

# Drilling fluid shear stress overshoot behavior

R. A. Speers, K. R. Holme, M. A. Tung, and W. T. Williamson

University of British Columbia, Vancouver, and Technifluids Research and Development, Calgary, Alberta (Canada)

*Abstract:* Shear stress overshoot behavior was studied in four drilling fluid systems and ten bentonite dispersions. These overshoot properties, also described by the American Petroleum Institute as gel strengths, were measured after gelation times of 10 s to 24 h at temperatures of 20–80 °C. Two different rheometers were used to measure overshoot behavior. Gel strength development with time followed a first-order model. Gel development rates at 20 °C varied from 0.005 to 0.01 min<sup>-1</sup> for drilling fluid systems and from 0.0004 to 0.02 min<sup>-1</sup> for bentonite dispersions. Increasing the gelation temperature for each drilling fluid system caused an increase in the gelling rate constant. Comparison of gel strengths in bentonite dispersions were made using a Fann 35 A viscometer and a Weissenberg Rheogoniometer. Higher gel strength values observed using the Rheogoniometer were believed to be due to differences in instrument spring stiffness and fixture inertia.

*Key words:* Gel strength, shear stress overshoot, drilling fluid, bentonite dispersion

## 1. Introduction

This paper describes an investigation into the shear stress overshoot properties of a number of drilling fluids. The two main objectives of this study were: (1) to measure and model the change in drilling fluid “gel strength” over times of up to 24 h and (2) to determine the effect of temperature on this increase in gel strength. A further objective of this research was to compare gel strength measurements made using a Fann 35A viscometer (Fann Instrument Operations, Houston, Texas, U.S.A.) and a Weissenberg Rheogoniometer (Sangamo-Schlumberger, Bognor Regis, England).

The term “gel strength”, as used by the drilling fluid industry, can be defined as, “the shear stress overshoot which occurs in a previously resting fluid which is suddenly sheared at a rate of 5.11 s<sup>-1</sup>”. This value is normally measured using a Fann 35 A or similar coaxial cylinder viscometer, according to a procedure specified by the American Petroleum Institute (API) [1]. Gel strength values are known to be influenced by drilling fluid shear history and chemical composition.

Recently, Technifluids Research and Development, Calgary, AB, received requests from several oil companies for information on gel strength values after specific resting times and temperatures in offshore drilling fluid systems. Thus, it is important to develop

improved methods for estimating down-hole gel strengths at different resting times and temperatures. It is also important to note how factors such as rotor fixture deflection rates and inertia (which may vary in different rheometers) affect the API gel strength values.

## 2. Background and literature review

Although past literature has dealt with the prediction of the low shear stress properties of bentonite (Garrison [2]) and other fluids [3] there is limited information available on the subject of gel formation in drilling fluids.

The American Petroleum Institute has published a standard method (API, 1982) to determine drilling fluid gel strength. It can be defined as the measurement of the peak stress value (the shear stress overshoot) upon the sudden application of a rate of shear of 5.11 s<sup>-1</sup>. While this value has been used for the determination of formation fracture pressures [4] and has been proposed for use in surge and swab pressure calculations [1], it is a rough estimate of down-hole low shear behavior during initial mud circulation. Factors which can influence down-hole mud gel strengths (and thus, calculated pressures) are the temperature, pressure, shear history, rate of application of shear and the rate

of fluid loss to the surrounding formation (i.e. solids content).

The measurement of API gel strength may also vary between viscometers. Two factors which differ between viscometers are fixture deflection and inertia during the sudden start-up of the test procedure. Coaxial cylinder viscometers which have a large bob inertia and a large bob deflection (relative to the measured shear stress) tend to give low gel strength values.

To date, only Garrison [2] has reported upon the effect of gelation time on the low shear behavior of bentonite dispersions. In his studies he measured the force which was needed to initiate rotation of a cylinder held in a bentonite suspension. The ratio of gelation time to this measurement (or yield stress) was found to be linearly correlated with gelation time. This relationship can be expressed as:

$$G_t = \frac{G_\infty k t}{1 + k t} \quad (1)$$

where  $G_t$  is the gel strength at any time  $t$ ,  $G_\infty$  is the equilibrium gel strength, and  $k$  is the gelation rate constant. Garrison [2] then attempted to justify this empirical relationship on a theoretical basis; however, the present authors have reservations regarding this justification. Eq. (1) appears to be an empirical formula which describes the change of gel strength with time.

