Rotational Speed (rpm)					
					600	300	200	100	6	3
					Viscometer Reading					
3300 – 3630	16”	WBM	8.8 – 9.2	1.40	34	24	19	14	7	6
3630 - 4145				2.91	38	27	22	16	8	7
4145 - 4680				2.38	37	26	22	16	7	6
6150 - 6720	12.25”	OBM	11.0 – 11.4	3.72	68	42	38	26	8	7
7100 -7530				4.69	75	48	41	30	10	9
7610 - 8395				5.13	78	49	42	33	10	9

Conversion of rpm to shear rate (sec-1) for Fann 35A six speed model viscometer is given by the Eq. (1) based on its geometry of the rotor and bob. The shear stress from this instrument is taken from the dial reading (R) and converted into Eq. (2). A suitable rheological model for the field measured data was selected based on the Absolute Average Percentage Error (ϵ_{AAP}) value using Eq. (3).

$$\textit{Shear rate (sec-1)} = \textit{rpm x 1.703} \tag{1}$$

$$\textit{Shear stress (Pa)} = \textit{R x 0.51} \tag{2}$$

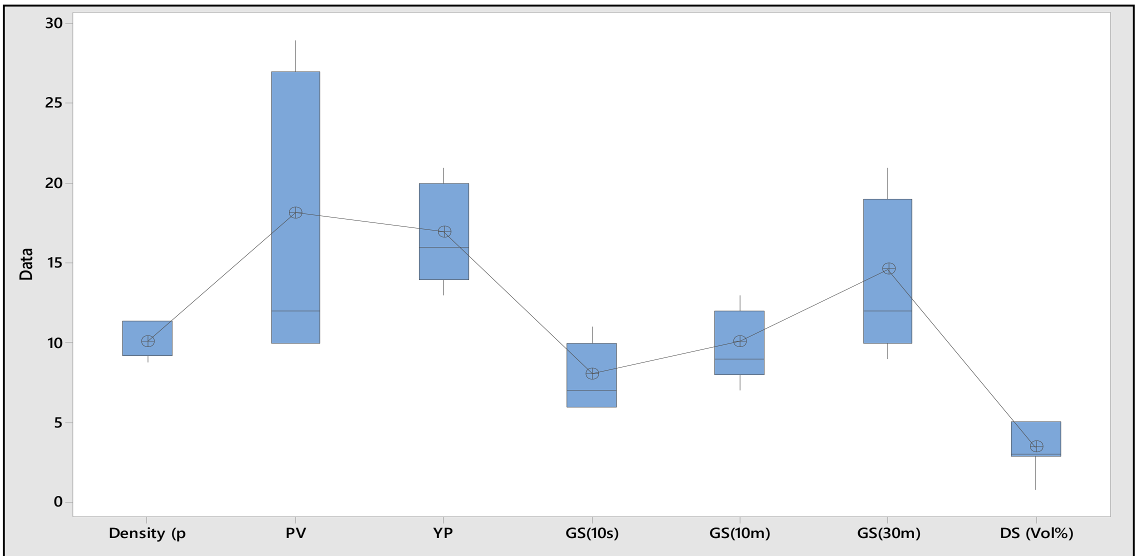
$$\epsilon_{AAP} = \left[\frac{1}{N}\sum\left|\frac{\tau_{measured}-\tau_{calculated}}{\tau_{measured}}\right|\right] \times 100 \tag{3}$$

3. Results

3.1 Relationship Between Drilled Solid and Mud Rheology

Thirty-one samples of mud rheology data such as density, plastic viscosity (PV), yield point (YP), gel strength (GS for 10 seconds, 10 minutes and 30 minutes) and drilled solid concentration data (DS) were utilized in these analyses. The drilled solid concentrations of the received data were in between 0.5 to 5.1 percent in volume (vol%). A boxplot graph was used to test for any outliers in the data where any data points falling outside the boxplot minimum and maximum limits are outliers [9]. The minimum and maximum values can be observed through the vertical line (whiskers) attached to the box while the horizontal line in the box indicates the median. The dotted-circle mark in the box indicates the mean value and the box itself represents 50% of the data [18]. Based on Figure 2, it was observed that there were no outliers shown in the graph. PV appears to have lower median data than YP while GS(10s) appears to have lower median data than those from GS(10m) and GS(30m). Among all these parameters, PV indicates a wider range in values while density shows a more condensed value. In overall, all the boxes show a skewed right data where the longer part of the box is to the above of the median. This indicates that the data were possibly not normal. A normal probability plot was used to confirm the normality of the data.

