On the Rheological Parameters Governing Oilwell Cement Slurry Stability

Roni Gandelman, Cristiane Miranda, Kleber Teixeira,
André L. Martins and Alex Waldmann

PETROBRAS, Rio de Janeiro, Brazil.

ABSTRACT

Cement slurry stability is a major requirement for successful oilwell cementing, especially in high angle or horizontal wells. The industry has provided different solutions for the subject always regarding the slurry response to standardized sedimentation and stability experiments.

The purpose of the present work is to analyze the rheological properties governing the sedimentation phenomenon. The strategy adopted was to choose a few different slurry systems which behave differently regarding sedimentation and perform their complete rheological characterization in shear flow.

Slurry compositions included conventional and high compacity systems. Rheological tests performed include low shear viscosity besides conventional oilfield rheological analysis. The final purpose is to establish rheological design parameters for different oilwell cementing operations.

INTRODUCTION

The productivity of an oilwell is quite affected by the cementing quality. The cementing job in an oilwell consists on pumping cement slurry into the well with proper physical and chemical properties which enables its displacement through a casing, previously run into the well, and its positioning between the casing and the rock formation.

The main objective of the cementing job is to assure zonal isolation avoiding flow of fluids along the cement sheath. Others objectives of the cementing job are to support the casing and to protect it against aggressive fluids existing in subsurface formations, to seal off abnormal pressure formations, to isolate incompetent formations and to shut off lost circulation zones.

Cement slurries for oil wells are composed by Portland Class G or H cement, water and chemical additives, which may provide the required physical properties. Rheology plays important roles on slurry design:

- In assuring that the cement slurry can be mixed at the surface and can be pumped into the well with minimum pressure drop.
- In governing the flow regime for optimum cement slurry placement.
- In maintaining the solid particles in suspension during the fluid state of the cement slurry.

The main goal of the present article is to establish the physical relations between slurry rheological properties and its tendency to sediment. Slurry sedimentation is a major issue in highly deviated or horizontal wells, where the formation of a free water channel will result in failures on zonal isolation, reducing dramatically the productivity of the well (Fig. 1).

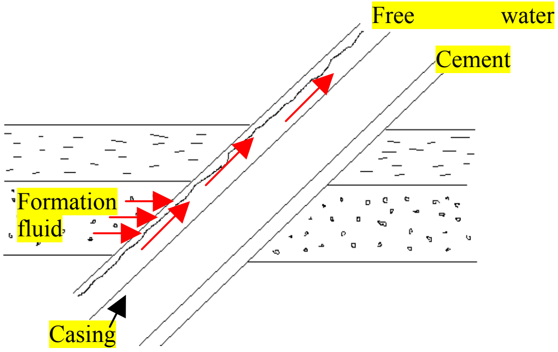

Figure 1. Free water channel

A simplified test matrix is proposed including slurries of different chemical natures and compositions to be evaluated regarding sedimentation and rheology. A brief analysis of the advantages and limitations of oilfield rheometer allows the development of comprehensive guidelines for slurry design.

TEST PROCEDURES

Several experiments were run with the selected slurry systems aiming the evaluation of their sedimentation and rheological behavior. Most experiments follow the American Petroleum Institute report[1]. Some additional rheological experiments were run in order to establish low shear rheology properties. A brief description follows.

Preparation of Cement Slurry Samples

Dry materials are weighed and then uniformly blended before being added to the mixing fluids. The mixer motor is turned on and maintained at 4000 ± 200 rpm. Water and fluid additives are then stirred at the above rotational speed to thoroughly disperse them prior to cement addition. The cement and solid additives blend should be added at an uniform rate, in not more then 15 seconds. After the addition of all dry materials to the mix water, the mixing speed is increased to 12000 ± 500 rpm for 35 seconds. Dry materials (cement and solid additives) and water temperature should be kept at 23.0 ± 1.1 °C prior to the mixing.

