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Can You Improve Rheology and Mitigate Barite Sag in Invert Emulsion Fluids through Brine Phase Treatment?

Ahmadi Tehrani and Andy Popplestone, M-I SWACO

Abstract

Traditionally, rheology control in invert emulsion drilling fluids (IEF) has been achieved by using organoclays, effective viscosifiers that have proved compatible with most other additives used in IEF. However, their effectiveness decreases with increasing Oil-to-Water Ratio (OWR)and they may suffer from a lack of long-term stability at higher temperatures. This can lead to a gradual but irreversible loss of low-shear-rate (LSR) rheology, responsible for the suspending capacity of the fluid, and a buildup of plastic viscosity as the organoclay degrades. This results in the need for frequent treatment and dilution in order to maintain the required rheological specifications of the fluid.

Efforts to improve rheology control and sag resistance in IEF have continued, but remain focused mainly on developing oil-phase viscosifiers, including polymeric materials, that retain their rheological properties over a wider range of temperatures than previously feasible. In addition, there have been developments in modifying the nature of the weighting agent as a means of controlling rheology and sag.[8-10]

An alternative approach, which has until now received comparatively little attention, is the effect of the internal phase of IEF on rheology and barite sag. The brine phase of an IEF contributes to rheology through both physical and chemical effects. The physical effect is due to the dispersed brine droplets behaving in much the same way as inert solid particles. The chemical effect is caused by the surface chemistry of brine droplets, which has a structure-forming potential through its interaction with other materials in the fluid, *e.g.,* the clay particles. This paper presents the results of laboratory experiments investigating the effect of brine-phase treatment on barite sag. The results will show that under certain conditions, brine additives combined with appropriate oil-phase viscosifiers can modify the rheology profile and produce significant improvement in barite sag resistance of the fluid.

Introduction

Barite sag can occur in both invert emulsion and water-based drilling fluids, but it is generally agreed that it is more severe in invert emulsion fluids. It can occur over a relatively wide range of fluid densities, 11.7 to 20.0 lb/gal, and density variations as much as ±4.0 lb/gal have been observed in the flowline.

Although barite sag can occur under both static and dynamic conditions, flow-loop data and field observations have shown that dynamic sag is more likely to produce the large-scale density variations seen at the flowline. The overall potential for barite sag is highest when the drilling fluid experiences low shear rates,[1,2] or is under the combined influence of low viscosity and low annular velocity. The latter can lead to the formation of a barite bed, which is difficult to remove. Bern, *et al.*[2] and Dye and Mullen[3] suggested a critical mean annular velocity of 100 ft/min above which barite bed formation was minimized.

Barite sag is related both to the drilling fluid properties and the drilling conditions and practices. The fluid properties affecting sag include rheology and the concentration and PSD of the solid particles dispersed in the fluid. It is generally agreed that the low-shear-rate (LSR) rheology affects the sag performance of the fluid.[2] Dye, *et al.*[4] suggested that the viscosity value at a shear rate of 0.5 $\sec^{-1}$ could be used as sag indicator, while others (*e.g.* Herzhaft, *et al.*[5], Saasen[6] and Tehrani, *et al.*[7]) argue that considerably lower values in the range 10^{-2} to 10^{-4} $\sec^{-1}$ may be more appropriate.

Herzhaft, *et al.*[5] performed cryomicroscopic observations on different invert emulsion fluids, which suggested that interaction of organoclay with emulsion droplets is responsible for a solid-like structure at very low shear rates. This structure, which breaks down rapidly upon shearing, is responsible for the yield stress of the fluid. Tehrani, *et al.*[7] estimated the true yield stress required for preventing the settling of a barite particle in a quiescent fluid from a balance of buoyancy and viscous forces to be 0.5 lb/100 ft^2. This value may be considerably higher if defined in terms of the yield points obtainable from field–type viscometers. Bern, *et al.*[2] defined a low-shear-rate yield point (LSYP) as the minimum yield stress required to prevent sag. This value is estimated from $LSYP = 2\theta_3 - \theta_6$, where θ_3 and θ_6 are the 3- and 6-rpm readings on the Fann 35 viscometer (shear rates of 5.1 and 10.2 $\sec^{-1}$, respectively). They suggested a value of 7– 15 lb/100 ft^2 for *LSYP*.

Viscoelastic behavior may also be important for reducing sag.[2] In particular, static sag is thought to be related to the viscoelastic properties of the fluid. Herzhaft, *et al.*[5] performed oscillatory measurements on a number of invert emulsion drilling fluids viscosified with organoclay. They concluded that, at rest or in the absence of appreciable shear, the viscoelastic properties of the fluid may influence sag. Tehrani, *et al.*[7] investigated the effect of viscoelastic properties and low-shear-rate rheology on dynamic sag of an extensive range of clay-based and polymer-based invert emulsion fluids. They reported good correlation between dynamic sag and both the low-shear-rate rheology (down to 10^{-4} sec^{-1}) and the viscoelastic properties of the fluids. They also observed that the correlations were stronger in the clay-based fluids than in the polymer-based fluids and suggested that this may be due to the existence of a structure created by the interaction of clay particles and emulsion droplets.

Traditionally, oil-phase viscosifiers have been used to control the rheology of IEF. The most common of these are hydrophobically modified bentonite or hectorite clay. However, the effectiveness of organoclays declines with increasing OWR and a majority may suffer from a lack of high-temperature stability. This can lead to a gradual but irreversible loss of LSR rheology and a build up of plastic viscosity as the organoclay degrades. Efforts to improve rheology control and sag resistance in IEF have been focused on developing alternative oil-phase viscosifiers, *e.g.,* polymeric materials, that retain their rheological properties over a wider range of temperatures than previously feasible.