An alternative approach would be to model the development of API gel strength over time by the use of first-order kinetic theory. If one assumes that the gel strength value is a measure of the build-up of structure in the drilling fluid and that the rate of structure build-up follows first-order kinetics, then the increase in gel strength can be easily modelled over time. In the case of a first-order reaction, the rate of build-up of product (or gel strength) can be shown to be governed by the following equation:

$$G_t = (G_0 - G_\infty) e^{-k t} + G_\infty \quad (2)$$

where  $G_0$  is the initial gel strength.

Due to the complex make-up of drilling fluids, it is difficult to speculate as to the reaction mechanism which would govern the build-up of structure within the dispersion. Nevertheless it may be reasonable to assume that a rate limiting step within the reaction (or series of reactions) would be first order. For this reason it may be preferable to describe this gelation phenomenon as pseudo-first-order rather than a true first-order reaction.

If the increase of drilling fluid gel strength could be shown to follow eq. (2), then it may also be possible to organize the rate constant and the equilibrium gel

strength with respect to temperature using an Arrhenius-type relationship. Models of this type have been used in this laboratory to predict the change in viscosity of some drilling fluid constituents such as xanthan gum [6]. The Arrhenius equation can be expressed as:

$$\eta = A e^{(\Delta E/RT)} \quad (3)$$

where  $\eta$  is the viscosity at any absolute temperature  $T$ ,  $A$  is the frequency factor,  $\Delta E$  is the activation energy of viscous flow, and  $R$  is the universal gas constant.

### 3. Research plan and experimental methods

#### 3.1 API gel strength procedure

The first portion of this research involved measurement of API gel strength over time at four different temperatures. The drilling fluids examined included four different mud systems and ten different bentonite samples. The four mud systems were as follows:

- a Dispersed Gel-Chemical,
- a Beaufort Lignosulfonate,
- an East Coast Biovert,
- an Extended Gel.

Details of the composition, rheological properties, density and pH of these systems are included in table 1. The ten bentonite samples used were made up to a concentration of 64.2 kg/m<sup>3</sup> and hydrated for 24 hours before testing. Table 2 shows the date sampled, origin and peptization status of each of the ten bentonites used in this study.

For each of the samples studied, API gel strengths were measured using a Fann 35 A viscometer at times of 0.16, 0.5, 1.0, 5.0, 10, 20, 30, 60 minutes and after 2, 4, 8, 16 and 24 hours at room temperature. For times longer than 10 minutes, the opening between the sample cup and rotor of the Fann viscometer was sealed with Parafilm (American Can Co., Greenwich, CT) in order to reduce evaporation.

In the case of the drilling fluid systems, measurements were also made at temperatures of 40, 60 and 80 °C. In this portion of the project, absorbant towels saturated with water were used in place of Parafilm as they proved more effective in preventing sample dehydration. Due to these elevated temperatures, measurements could only be made at times of up to 2 hours at 40 °C and 1 hour at 60 and 80 °C. Examination of the sample at these limits of time and temperature showed no signs of surface drying.

Once these data had been collected, they were examined using a non-linear regression computer program P:3R which is part of the BMDP package