Based on the normal probability plot (Figure 3), it was obvious that the normality assumption was not fulfilled by the response variables. The structure of the plot in Figure 2 displays the deflections in point whereby the curvature evinces bimodality. In addition, Table 4 shows the Anderson Darling Normality test results and it was observed that all the measurements demonstrated the p-value of less than 0.05. Thus, there is enough evidence to say that the normality assumption was contravened in this case. The data also failed to be transformed into a normal distribution data. As such, a non-parametric test (Spearman rank correlation method) was used to assess the relationship between drilled solid and mud rheology. Hence, the first step was to convert the original data in Table 6 into ranks before calculating the Spearman correlation coefficient and this is summarized in Table 5.



Statistics	Density (p	PV	YP	GS(10s)	GS(10m)	GS(30m)	DS (Vol%)
N	31	31	31	31	31	31	31
Mean	10.110	18.161	16.968	8.0645	10.097	14.613	3.4803
StDev	1.1508	8.4147	2.8923	1.9483	1.9554	4.3411	1.5232
Minimum	8.8	10	13	6	7	9	0.77
Maximum	11.4	29	21	11	13	21	5.16

Fig. 2. Boxplots graph for Mud Rheology and Drilled Solid concentration data

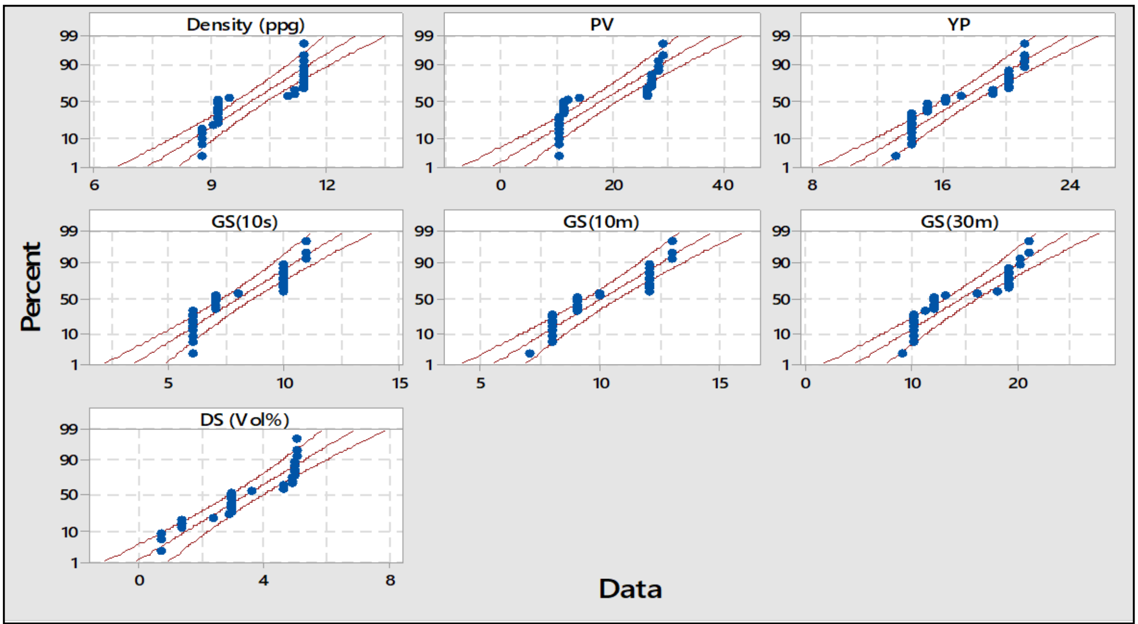


Fig. 3. Normal probability plot of original Mud Rheology and Drilled Solid concentration data