In addition to rheology, other properties of the fluid also affect barite sag. The high solids content of drilling fluids increases the resistance to the settling motion of barite particles. Hindered settling in a concentrated suspension of particles has been the subject of many studies, most of which have treated the effect of the solids as an increase in the bulk density and rheology of the continuum. Recent developments in ultrafine weight materials, have succeeded in producing charge- or Van der Waals-stabilized suspensions with significantly lower barite sag.[8-10] This is achieved through the dual effect of slower particle settling (reduced size) and enhanced hindering effect (greater particle numbers).

The internal phase of an IEF, *i.e.,* the brine phase, also contributes to fluid rheology, through both chemical and physical effects. Albertsen, *et al.*[11] found that brine type could affect the sag resistance of invert emulsion fluids. Their studies showed that a fluid formulated with an ammonium calcium nitrate gave better sag performance than one containing calcium chloride brine. The interfacial chemistry of the dispersed phases, *i.e.,* the solids and emulsion droplets, can also influence barite sag. The type and concentration of the emulsifier and wetting agent affect emulsion stability and the wettability of the solids, including organoclays, and may have an effect on sag.[2,6]

The physical effect of the internal phase is due to the concentration of brine droplets (in a manner similar to inert solids particles) and is an inverse function of the OWR of the fluid. This paper describes a novel approach in which the physical effect of the brine phase is enhanced by increasing the rigidity of the droplets through viscosification of the brine phase. Some of the materials used for this purpose may also modify the interfacial chemistry of the droplets. Such modification may enhance the interaction between the droplets and the clay particles, resulting in additional contribution to low-end rheology and sag resistance. It will be shown that with appropriate materials, it is possible to enhance the low-end rheology with only a small effect on the high-shear-rate viscosity. The results will show that it is possible to achieve more than 20% reduction in dynamic sag with this simple approach.

Fluid Description

The invert drilling fluids used in this work differed only in the type and concentration of the rheology-control additives. The fluids were formulated to the same OWR (80/20) and density (13 lb/gal). Calcium chloride brine was used as the internal phase with a water-phase salinity of 173,887 mg/L. The base mud formulation (**Table 1**) contained 3 lb/bbl of a standard organoclay to impart a degree of emulsion stability to the fluid before addition of candidate rheology additives. The test fluids were formulated with a low toxicity mineral oil, but it is understood that the nature of the base oil affects the rheology of the formulated fluid.

The rheology additives consisted of solid and liquid aqueous-phase viscosifiers.. The solid products included scleroglucan gum, two grades of sepiolite designated as S1 and S2, and a water-soluble polyethylene glycol (PEG). The liquid brine viscosifiers were ionic polymers designated as IP-A and IP-B.

Prior to product evaluation for dynamic sag, the viscosified brines were hot rolled for 16 hr at 250ºF to assess the thermal stability of the products. The PEG additive lost some rheology, seeming to recover when ambient temperature was regained. Scleroglucan showed color change but retained viscosity. The sepiolites and the ionic additives retained rheology after hot rolling.

The concentration of the test additives was adjusted to produce a 3-rpm Fann-35 reading of 5–10 $\text{lb}/100\text{ft}^2$ in the fully formulated fluid. In a majority of the tests, the test products were added to the brine phase before being added to the fluid. The invert emulsion fluids were hot rolled for 16 hr at 250ºF.

Test methods

The rheology of the fluids was measured before and after hot rolling. The measurements were carried out at 120ºF on a Fann 35 viscometer.

Laboratory measurement of dynamic sag is commonly carried out with the viscometric sag test (VST) device introduced in 1991 by Jefferson.[12] The technique allows measurements of mud-weight change over a period of time as the fluid is being sheared at a fixed shear rate in a Fann-type thermo-cup. The work reported here used an improved version of the original device, referred to as the VST sag-shoe device by its developers Zamora and Bell.[13] The improvements made in the new device were designed to eliminate problems arising from inconsistent procedures and from sampling errors.

The VST sag-shoe utilizes the heating cup of the Fann 35 rotational viscometer to apply shear to the test fluid. An improvement to the device consists of a sloped disc (“shoe”) which sits at the bottom of the thermo-cup beneath the rotating sleeve of the viscometer, and channels any settled barite into a sample well. The sample well, whose position is fixed in the procedure, allows removal of samples by a suitable syringe for density measurements before and after the test.

Dynamic sag measurements were carried out at 120ºF. Before measurements began, the fluid was sheared at a rate of 1022 sec^{-1} (600 rpm) to achieve thermal equilibrium. [The high shear rate prevents barite settling during the equilibration period.] Once thermal equilibrium was achieved, the shear rate was reduced to 170.3 sec^{-1} (100 rpm) and maintained for 30 min. Samples were removed for density measurement at the beginning and end of the 30-min measuring period. Dynamic sag was measured as the increase in mud weight (δMW) at the bottom of the thermo-cup. The effectiveness of the each product was evaluated by comparing its dynamic sag with that of the base mud:

$$\%\,\text{Sag reduction} = 100\,\frac{(\delta MW_{\text{Base mud}} - \delta MW)}{\delta MW_{\text{Base mud}}}$$

Results

The rheological properties of the fluids are summarized in **Table 2.** Additives that gave better performance are shown at more than one concentration. **Fig. 1** summarizes the data further by showing the best rheological performance for each additive. The flow curves for all the additives lie above that of the base mud, indicating that the brine additives affect fluid rheology, albeit to different extents. Polymer IP-A has the greatest effect and produces the highest low-end rheology. At 2% concentration in brine (1.4 lb/bbl of mud) it increases *YP* by more than 150%, with only 35% increase in *PV*. The effect of the additives on *PV* and *YP* is illustrated in **Fig. 2**.

Polymer IP-B is the next most effective brine viscosifier, but its performance falls well below that of IP-A. The sepiolites S1 and S2 and scleroglucan give fairly similar performance. The data in **Table 2** indicate that the performance of some of the products is concentration dependent, notably polymer IP-A. It is also evident that the peak performance does not necessarily coincide with the highest concentration, suggesting the existence of an optimum concentration.