Table 1. Field mud formulations

System	Material	Concentration (kg/m <sup>3</sup> )	Plastic viscosity (mPa · s)	Yield stress (Pa)	API fluid loss (mL)	Initial gel strength (Pa)
1) Dispersed gel chemical 1,440 kg/cm <sup>3</sup> pH 10.5	Bentonite	5.0	15	4.5	11.0	2.0
	Lignosulfonate Dis-	3.0				
	persant Drilled solids	50.0				
2) Beaufort lignosulfonate 1,850 kg/cm <sup>3</sup> pH 10.5	Bentonite	115	(Premixed in fresh water, and used in formulation as shown below)			
	NaOH	2.0				
	Peltex	5.0				
	Beaufort seawater	80.0				
	Soda ash	2.0				
	KCl	30.0				
	NaOH	5.0				
	Premix	20.0				
	Peltex	35.0				
	Drilled solids	200.0				
3) Offshore biovert	PAC	6.0	50	25.0	6.0	5.5
	Mineral oil	80.0				
	Primul	22.8				
	Technimul	17.1				
	Technivis H.T.	28.5				
	Technitrol L.	28.5				
	CaCl <sub>2</sub> brine	20.0				
	CaO	28.5				
	Hematite	(to 1,620 kg/m <sup>3</sup> )				
	Drilled solids	50.0				
4) Extended gel pH 10.5	Bentonite	60.0	11	7.5	Not tested	2.5
	Drilled solids	100.0				
	TF-Ex	0.01				
	(Barite	to 1,100 kg/m <sup>3</sup> )				

Table 2. Origin of bentonite samples

Sample no.	Date sampled	Origin	Peptization status
1	01-09-83	Saskatchewan	Unpeptized
2	02-07-77	Saskatchewan	Unpeptized
3	01-08-80	Wyoming	Unpeptized
4	01-08-80	Wyoming	Unpeptized
5	01-09-83	Wyoming	Unpeptized
6	01-08-80	Wyoming	Unpeptized
7	15-09-83	Wyoming	Unpeptized
8	01-07-83	Saskatchewan	Peptized
9	01-09-83	Saskatchewan	Peptized
10	01-07-83	Wyoming	Peptized

available from the University of California [7]. This program was able to derive the initial gel strength, equilibrium gel strength and gelation rate values in eq. (2) which best fit the data for each of the mud systems and bentonite suspensions tested.

Once the initial and equilibrium gel strengths and gelation rate for each drilling fluid system were calculated, they were examined to determine whether tem-

perature changes had resulted in an Arrhenius-type trend.

### 3.2 Weissenberg Rheogoniometer procedure

A study was also carried out using a Weissenberg Rheogoniometer to measure the gel strength of a 50.0 kg/m<sup>3</sup> bentonite dispersion to compare it with the value, determined with a Fann rheometer. The Weissenberg Rheogoniometer was selected for this comparison as it has relatively low fixture inertia and deflection properties as well as being suitable for interfacing with high speed data logging equipment.

The Weissenberg Rheogoniometer was configured with a no. 8 torsion bar and a coaxial cylinder fixture which had a spindle to cup radius similar to that of the Fann 35 A (see figure 1). The gel strength procedure used with the Rheogoniometer was identical to the API procedure. Gel strength and overshoot stresses from both viscometers were recorded during simultaneous testing of the bentonite dispersions held at 26 °C after resting times of 0.166, 1.00, 5.00, 10.0 and 15.0 minutes.

In order to obtain an accurate and rapid shear stress signal from the Rheogoniometer, the instrument was interfaced with an Apple II microcomputer (Apple Computer Inc., Cupertino, CA) which contained a AI 13 Data Acquisition system (Interactive Structures Inc., Bala Cynwyd, PA). This system was used to record the torsion head transducer output at high speed (1000/s) in order to find the transient peak value or gel strength.

The raw shear stress signal from the Weissenberg Rheogoniometer has been reported to have extraneous electronic noise in the 2000 and 60 Hz regions [8, 9]. In order to remove this electronic noise a frequency domain time series program BMDP-P:1T [10] was used to filter out noise at 60 and 2000 Hz.

Modelling of this filtered data was then attempted using a four-parameter relationship of Leider and Bird [11]. It was hoped that successful modelling of these data would facilitate the determination of the peak torque values [3].