Table 4
Anderson Darling Normality test results

Sample	Sample size	Mean	Std. Dev	Anderson Darling Normality Test	
				P-value	*Decision*
Density	31	10.11	1.15	<0.005	Fail
PV	31	18.16	8.41	<0.005	Fail
YP	31	16.97	2.89	<0.005	Fail
GS (10s)	31	8.06	1.94	<0.005	Fail
GS (10m)	31	10.10	1.96	<0.005	Fail
GS (30m)	31	14.61	4.34	<0.005	Fail
Drilled Solid	31	3.48	1.52	<0.005	Fail

Table 5
Rank data for Spearman correlation analysis

Data entry	Hole Section	MD (ft)	Rank Density	Rank PV	Rank YP	Rank GS 10sec	Rank GS 10min	Rank GS 30min	Rank DS
1	22.00	1,215	4	5	5	4	4	8	11
2	16.00	1,500	7	6	5	4	4	7	13
3		2,270	7	8	6	4	4	7	13
4		3,300	7	8	6	4	4	7	13
5		3,500	7	8	7	4	4	7	12
6		3,630	7	8	7	4	4	7	12
7		4,145	6	7	5	4	3	6	9
8		4,680	5	7	6	5	4	7	10
9		4,680	5	7	7	5	5	9	8
10		4,680	5	7	7	5	5	9	8
11		5,445	5	7	7	5	5	9	8
12		6,006	5	8	7	5	5	9	8
13		6,150	5	7	7	5	5	9	8
14		6,150	5	8	7	5	5	9	8
15		6,150	5	8	7	5	5	9	8
16		6,150	5	8	8	5	6	10	8
17		6,150	5	8	6	5	5	9	8
18	12.25	6,720	3	4	4	3	3	5	7
19		7,100	2	3	2	2	2	4	5
20		7,530	2	3	1	2	2	3	6
21		7,610	1	2	1	2	1	2	1
22		7,990	1	1	2	1	1	1	2
23		8,395	1	1	2	1	1	1	2
24		8,952	1	3	2	2	2	3	3
25		8,952	1	2	1	1	2	2	3
26		8,952	1	2	1	2	2	3	3
27		8,952	1	3	3	2	2	3	3
28		8,952	1	3	3	2	2	3	3
29		8,952	1	4	2	2	2	3	4
30		8,952	1	4	2	2	2	3	4
31		8,952	1	4	2	2	2	3	4

Table 6
Well Data Information

Data Entry	Hole Section	MD (ft)	Density (ppg)	PV (cP)	YP ($lbf/100ft^2$)	GS 10sec ($lbf/100ft^2$)	GS 10min ($lbf/100ft^2$)	GS 30min ($lbf/100ft^2$)	DS (Vol%)
1	22.00	1,215	9.50	14	16	7	9	11	1.41
2	16.00	1,500	8.80	12	16	7	9	12	0.77
3		2,270	8.80	10	15	7	9	12	0.77
4		3,300	8.80	10	15	7	9	12	0.77
5		3,500	8.80	10	14	7	9	12	1.40
6		3,630	8.80	10	14	7	9	12	1.40
7		4,145	9.10	11	16	7	10	13	2.91
8		4,680	9.20	11	15	6	9	12	2.38
9		4,680	9.20	11	14	6	8	10	3.01
10		4,680	9.20	11	14	6	8	10	3.01
11		5,445	9.20	11	14	6	8	10	3.01
12		6,006	9.20	10	14	6	8	10	3.01
13		6,150	9.20	11	14	6	8	10	3.01
14		6,150	9.20	10	14	6	8	10	3.01
15		6,150	9.20	10	14	6	8	10	3.01
16		6,150	9.20	10	13	6	7	9	3.01
17		6,150	9.20	10	15	6	8	10	3.01
18	12.25	6,720	11.00	26	16	8	12	17	3.72
19		7,100	11.20	27	20	10	12	18	4.74
20		7,530	11.20	27	21	10	12	19	4.69
21		7,610	11.40	28	21	10	13	20	5.16
22		7,990	11.40	29	20	11	13	21	5.13
23		8,395	11.40	29	20	11	13	21	5.13
24		8,952	11.40	27	20	10	12	19	5.10
25		8,952	11.40	28	21	11	12	20	5.10
26		8,952	11.40	28	21	10	12	19	5.10
27		8,952	11.40	27	19	10	12	19	5.10
28		8,952	11.40	27	19	10	12	19	5.10
29		8,952	11.40	26	20	10	12	19	4.97
30		8,952	11.40	26	20	10	12	19	4.97
31		8,952	11.40	26	20	10	12	19	4.97