The dynamic sag data for the fluids are given in **Table 3**. The fluids with PEG-containing brine showed no improvement in dynamic sag as compared to the base mud of **Table 1**. Of the remainder of the additives, ionic polymer IP-A and scleroglucan gave the highest improvement in sag, 28.7% and 27.8% reduction, respectively. Sepiolite S2 gave 15-16% reduction over the concentration range used. This additive seems to have reached its limit of sag reduction at around 4% in brine (2.8 lb/bbl of mud).

The above observations are illustrated more clearly in **Fig. 3**. The result also shows that dynamic sag, as measured by the VST sag-shoe method, correlates well with *LSYP* of the test fluids (data excludes PEG-containing fluids).

The contribution of brine viscosifiers to sag reduction was also investigated in combination with oil-phase viscosifiers. The brine viscosifier used in these tests was the ionic polymer IP-A. The oil-phase viscosifiers included a hydrophobically modified bentonite clay (HMBC), a hydrophobically modified sepiolite (HMS) and a high-molecular-weight polyamide (PA). The test results for rheology and dynamic sag are given in **Tables 4** and **5**.

The effect of brine additive IP-A in combination with modified bentonite clay (HMBC) on rheology of the invert fluid is shown in **Fig. 4**. There appears to be an additive effect which boosts the low-end rheology of the fluid. This is to some extent reflected in the dynamic sag results shown in **Fig. 5**, where the combination of the two additives gives slightly lower sag than that obtained with the individual additives.

The rheological performance of the combination of IP-A and the modified sepiolite HMS is shown in **Fig. 6**. This combination exhibits a synergistic effect evidenced by the rise in the low-end rheology. IP-A and HMS give *YP* values of 23 and 35, respectively, when used individually. But, in combination, they give a *YP* of 83. This is clearly too high, but allows a reduction in the loading of the modified sepiolite. The effect of this combination on dynamic sag is illustrated in **Fig. 7**.

The effects of combining the brine additive IP-A with oil-phase polymeric additive PA on rheology and dynamic sag are demonstrated in **Figs. 8** and **9**. **Fig. 8** shows that the high-MW polyamide is efficient in boosting the low-end rheology of the base mud beyond that obtained with the brine viscosifier. In addition it also gives a lower *PV* than IP-A. However, when the two additives are used together, the improvement in low-end rheology disappears completely and *PV* increases. The incompatibility of the two additives is also observed in the dynamic sag data of **Fig. 9**. The combined additives give higher dynamic sag than that obtained individually.

The above observation points to the possibility that the brine additives may contribute to rheology and to sag reduction through two separate mechanisms: viscosification of the brine phase and interfacial chemical modification of the brine droplets. If this modification is incompatible with other components in the fluid system (as with the polyamide additive), it results in an adverse effect on both rheology and sag control. If the interfacial modification is actively compatible with the system components (as with the modified clay), a synergistic effect may be observed which boosts low-end rheology and improves sag.

Conclusions

The effect of brine viscosifiers on the rheology and dynamic sag of invert emulsion fluids was investigated. Dynamic sag was measured by the VST sag-shoe method for a number of fluids containing clay-based and polymeric brine viscosifiers. The brine additives were evaluated on their own and in combination with other oil-phase viscosifiers.

An ionic polymer brine viscosifier was found to boost the low-end rheology of the fluid and to reduce dynamic sag by about 30%. Scleroglucan was also found to be effective and produced comparable results. Certain grades of sepiolite can be effective but to a lesser extent.

When used in combination with an effective oil-phase viscosifier, the polymeric brine additive showed a range of behaviour. It was incompatible with a polyamide oil-phase viscosifier, lowering the rheology and increasing dynamic sag. With hydrophobically modified clay, particularly modified sepiolite, it behaved synergistically and gave improved sag resistance.

It is thought that the brine viscosifiers contribute to rheology and sag control by increasing the rigidity of the brine droplets. They may also modify the surface chemistry of the brine droplets, thus promoting interaction with some of the additives dispersed in the oil phase. This may be the reason for the observed improvement in the low-end rheology of the test fluids.

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Nomenclature

PSD = *partcle size distribution*
lb/bbl = lb_m*/barrel*
lb/gal = lb_m*/gallon*
rpm = *revolutions per minute*

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Table 1. Formulation for 13.0-lb/gal Base Mud

Product	**lb/bbl**
Mineral oil	168.5
Organoclay	3.0
Lime	7.7
Invert emulsifier	4.55
Wetting agent	4.55
Fresh water	51.20
$CaCl_2$ (83.5%)	18.31
API barite	273.4
HMP clay	15.0

Table 2. Rheology Data for Fluids Containing Different Brine Viscosifiers

Fluid	**Additive**	**Conc. in brine (% w/w)**	**Conc. in mud (lb/bbl)**	**Fann 35 readings at 120°F rpm**						**Gels (lb/100 ft^2)**		***PV***	***YP***
				600	**300**	**200**	**100**	**6**	**3**	**10-s**	**10-min**		
Base mud	-	-	-	55	32	24	15	6	5	7	12	23	9
Base mud + brine viscosifier	PEG	12.5	8.70	57	33	24	16	6	5	6	9	24	9
		18.75	13.00	60	34	25	16	6	6	7	11	26	8
	Scleroglucan	0.25	0.18	58	33	26	16	6	5	6	10	25	8
		0.5	0.35	57	34	26	17	6	6	6	10	23	11
		1	0.70	57	32	24	15	8	8	7	11	25	7
	Sepiolite S1	2	1.40	60	36	27	18	6	5	7	13	24	12
	Sepiolite S2	2	1.40	57	34	26	18	7	6	7	11	23	11
		4	2.80	57	32	25	16	6	6	7	11	25	7
		6	4.20	61	36	27	19	8	7	8	13	25	11
	Polymer IP-A	1	0.7	68	39	29	19	8	8	7	11	29	10
		2	1.40	85	54	44	30	11	10	9	13	31	23
		3	2.1	76	46	35	23	8	7	8	12	30	16
	Polymer IP-B	2	1.40	65	38	29	19	7	6	7	11	27	11