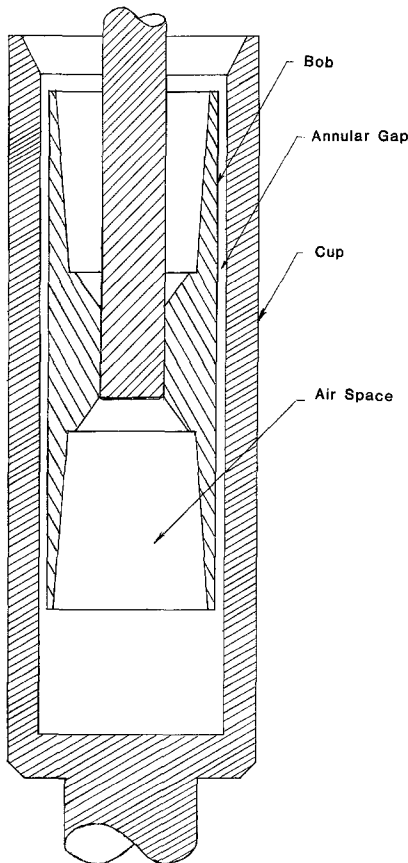


Fig. 1. Schematic diagram of Weissenberg Rheogoniometer coaxial cylinder fixture where spindle diameter is 25.0 mm, height is 75.2 mm and cup diameter is 27.5 mm

## 4. Results and discussion

### 4.1 API gel strength results

The results of this portion of the research were encouraging in that the gel strength values could be modelled by a pseudo-first-order kinetics as described earlier. In all cases the gel strength values increased from an initial value and gradually approached an equilibrium value. Figure 2 shows the increase in gel strengths of the Dispersed Gel-Chemical system. The solid curve in the figure represents the best fit non-linear function as found by the BMDP computer program.

While some scatter is evident about the regression line (due in part to the sensitivity limits of the Fann viscometer), examination of all of the results shows that a pseudo-first-order model can give a good prediction of the change in gel strength with time. Table 3 displays the initial and equilibrium gel strength as well as the rate constant for each drilling fluid system and bentonite dispersion tested. Also included in this table are the coefficients of determination which indicate the goodness of fit of the model to the data.

Some conclusions can be drawn from the results shown in table 3. First, the build-up of gel strength appears to follow a first-order model and can be successfully described by eq. (2). Second, temperature seems to have a varying effect on the different drilling fluid systems examined. No strong Arrhenius-type relationship, eq. (2), was evident between temperature and initial or equilibrium gel strengths, or between temperature and the rate constants. However, there is a

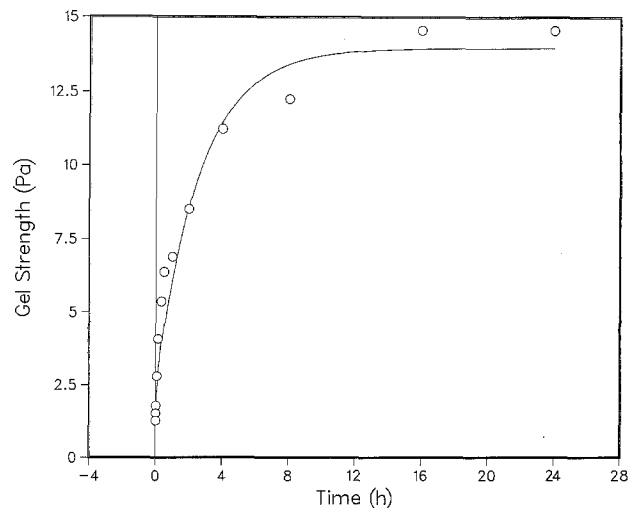


Fig. 2. Increase in gel strength over time for a gel-chemical mud system at 20 °C