Spearman coefficient analysis revealed statistically significant evidence that the drilled solid concentration is positively influenced by the mud rheology parameters with the P-value of less than 0.05 as shown in Table 7. Figure 4 also shows that all the variables are positively monotonic correlated. There was a very strong positive correlation between drilled solid concentration and density with a Spearman coefficient (ρ) of 0.942, followed with PV, GS-30m, GS-10m, GS-10s and YP with a positive Spearman coefficient (ρ) of 0.833, 0.716, 0.715, 0.711 and 0.704 respectively. The drilled solid concentration positively influenced the mud rheology be theoretically, as the volume percent of drilled solids increases, the density increases. Typically, drilled solids have a specific gravity (SG) in the range of 2.1 to 2.8 [34]. Since the SG of mud used for drilling this well is in between 1.05 to 1.37, the addition of higher SG of drilled solid will dramatically increase the fluid's density.

Plastic viscosity (PV) is another parameter that demonstrates a strong relationship with drilled solid concentration. However, its effectiveness was not as great as density because it depends on the reactivity scale or swelling ability of the solid into the mud. Swelling solid like clay can increase the PV of the mud while low-swelling clay or inactive solid may not really affect the PV [35]. Furthermore, it also depends on the type of the base mud used. Theoretically, when the free water in water-based mud is chemically attached to the solids, it will gradually increase the internal friction between particle and fluid, and also increase the fluid's viscosity. However, excessive and insufficient PV is unfavourable as it will reduce the ability to bring the cuttings to the surface and allow the cuttings to be grounded into a smaller size. In practical field application, PV is generally used as a guide for solid control where the removal of drilled solid from drilling fluid will decrease PV [36,37].

Moreover, Gel strength (GS) is a rheological measurement taken after varying the length of static condition such as 10 seconds, 10 minutes and 30 minutes. It relates to the suspension capacity of drilling fluid at rest [38]. The suspension capacity of the drilling fluid is important as it helps in hole cleaning. It prevents the differential sticking as well as accumulation of cuttings that causes the pressure build up and frac out. Severe increase in GS can exert excessive subsurface pressure when flow is re-established making them more problematic. High GS is not desired for removing cutting through gravity settling at surface. Based on Table 7, DS concentration has also affected the GS significantly. The correlation is greater for GS-30m as compared with GS-10s and GS-10m. This suggests that close monitoring of GS-30m should be more vigorous for drilled solid build-up. In a condition where the mud has high GS and the mud is static for a long period, the subsequent build-up of pressure in the pump is required to break circulation. Hence, further treatment is needed to reduce the progressive gel build-up such as addition of chemicals or perform dilution. Many drilling fluids have thixotropic properties where it becomes gel in static condition and will flow over time when sheared or stressed [36].

In addition, DS concentration was also a strong contributor to the positive association of YP (ρ = 0.704). This is consistent with previous work which showed that YP rises while DS concentration increases [36]. Yield point (YP) is the initial resistance to flow caused by the electrochemical forces between the particles. Increase in solid content decreases the interparticle distance and consequently increases the forces between the drilled solid and other mud particles. This would result in difficulty for solid removal at the shale shaker as it cannot handle the smaller mesh screen size [36].

Table 7
Spearman Rho of the relation between drilled solid concentration and mud rheology parameters

Content	Density	PV	YP	GS (10s)	GS (10m)	GS (30m)
Spearman ρ	0.942	0.833	0.704	0.711	0.715	0.716
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
Strength	Very strong	Strong	Strong	Strong	Strong	Strong