Table 3. Dynamic Sag Data Measured by VST Sag-Shoe Method at 120ºF for Fluids of Table 2

Fluid	**Additive**	**Conc. in brine (% w/w)**	**Conc. in mud (lb/bbl)**	**3-rpm**	***PV***	***YP***	***LSYP***	**δ *MW* (lb/gal)**	***Sag reduction (%)***
Base mud	-	-	-	5	23	9	4	2.653	-
Base mud + brine viscosifier	PEG	12.5	8.70	5	24	9	4	2.712	-0.059
		18.75	13.00	6	26	8	6	2.694	-0.041
	Scleroglucan	0.25	0.18	5	25	8	4	2.492	6.1
		0.5	0.35	6	23	11	6	2.142	19.3
		1	0.70	8	25	7	8	1.915	27.8
	Sepiolite S1	2	1.40	7	24	12	4	2.406	9.3
	Sepiolite S2	2	1.40	6	23	11	5	2.258	14.9
		4	2.80	6	25	7	6	2.235	15.8
		6	4.20	7	25	11	6	2.22	16.3
	Polymer IP-A	1	0.70	6	29	10	8	1.909	28
		2	1.40	10	31	23	9	1.892	28.7
		3	2.10	7	30	16	6	2.147	19.1
	Polymer IP-B	2	1.40	6	27	11	5	2.438	8.1

Table 4. Rheology data for invert fluids containing a brine viscosifier and an oil-phase viscosifier

Fluid = Base mud +	**Fann 35 readings at 120°F**						**Gels**		***PV***	***YP***
	rpm									
	600	**300**	**200**	**100**	**6**	**3**	**10-s**	**10-min**		
-	55	32	24	15	6	5	7	12	23	9
IP-A (1.4 lb/bbl of mud)	85	54	43	30	11	10	9	13	31	23
HMBC (2 lb/bbl)	71	43	34	23	9	8	9	16	28	15
HMBC (2 lb/bbl) + IP-A (1.4 lb/bbl)	96	58	47	31	12	11	11	16	38	20
HMS (8 ppb)	135	85	67	46	21	20	34	46	50	35
HMS (8 ppb) + IP-A (1.4 lb/bbl)	211	147	121	87	40	38	47	59	64	83
PA (2 lb/bbl)	71	43	33	21	10	10	19	40	28	15
PA (2 lb/bbl) + IP-A (1.4 lb/bbl)	68	35	24	13	4	4	6	17	33	2

Table 5. Dynamic sag data at 120ºF for fluids of Table 4

Fluid = Base mud +	3-rpm	*PV*	*YP*	*LSYP*	δ MW (lb/gal)	Sag reduction (%)
-	5	23	9	4	2.653	-
IP-A (1.4 lb/bbl of mud)	10	31	23	9	1.892	28.7
HMBC (2 lb/bbl)	8	28	15	7	1.684	36.5
HMBC (2 lb/bbl) + IP-A (1.4 lb/bbl)	11	38	20	10	1.61	39.3
HMS (8 ppb)	20	50	35	19	0.687	74.1
HMS (8 ppb) + IP-A (1.4 lb/bbl)	38	64	83	36	0.398	85.0
PA (2 lb/bbl)	10	28	15	10	1.006	62.1
PA (2 lb/bbl) + IP-A (1.4 lb/bbl)	4	33	2	4	2.897	-9.2

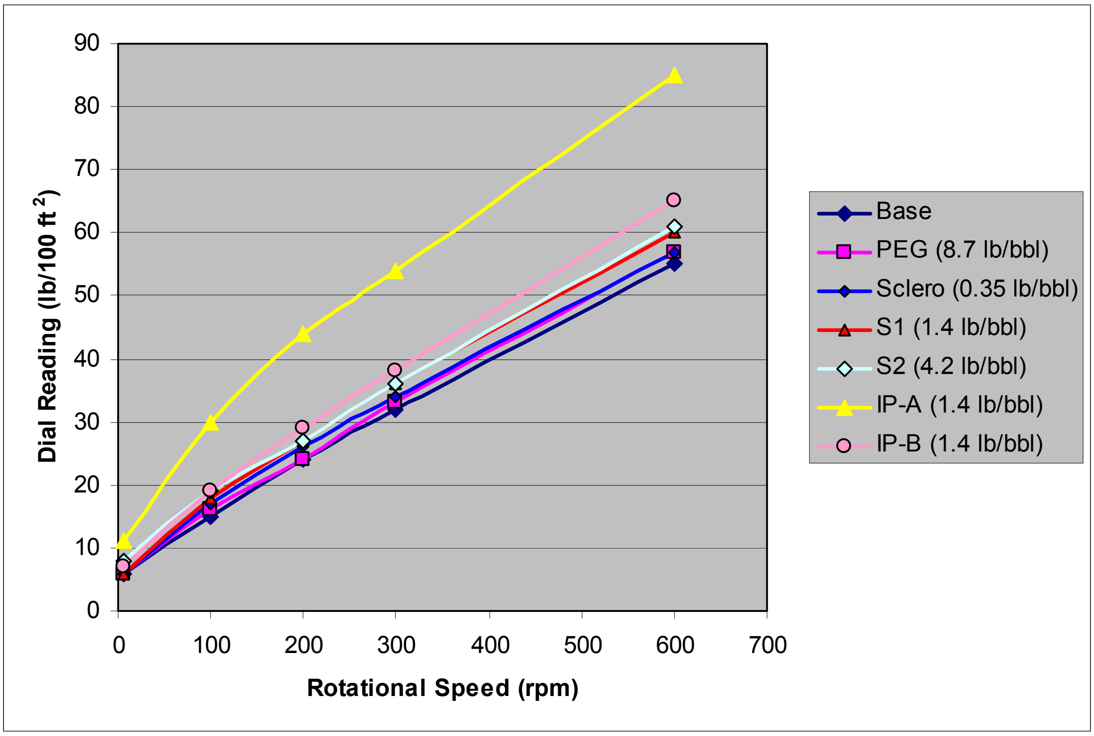

Fig. 1 – Fann data at 120°F for fluids of Table 2.