Table 3. Results of first-order kinetic fit of gel strength increase with time

Mud system	Temperature (°C)	Initial gel strength $G_0$ (Pa)	Gelation rate $k$ (h <sup>-1</sup> )	Equilibrium gel strength $G_\infty$ (Pa)	Coefficient of determination $r^2$	
Dispersed gel-chemical	20.0	2.43	0.00637	14.0	0.960	
	40.0	2.24	0.0253	4.68	0.986	
	60.0	1.84	0.0280	4.18	0.985	
	80.0	1.83	0.0342	4.28	0.993	
Beaufort lignosulfonate	20.0	4.96	0.00609	16.5	0.908	
	40.0	1.55	0.0535	3.07	0.924	
	60.0	1.64	0.0165	4.83	0.933	
	80.0	1.41	0.0607	3.78	0.964	
E. Coast biovert	20.0	2.65	0.00595	14.1	0.950	
	40.0	1.45	0.0467	7.83	0.991	
	60.0	1.72	0.0681	9.68	0.986	
	80.0	1.98	0.100	11.8	0.996	
Extended gel	20.0	5.78	0.0522	10.9	0.932	
	40.0	5.19	0.172	8.01	0.977	
	60.0	3.93	1.42	4.89	0.923	
	80.0	2.68	0.146	3.91	0.956	
Gel No.	1	20.0	2.53	0.00237	16.6	0.962
	2	20.0	8.05	0.000378	16.6	0.956
	3	20.0	1.76	0.0154	15.0	0.986
	4	20.0	13.7	0.0215	24.5	0.981
	5	20.0	1.11	0.0166	13.6	0.990
	6	20.0	13.5	0.0137	34.0	0.958
	7	20.0	1.19	0.00264	14.3	0.958
	8	20.0	4.51	0.00767	16.0	0.930
	9	20.0	5.18	0.576	10.6	0.954
	10	20.0	3.14	0.0132	14.2	0.913

Table 4. First-order modelling of API bentonite gel strength increase with time as measured by the Fann 35 A and the Weissenberg Rheogoniometer

Viscometer	Initial gel strength $G_0$ (Pa)	Gelation rate $k$ (h <sup>-1</sup> )	Equilib- rium gel strength $G_\infty$ (Pa)	Coefficient of deter- mination $r^2$
Fann 35 A (Dial reading)	2.52	0.112	4.71	0.990
Weissenberg Rheogoniometer	4.56	0.267	7.36	0.988

decrease in the initial and equilibrium gel strength values and an increase in the rate of gel strength development with increasing temperature. This was not unexpected as it is known that temperature has a large effect on the viscosity of water and oil which are the major constituents of these fluids. In addition, one would also expect a reaction rate to increase with increasing temperature.

Caution should be used in extrapolating these values as field experience has shown that high temperature

wells often develop very high gel strengths. Presumably, development of these high gel strengths in the field is due to the mud being subjected to drill hole conditions for longer times than those used in this study.

#### 4.2 Weissenberg Rheogoniometer results

The results of this portion of the study are displayed in figures 3 and 4 and summarized in table 4. Figure 3 shows the raw and filtered shear stress overshoot data obtained from the Rheogoniometer for a 64.2 kg/m<sup>3</sup> bentonite dispersion that had been allowed to rest for 15.0 minutes. These results are typical of the overshoot data from the 5 gelation times examined in this study. Modelling of the filtered data was attempted using the Bird-Leider model [11]. However, this model did not accurately predict the shear stress decline which occurred after a peak (gel strength) was reached. Therefore peak overshoot or gel strength values were selected by visual examination of the filtered data.

Selected gel strength values as well as duplicate Fann 35 A measurements were then modelled by eq. (2). Table 4 shows the results of this modelling while

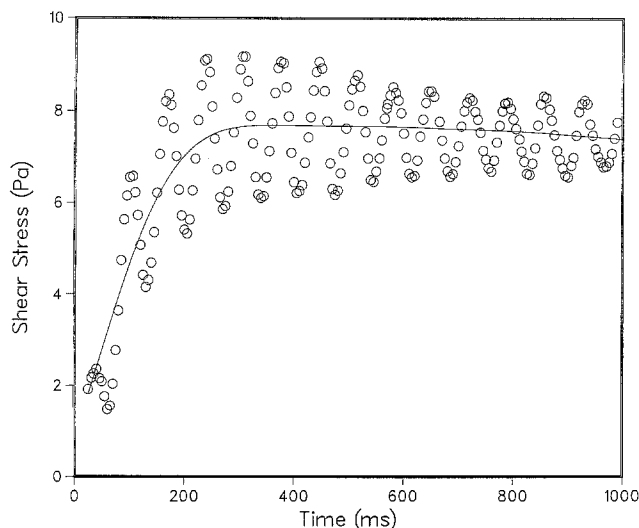


Fig. 3. Weissenberg Rheogoniometer shear stress overshoot data (every 10th data point plotted) before filtering ( $\circ$ ) and after frequency domain time series filtering (—)