Rheology

After the sample preparation, the cement slurry is homogenized at a rotational speed of 150 rpm for 20 minutes in an atmospheric consistometer. The temperature is kept constant at 80 °F. The apparatus used for the test is a concentric cylinder device (Couette Flow) commonly used in the oilfield (Fann VG 35 A). After the homogenization, the slurry is placed at the test vessel. The torque response for each rotational speed provided by the equipment (300, 200, 100 and 6 rpm) (511, 340, 171 and 10 s^{-1}, respectively) is recorded. In fact the equipment also provides readings at 600 and 3 rpm, but they were not considered in this study for the following reasons: there is controversy concerning the guarantee of a laminar rheometric flow at the higher speed for several slurries and there is frequently poor repeatability of readings at the lower speed. With the rotational speed adopted, shear rates ranged from 10–511 s^{-1}. After this, initial and final gel strength measurements are performed, as follows:

- The slurry is submitted to 600 rpm for 1 minute.
- The rotor movement is ceased for 10 s.
- The rotor is started at 3 rpm and the maximum torque value is recorded (initial gel).
- The rotor is ceased for 10 min.
- The rotor is started at 3 rpm and the maximum torque value is recorded (final gel).

Additional rheological experiments were performed: properties were obtained at the rotational rheometer “Advanced Rheometric Expansion System” (ARES, Rheometric Scientific), with cone-and-plate geometry, 50 mm diameter and a gap equal to 0.05 mm.

In these experiments, it is possible to evaluate low shear rate viscosity and viscoelastic behavior. For the present article, only low shear viscosity results are presented. Since time is an important variable on the slurry rheological properties development, different tests were run with the same sample at different times and mixing procedures.

Free Fluid

After the sample preparation, the cement slurry is homogenized with a rotational speed of 150 rpm for 20 minutes in an atmospheric consistometer. The temperature is kept constant at 80 °F. After that, the slurry sample is poured into a clear graduated tube with a precision of 2 mL. The free fluid test slurry volume is 250 mL. The 2 hours test period is initiated when the conditioned slurry is poured into the graduated tube at essentially vibration free conditions. The graduated cylinder is sealed with a plastic film wrap to prevent evaporation. Total water segregation is recorded after 2 hours.

Sedimentation[2]

After preparation, the cement slurry is poured into a sedimentation cylinder until the top. The internal diameter of the sedimentation tube is 25 mm and its length is 200 mm. The slurry is cured for 24 hours. After this time, the cement is removed from the tube. The length of the set cement specimen is measured. The sample is then mechanically divided in four segments of 50 mm. The specific gravity of each segment is measured and the difference between the top and the bottom segments is related to the slurry sedimentation.

Thickening time

A rotating cylindrical slurry container equipped with a stationary paddle assembly essentially forms the equipment used in these tests, named consistometer. The slurry container is rotated at a speed of 150 rpm (2.5 rad/s) ± 15 rpm (0.25 rad/s). The consistency of the cement slurry is indicated by the amount of deformation of a standardized coil spring connecting the stirring paddle and the stationary head. The cement slurry is kept in the container at this constant rotational speed and its consistency time dependency is recorded. The main purpose of this test is to evaluate the evolution of apparent viscosity of the slurry with time.

EXPERIMENTAL WORK

Six different cement slurries were chosen to perform the analysis. The idea was to mix slurries with different formulations where different rheological and sedimentation properties were expected. A brief description of each one follows:

- Slurry A – Contains a pozzolanic material, dispersant, fluid loss additive and accelerator. Specific gravity = 1.67 g/cm^3.
- Slurry B - Cement slurry containing microspheres, retarder and dispersant. Specific Gravity 1.62 g/cm^3.
- Slurry C - Cement slurry containing microspheres, dispersant and retarder. Specific gravity = 1.38 g/cm^3.
- Slurry D - Cement slurry with no additives, just water. Specific Gravity = 1.87 g/cm^3.
- Slurry E - Cement slurry containing retarder. Specific Gravity = 1.92 g/cm^3.
- Slurry F - Cement slurry containing retarder. Specific Gravity = 1.89 g/cm^3

These slurries were classified at an increasing degree of free water or instability as detailed in Table 1.