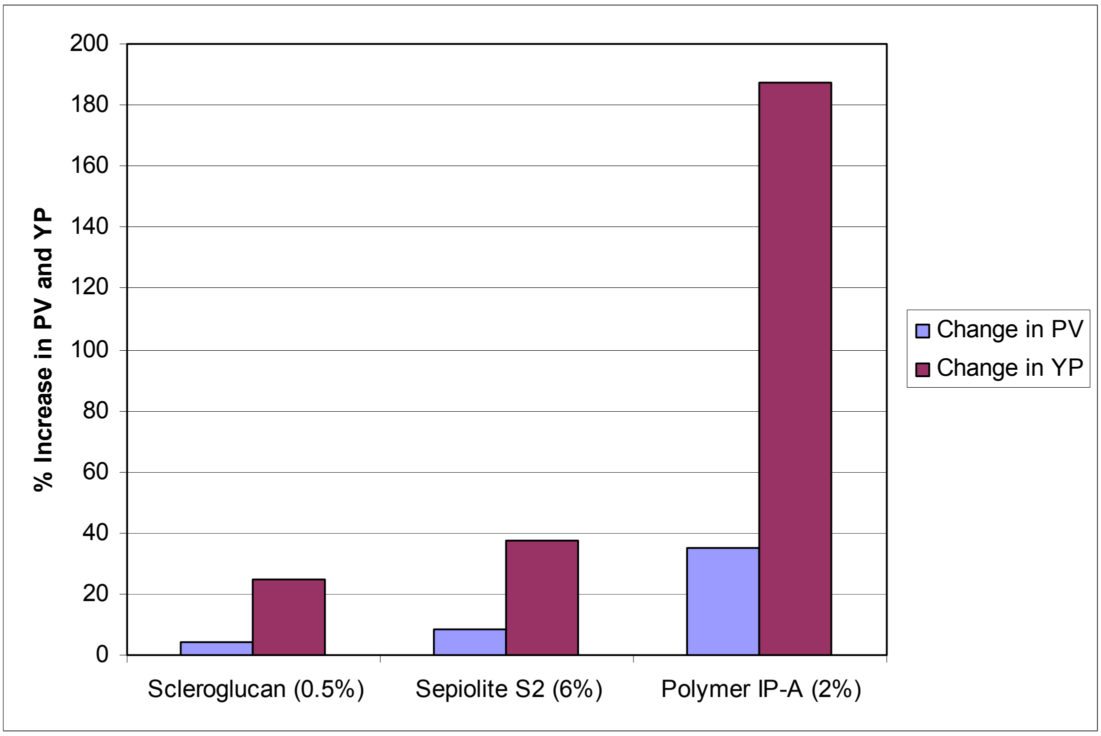

Fig. 2 – Effect of brine viscosifiers on PV and YP of fully formulated invert emulsion fluid.

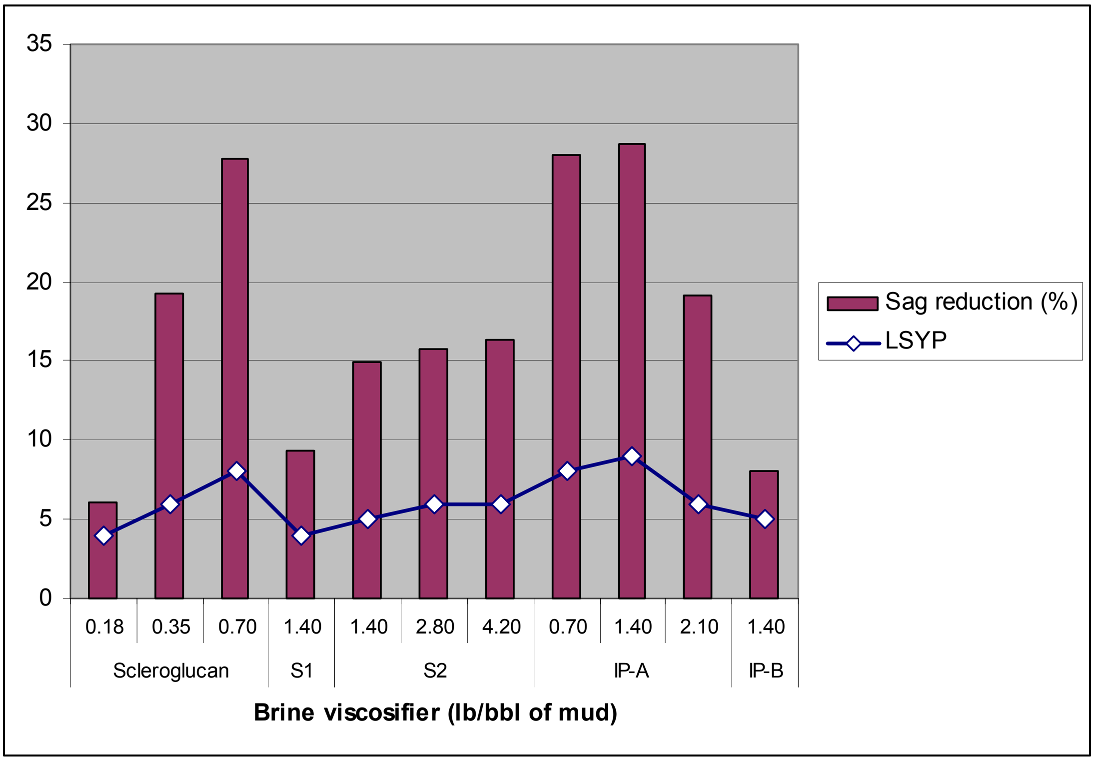

Fig. 3 – Percent reduction in dynamic sag and the LSYP of fluids containing different brine viscosifiers.