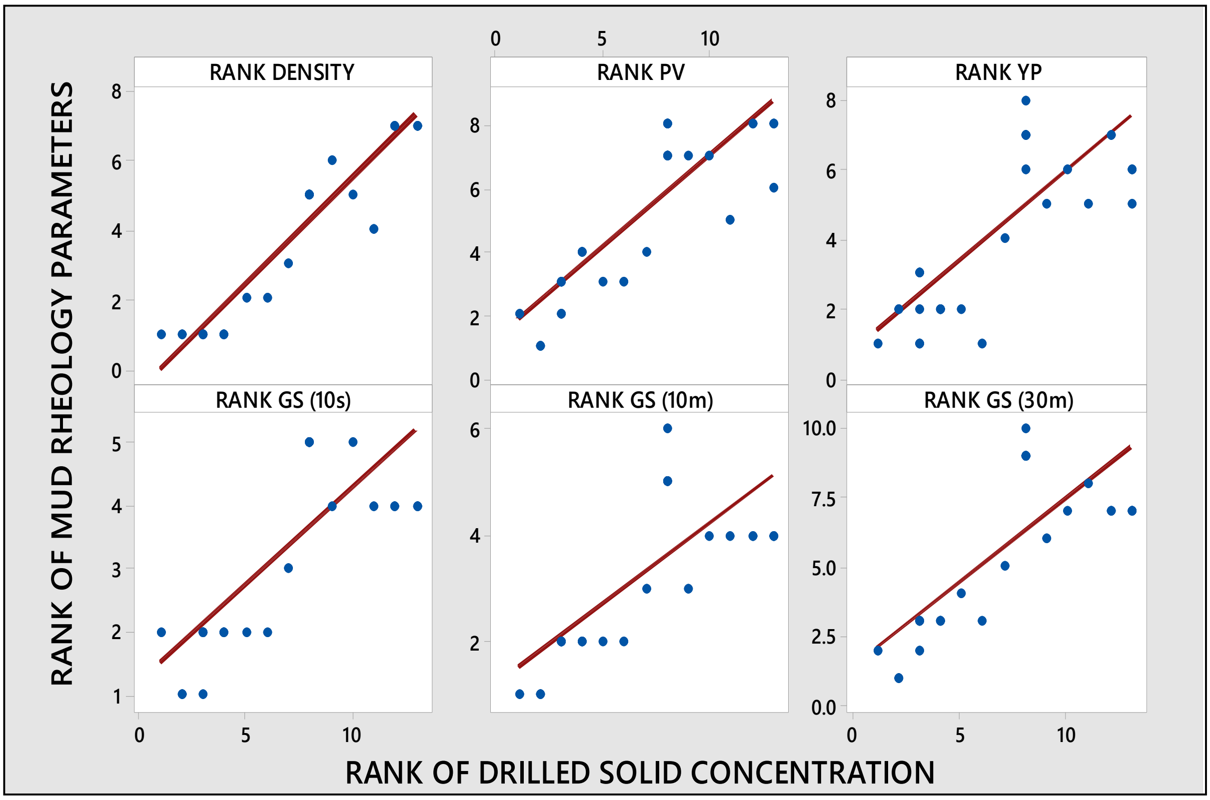


Fig. 4. Scatterplot of Mud Rheology Parameters Rank vs Drilled Solid Concentration Rank

3.2 Rheological Model Property

Table 8 shows the summary of two different mud systems used for drilling the well which are Water based mud (WBM) and Oil-based Mud (OBM). It is noteworthy to identify their rheological models in order to predict the shear stress-shear rate behaviour of both systems. Four models were compared which are Bingham Plastic, Power Law, Herschel-Bulkley and Robertson-Stiff using the flow curve of the shear stress vs. shear rate plots. The results are shown in Figure 5 (WBM) and Figure 6 (OBM). According to these two plots, the flow curve is curvilinear and an intercept of flow curve at the vertical axis shows a yield stress value of the samples. WBM appears to have a lower shear stress value compared to OBM due to a smaller amount of drilled solid presence in this mud. An abrupt increase in shear stress was observed for OBM at low shear rate due to the higher density of this region than the WBM. Selection of the best goodness-of-fit model was done based on its Absolute Average Percentage Error (ϵAAP) between the models and field data in which the closer the error to zero, the better the fit is [32]. Table 9 shows that Bingham Plastic model was not suitable for the both mud systems (WBM and OBM) due to the straight flow curve especially for high shear stress mud (OBM) with the absolute percentage error of 32.11%. It was also observed that the poor performance of Bingham model was due to the large deviation of predicted shear stress at high shear rates for both systems. The Power Law model showed a poor fit to both systems due to the lack of the yield stress in this model as compared to the field measured data. The best fitting model would be Herschel-Bulkley model followed by Robertson & Stiff model with the absolute average percentage errors of less than 5% for both systems. These models used non-linear shear-stress rate behaviour along with a yield stress that could cater a high yield stress mud [36]. This finding is consistent with previous published work that used KCL-polymer mud in their analysis and had selected Herschel-Bulkley model for that system [6]. However, Du *et al.,* [6] studied the effects of mudstone cuttings addition into KCl-polymer mud whilst this study generally focused on the effects of drilled solid mainly from limestone cuttings (based on major limestone formation in North Kuwait field) into water-based mud and oil-based mud. Similar with our case, J. Sadigov [39] conducted rheology model prediction using field measured data [39]. They proposed the least error model was Robertson-Stiff (1.93% error) followed by Hershel Buckley (4.25% error), Power Law (6.55% error) and the highest error was Bingham Law model (26.79%). However, the type of mud system used was not mentioned in their study, thus, these results are not directly comparable to theirs. As such, it is noteworthy to mention that different application of rheological model is required for different mud system and selection of proper rheological model is important for further analysis on the frictional pressure losses or pressure drops associated with the flow of the drilling fluids in the wellbore [40].