The time dependent behaviors of the slurries were identified by two different manners:

- Thickening time tests which, for the six slurries, showed no influence of time in the consistency index. This behavior is explained by the addition of retarding additives in the slurry in order to prevent setting during testing time.

Table 1. Sedimentation properties of each cement slurry.

Slurry	Free water (cm^3)	Stability* $\Delta\rho$ (g/cm^3)
A	0.0	0.0
B	0.5	0.036
C	1.6	0.012
D	2.0	0.024
E	4.0	0.048
F	8.0	0.060

*Stability: difference between the specific gravity of the top and bottom cement segment.

- Rheological tests at different times in order to capture hydration and sedimentation responses. All shear tests were run at an increasing and then decreasing ramp of shear rates. Such tests were run at the cone and plate geometry instrument according to the following schedule:
    - T1: test started immediately (1 min) after the end of slurry mixing.
    - T2: test started 50 min after the end of slurry mixing. No further homogenization was performed.
    - T3: test started 100 min after the end of slurry mixing. In this test, the slurry was re-stirred for 5 minutes immediately before the beginning of the test.
    - T4: test started 100 min after the end of slurry mixing. No further homogenization was performed.

Time dependency was quite different for each slurry. Possibly due to the sedimentation process, several slurries started to change properties in T1 to T4 process. Fig. 2 illustrates the excellent repeatability for slurry A (very stable) while Fig. 3 shows the different viscosity curves for slurry E (highly unstable). The least stable slurry (F) was not possible to be tested in the cone-plate rheometer.

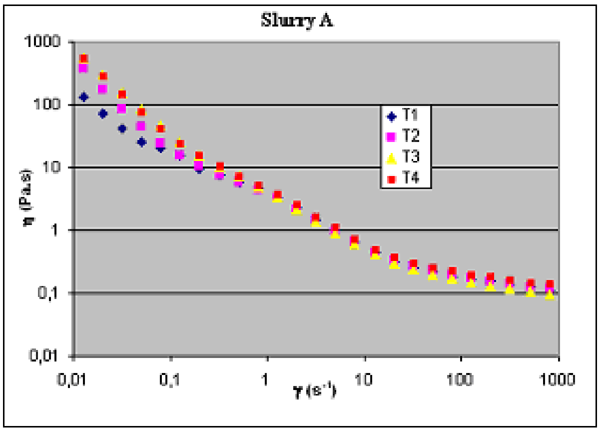

Figure 2. Viscosity response at different times – Slurry A

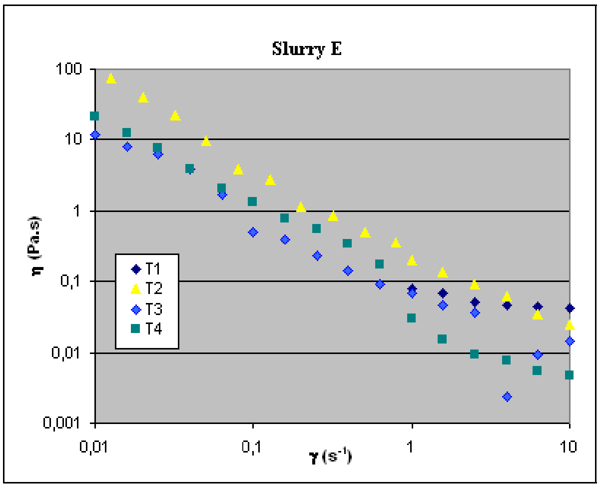

Figure 3. Viscosity response at different times – Slurry E.

Table 2. Low shear viscosity values for 5 slurries

	η (Pa.s)		
Slurry	@ (0.1s^{-1})	@ (1s^{-1})	@ (10s^{-1})
A	15.30	6.87	0.94
B	11.12	0.98	0.18
C	8.51	0.49	0.14
D	66.64	2.34	0.16
E	3.05	0.20	0.02
F	-	-	-

Table 2 details the shear rheological properties obtained with the cone-plate rheometer. Fig. 4 shows the viscosity plot of five slurries for T2.