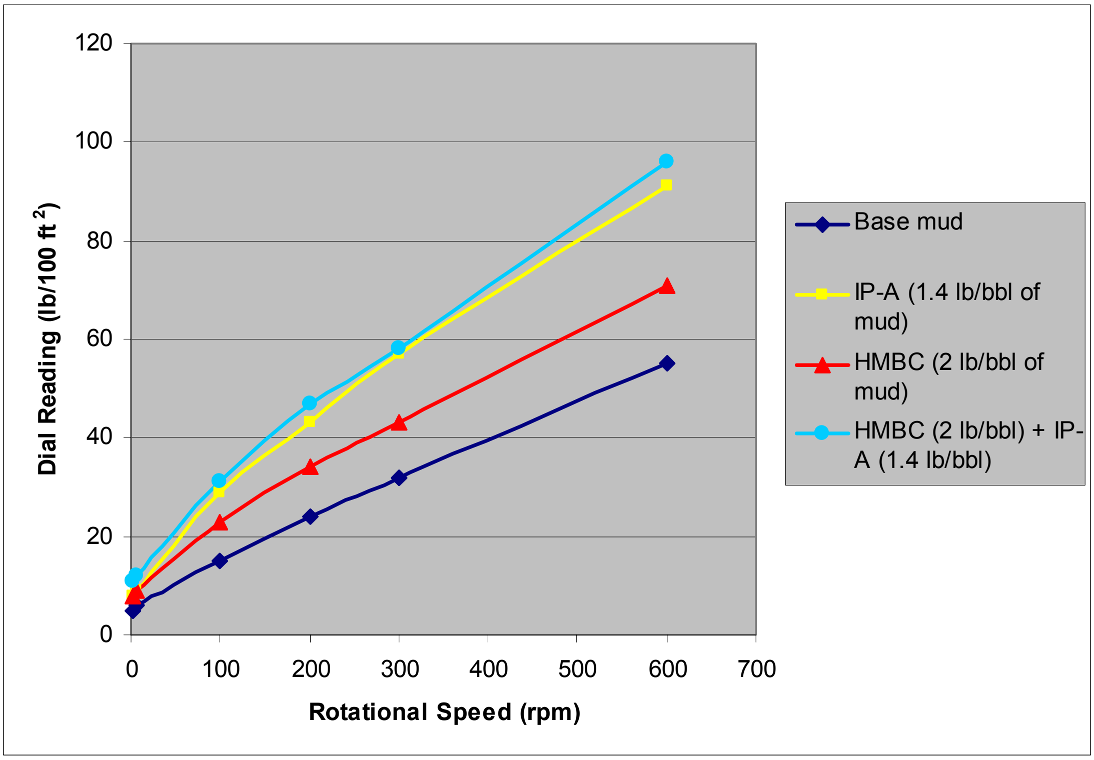

Fig. 4 – Fann data at 120°F for fluids containing ionic polymer IP-A as brine viscosifier and hydrophobically modified bentonite as oil-phase viscosifier.

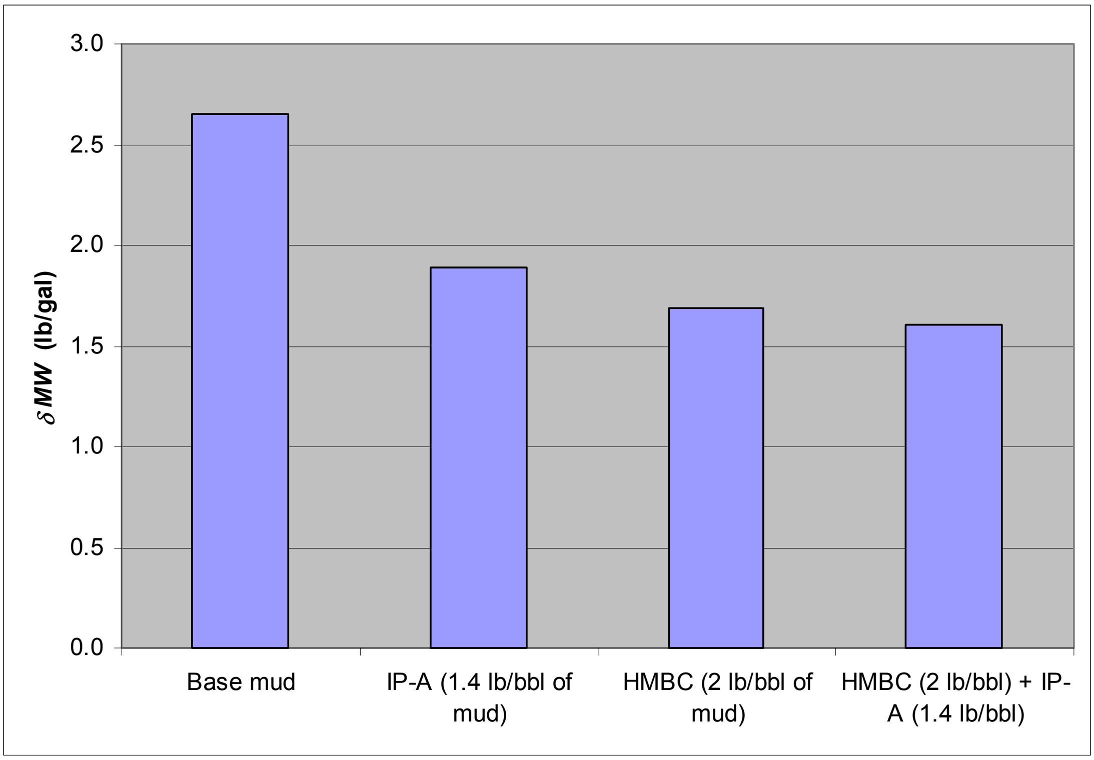

Fig. 5 – Comparison of dynamic sag for fluids containing ionic polymer IP-A as brine viscosifier and hydrophobically modified bentonite as oil-phase viscosifier.