Table 8
Summary of Shear Stress Values of drilled solid-laden water-based mud (DS_{conc} = 2.91 vol%) and oil-based mud (DS_{conc} = 5.13 vol%) using Different Rheological Models

Speed (RPM)	Dial Reading (lb/100ft^2)	Shear Rate (S^{-1})	Shear Stress Values of drilled solid-laden Water-based mud (DS_{conc} = 2.91 vol%)				
			Measured (Pa)	Bingham Plastic (Pa)	Power Law (Pa)	Herschel-Bulkley (Pa)	Robertson-Stiff (Pa)
600	38	1022	19.38	13.28	19.09	20.00	19.40
300	27	511	13.77	9.19	13.59	13.34	14.04
200	22	340.6	11.22	7.82	11.14	10.78	11.68
100	16	170.3	8.16	6.46	7.93	7.86	8.69
6	8	10.22	4.08	5.18	2.00	4.09	4.13
3	7	5.11	3.57	5.14	1.42	3.88	3.89
Speed (RPM)	Dial Reading (lb/100ft^2)	Shear Rate (S^{-1})	Shear Stress Values of drilled solid-laden Oil-based mud (DS_{conc} = 5.13 vol%)				
			Measured (Pa)	Bingham Plastic (Pa)	Power Law (Pa)	Herschel-Bulkley (Pa)	Robertson-Stiff (Pa)
600	78	1022	39.78	19.89	39.46	47.82	40.35
300	49	511	24.99	12.50	24.80	27.28	25.91
200	42	340.6	21.42	10.03	18.90	20.15	20.16
100	33	170.3	16.83	7.56	11.88	12.76	13.45
6	10	10.22	5.1	5.25	1.80	5.19	4.86
3	9	5.11	4.59	5.17	1.13	4.90	4.48

Table 9
Summary of Absolute Average Percentage Error, ϵAAP of drilled solid-laden water-based mud (DS_{conc} = 2.91 vol%) and oil-based mud (DS_{conc} = 5.13 vol%) using Different Rheological Models

Mud system	Absolute Average Percentage Error, ϵ_{AAP}			
	Bingham Plastic (Pa)	Power Law (Pa)	Herschel-Bulkley (Pa)	Robertson & Stiff (Pa)
WBM	7.49	19.59	0.23	3.81
OBM	32.11	30.47	1.30	4.66