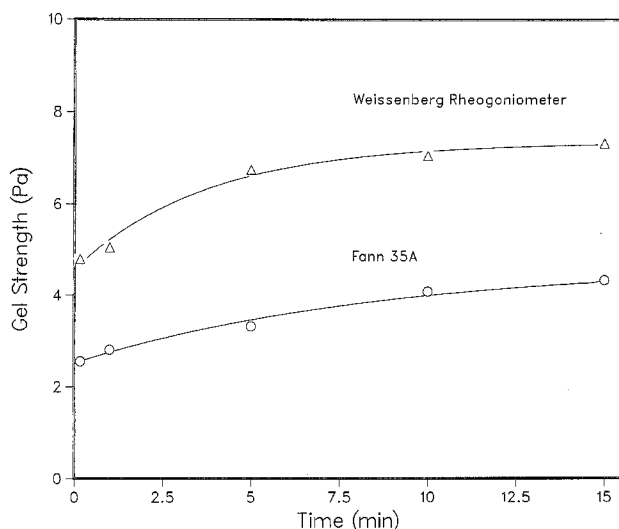


Fig. 4. Increase in gel strength of bentonite dispersion over time as measured by the Fann 35 A and the Weissenberg Rheogoniometer and modelled by eq. (2)

figure 4 displays both the measured data as well as the best fit regression lines for both the Fann 35 and Rheogoniometer data. It is obvious that the Weissenberg Rheogoniometer values are higher than those found with the Fann 35 A.

This is very likely due to the low fixture inertia and high spring stiffness which make the Weissenberg Rheogoniometer a much more sensitive instrument for measurement of actual gel strength values.

## 5. Conclusions

Three conclusions can be drawn from this research. First the API gel strength increase over time can be accurately predicted by first-order kinetic theory. It has also been shown that in general, increasing temperature causes a reduction in initial and equilibrium gel strength values while increasing the gelation rate coefficient. Finally, this research has shown that the Weissenberg Rheogoniometer, a rheometer which has a low fixture inertia and high spring stiffness tends to give higher gel strength values than the Fann 35 A viscometer.

While the Fann 35 A viscometer will continue to be the rheometer used by the majority of oilwell drilling fluid researchers, one should be aware of its limitations when using gel strength data in down-hole pressure calculations.

## Acknowledgements

The authors acknowledge partial support by the Industrial Research Assistance Program of the National Research Council and by the Natural Sciences and Engineering Research Council of Canada.

(Received March 3, 1987)

## References

1. American Petroleum Institute (1982) Standard Procedure for Testing Drilling Fluids. API Bull 13 B, 9th Ed, Dallas TX p. 1
2. Garrison AD (1939) Trans AIME 128:191
3. Dickie AM, Kokini JL (1982) J Food Process Eng 5:157
4. Chenevert ME, McClure LJ (1978) Oil & Gas J 76:(9)
5. Fontenot JE, Clark RK (1974) Soc Pet Eng J 24:451
6. Speers RA, Tung MA (1986) J Food Sci 51:96
7. Jennrich R (1983) in: Dixon WJ (ed) BMDP Statistical Software, University of California Press, Berkeley, CA, p 289
8. Lewis JI, Shoemaker CF (1984) J Food Sci 49:741
9. Lewis JI, Shoemaker CF (1985) Rheol Acta 24:58
10. Dixon WJ (1983) BMDP Statistical Software, University of California Press, Berkeley, CA, p 595
11. Leider PJ, Bird RB (1974) I & EC Fund 13:336

Authors' addresses:

R. A. Speers\*), K. R. Holme, M. A. Tung  
University of British Columbia  
Suite 248 - 2357 Main Mall  
Vancouver, B.C., V6T 2A2 (Canada)

W. T. Williamson  
Technifluids Research and Development  
206-601-17th Avenue S.W.  
Calgary, Alberta, T2S 0B3 (Canada)

\*) To whom correspondence should be addressed