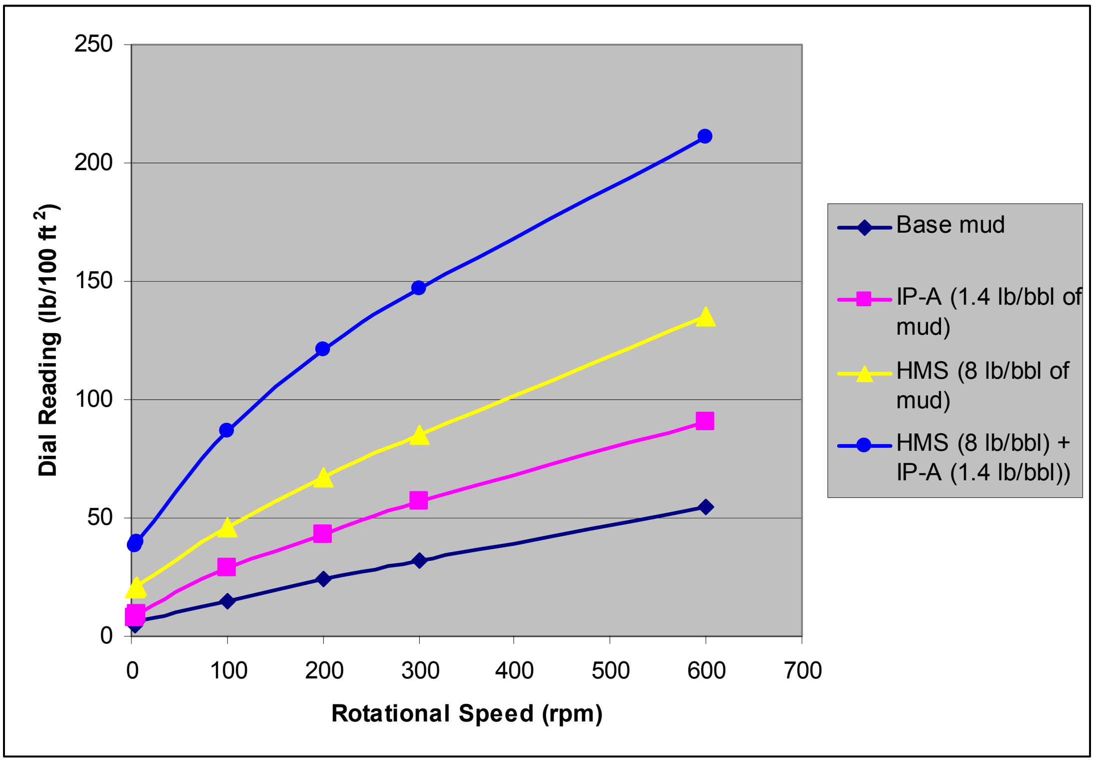

Fig. 6 – Fann data at 120°F for fluids containing ionic polymer IP-A as brine viscosifier and hydrophobically modified sepiolite as oil-phase viscosifier.

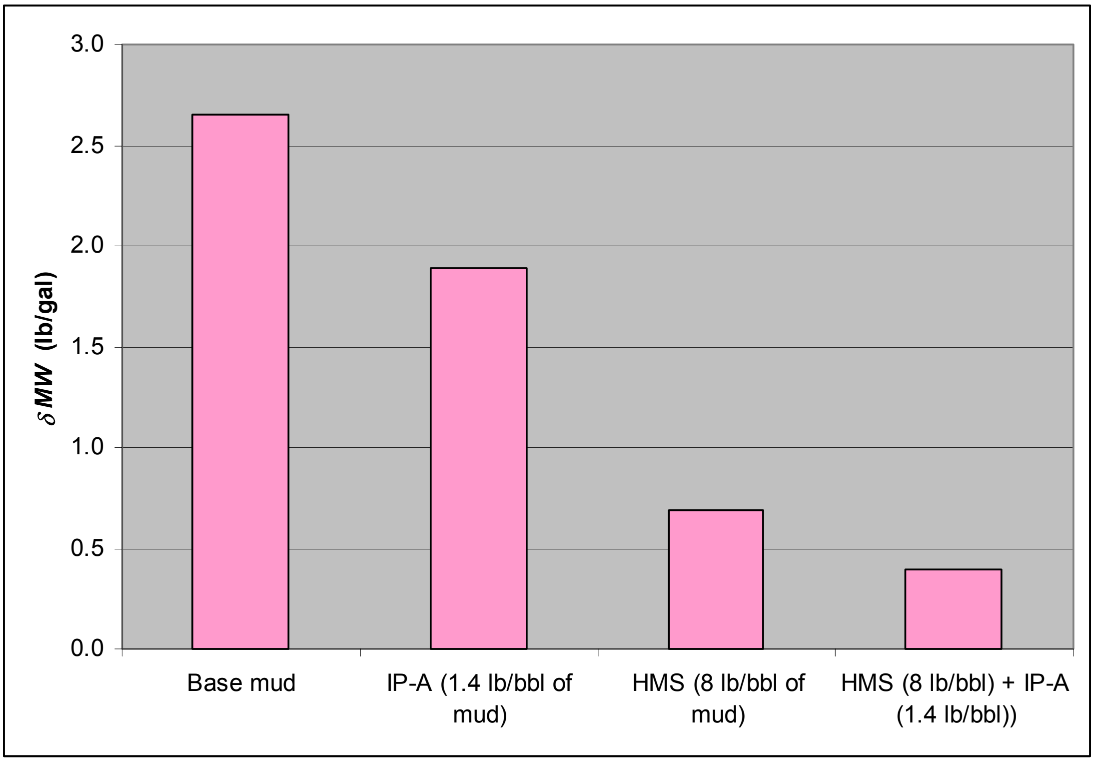

Fig. 7 – Comparison of dynamic sag for fluids containing ionic polymer IP-A as brine viscosifier and hydrophobically modified sepiolite as oil-phase viscosifier.