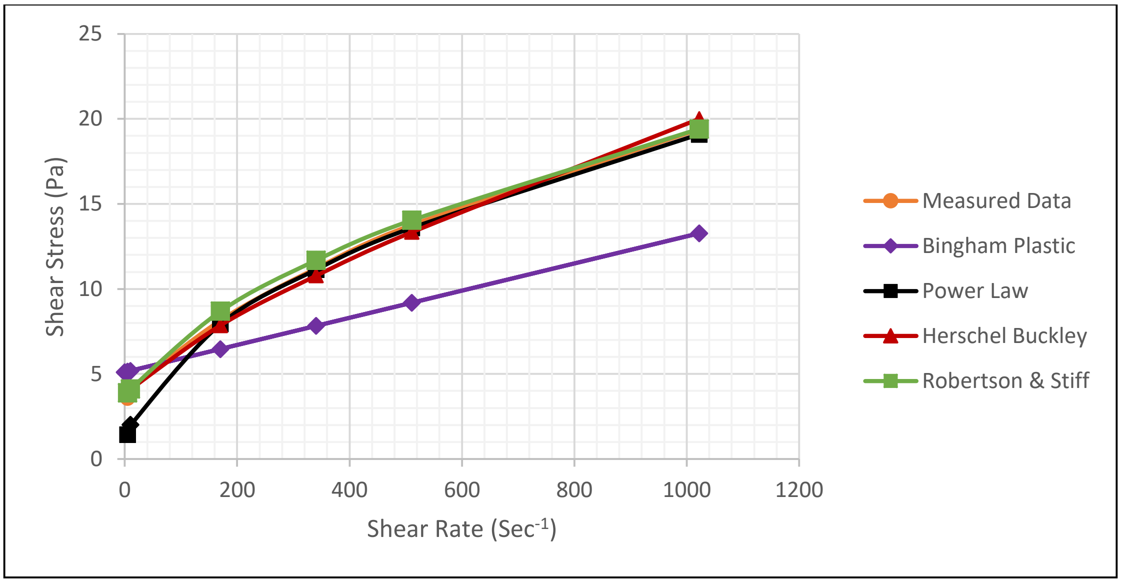


Fig. 5. Shear Stress-Shear Rate Graph of drilled solid-laden water-based mud (DS_{conc} = 2.91 vol%) using Different Rheological Models

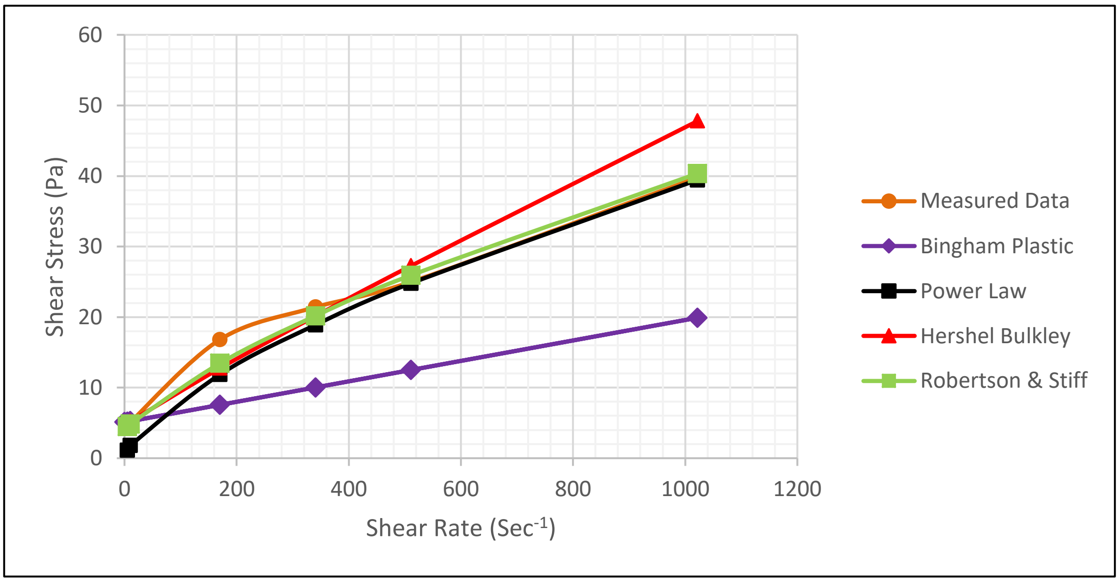


Fig. 6. Shear Stress-Shear Rate Graph of drilled solid-laden oil-based mud (DS_{conc} = 5.13 vol%) using Different Rheological Models

4. Conclusions

Based on the field data collected from North Kuwait field, it can be concluded that the effects of drilled solid concentration on mud rheology is significant. The highest correlation was found between drilled solid concentration and density followed by plastic viscosity, gel strength (30 min), gel strength (10min), gel strength (10 sec) and yield point. The rheology behaviour for the mud used in this field i.e. water-based mud and oil-based mud are both well depicted by Herschel Buckley and followed by Robertson-stiff model. It is hoped that these findings would stimulate further study on the application of selected models for determining frictional pressure losses, flow regime and their impact towards drilling rate.

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