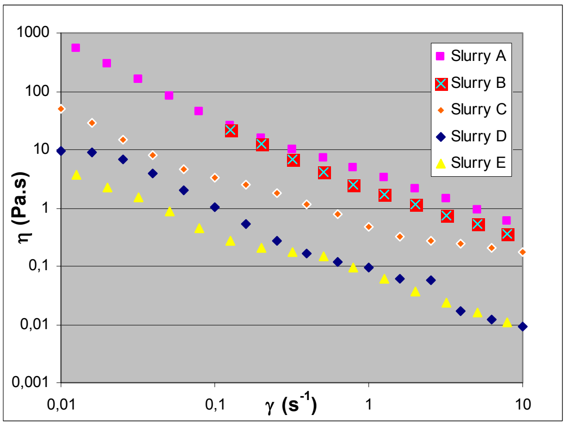

Figure 4. Viscosity plots for five slurries

There is good correlation between free water and sedimentation results and the effective viscosities obtained at 0.1, 1 and 10 s^{-1} (Tables 1 and 2). An exception is slurry D where the rheology results seem to be unreliable at 1and 10 s^{-1}.

Table 3 shows the rheometric results for the concentric cylinder apparatus.

Table 3. Oilfield Rheometer Readings for the 6 Slurries

Slurry	Shear Stress (Pa)					
	Shear rate (s^{-1})				Initial Gel	Final Gel
	511	340	171	10		
A	153	135	102	71	72	94
B	92	72	50	15	19	31
C	52	33	15	3	4	7
D	62	52	37	11	10	12
E	30	22	13	4	3	6
F	20	16	10	3	2	6

Interesting conclusions, however, can be drawn from the oilfield equipment: although the 6 rpm (10 s^{-1}) reading does not correlate properly with free water and sedimentation results (probably due to instrument precision), initial and final gel readings perform better. This fact confirms that hydration and gelation tendencies play an important role on the process. Gel strength is a measurement of the attractive forces under static or non-flowing conditions. Again, results from slurry D are not in accordance with the tendency.

Table 4 presents the rheological parameters for the Bingham, power law and Herschel–Bulkley models. Eq. 1 defines the Herschel–Bulkley model, while the other models are two parameters simplifications of the equation.

$$\begin{cases} \eta = \dfrac{\tau_0}{\dot{\gamma}} + k\dot{\gamma}^{-1} & if \quad \tau \geq \tau_0 \\ \eta \to \infty & if \quad \tau < \tau_0 \end{cases} \qquad (1)$$

Parameters were adjusted from data between 10 s^{-1} (6 rpm) and 511 s^{-1} (300 rpm).

Table 4 – Rheological model parameters for the 6 slurries

Slurry	**Power Law Parameters**		**Bingham Parameters**		**Herschel - Bulkley Parameters**		
	K (Pa.s ^{n})	**n**	**τ_o (Pa)**	**μ_p (Pa.s)**	**τ_o (Pa)**	**K (Pa.s ^{n})**	**N**
A	42.58	0.18	64.98	0.19	70.67	0.06	1.19
B	3.74	0.51	17.43	0.15	8.12	1.49	0.64
C	0.06	1.09	0.47	0.10	2.44	0.03	1.22
D	3.47	0.46	13.59	0.10	1.41	2.92	0.48
E	0.38	0.69	3.39	0.05	2.49	0.12	0.87
F	0.59	0.56	3.33	0.04	1.72	0.23	0.71

Among the parameters proposed in the three rheological models considered, physics suggest that yield stresses would relate to the minimum stress to start movement. The yield stress adjusted by Herschel–Bulkley model reflects sedimentation tendencies more adequately than the Bingham model. This fact highlights the superiority of the 3–parameter model in extrapolating the flow curve for the low shear rate region.

Massarani[3] presents a methodology for the prediction of characteristic shear rates for the sedimentation process. Wall and concentration effects are considered. This methodology depends on the particle slip velocity that is a function of the slurry viscosity. Due to the shear thinning properties of the cement slurries, the estimation of shear rates requires an iterative approach which will converge on the low shear Newtonian plateau of the rheogram. For all the slurries tested the Newtonian plateau was not observed at shear rates as low as 0.01 s^{-1}.