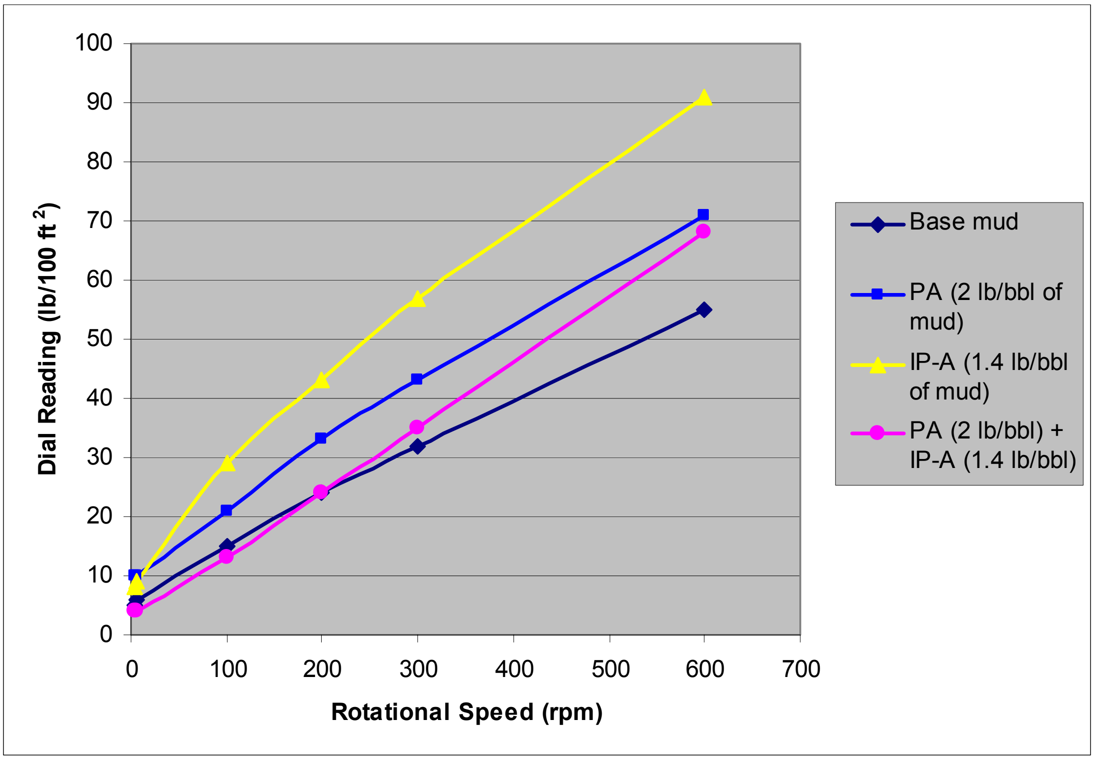

Fig. 8 – Fann data at 120°F for fluids containing ionic polymer IP-A as brine viscosifier and a high MW polyamide as oil-phase viscosifier.

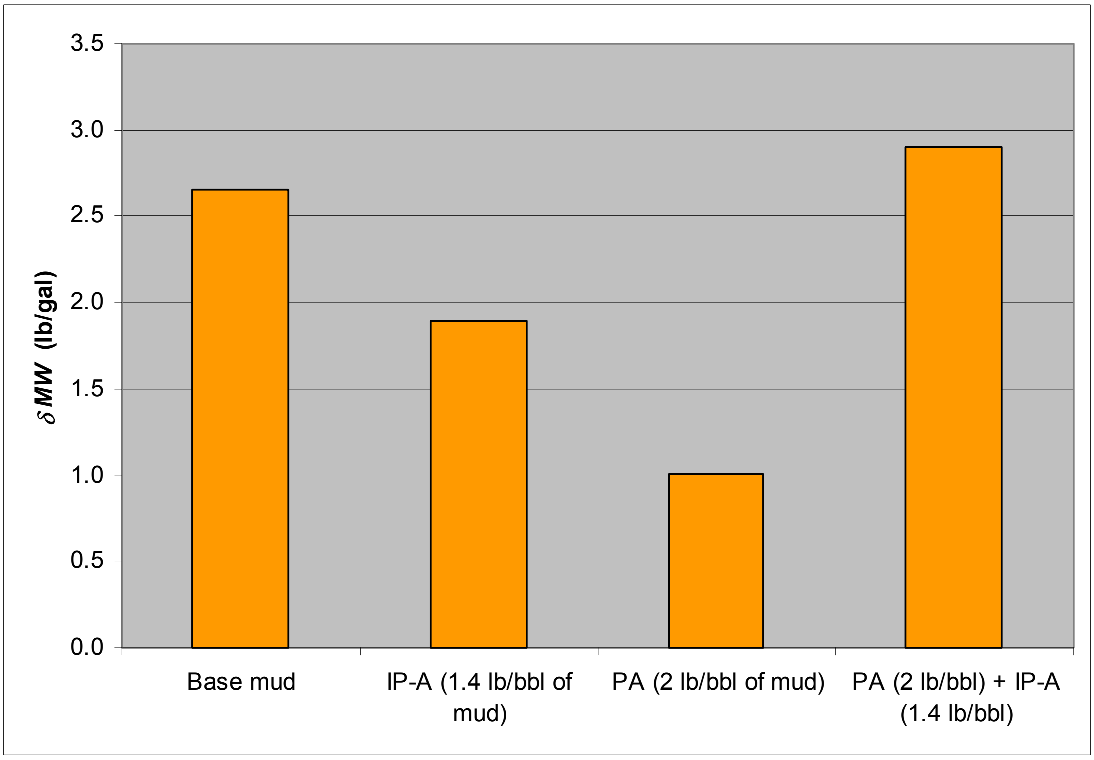

Fig. 9 - Comparison of dynamic sag for fluids containing ionic polymer IP-A as brine viscosifier and a high MW polyamide as oil-phase viscosifier.