The previous results highlight the importance of low shear viscosity measurements for an optimized cement slurry design.

FINAL REMARKS

- Cement slurry rheology is a complex task, due to the high solids concentration and to the aggressive characteristics of the systems. This work represents an initial effort of obtaining experimental data of such slurries in other equipment than the conventional oilfield apparatus.
- The nature of the process suggests that the dynamic viscosity at low shear rates (between 0.01 and 10 s^{-1}) would govern sedimentation. The oilfield rotational rheometer is limited to 5 s^{-1} shear rates and there is a lot of controversy concerning the repeatability of these readings (normally discarded in cement slurry rheology analysis). In this scenario, the data from the cone and plate rheometer provided an interesting additional input for this study and should be considered for slurry design. For field use low shear Searley type rotational viscometers may be a powerful tool.
- The adjustment of rheological models is a useful tool for design purposes. Such parameters are important inputs for hydraulics, sedimentation and other relevant models for well cementing design. The experimental results from the oilfield equipment reinforce the advantages of considering yield stresses estimated by the Herschel-Bulkley model (3 parameters).
- Viscoelasticity may also play an important role on the sedimentation process. Initial and final gel measurements seemed to correlate properly and are useful field guidelines. Additional effort, however, is required, in the evaluation of viscoelastic and gelation properties of cement slurries with more precise techniques[4].
- Besides sedimentation, several other design items may be optimized with the proper knowledge of cement slurry rheological properties[5]. Present research focus contemplates cement slurry designs to avoid gas migration[6] (where fast gelation is required) and to be displaced at long intervals[7,8] (where friction losses have to be minimized).

NOMENCLATURE

$\Delta\rho$ = Density difference between bottom and top segments - sedimentation, lb/gal.

η = Apparent viscosity, Pa.s.

μ_p= Plastic viscosity – Bingham model, Pa.s

τ = Shear stress, Pa.

τ_0 = Yield stress – Bingham and Herschel–Bulkley models, Pa.

$\dot{\gamma}$ = Shear rate, s^{-1}.

$\dot{\gamma}_p$= Characteristic shear rate – isolated particle, s^{-1}.

$\dot{\gamma}_{conc}$= Characteristic shear rate – set of particles, s^{-1}.

K = Consistency index – Power Law and Herschel–Bulkley models, Pa.s^n.
n = Behavior index – Power Law and Herschel–Bulkley models, dimensionless.

REFERENCES

1. API Specification 10A: Specifications for Cementing and Materials for Well Cementing. 23rd Ed. April 2002.

2. API Specification 10B: Recommended Practice for Testing Well Cements. 23rd Ed. December 1997.

3. Massarani G. "Fluidodinâmica em Sistemas Particulados" - Rio de Janeiro, Editora UFRJ, 1997 p.190.

4. Bird, R. B., Armstrong, R. C., Hassanger O., 1987, "Dynamics of Polymeric Liquids", vol. 1, Wiley, 1987.

5. Thomas W. C., L. V. McIntlre, Kenneth R. K., Claude E. C., 1988 - "The Rheological Properties of Cement Slurries: Effects of Vibration, Hydration Conditions and Additives" – Society of Petroleum Engineering – (SPE) # 13936.

6. Martins A.L., Campos G., Silva M.G.P., Miranda C. R. and Teixeira K.C, 1997 – "Tools for Predicting and Avoiding Gas Migration After Casing Cementing in Brazilian Fields" - Society of Petroleum Engineering – (SPE) # 39008.

7. Jakobsen J., Sterri N., Saasen A., Aas B., Kjosnes I., Vigen A., 1991 – "Displacement in Eccentric Annuli During Primary Cementing in Deviated Wells" – Society of Petroleum Engineers – (SPE) #21686.

8. Becker T. E., Morgan R.G., Chin W.C and Griffith J.E., 2003 – "Improved Rheology Model and Hydraulics Analysis for Tomorrow's Wellbore Fluids Applications" - Society of Petroleum Engineering – (SPE) # 82415.