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Research Article

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Drilling Optimization for Improved Hole Cleaning and Cement Bonding using Efficient Spacer and Flow Dynamics

Eke Paul Chukwukpe, Prof. Ogbonna F. Joel, Dr. Ndubuisi E. C.

*The Department of Petroleum and Gas Engineering, Faculty of Engineering, University of Port Harcort, Nigeria

Abstract The challenges of hole cleaning and casing cementing in oil and gas drilling operations is enormous. Inadequate cleaning of the wellbore and placing of casing cement has led to many failed cementing jobs in the industry. To avert these failures, spacer fluid is introduced to displace the entrained drilling mud before cement slurries are pumped into the annulus after running the casing for zonal isolation. This research targets the provision of efficient techniques for good hole cleaning and cement placement. Oil-based mud, (OBM) and spacer fluid were designed and formulated. The spacer and the OBM were conditioned to the bottom hole temperature in an atmospheric consistometer for 30 minutes. The rheological properties of the OBM and spacer were investigated at temperatures of 80°F, 100°F, 120°F and 151°F. The results showed an inverse relationship with temperature. As the temperature increased from 80 to 151°F, the plastic viscosity of OBM decreased from 45 cP to 30 cP while the plastic viscosity of the spacer decreased from 17 cP to 2 cP. The results established that both spacer and oil-based mud shared the same characteristic response to changes in temperature. To determine the compatibility of the OBM and spacer, the spacer and the mud were mixed after conditioning, at various ratios of 25/75, 50/50, and 75/25. The rheological properties of the mixture and control samples (100% volumes) were investigated and was found to have responded similarly, except for 25/75 that inverted, confirming their compatibility after being subjected to compatibility tests. The results of the wettability tests indicated that the spacer/OBM admixture was poorly water wet at 25/75%, but performed better at 50/50 and 75/25. Also, the investigation of flow regimes using mathematical model showed that good hole cleaning and cement placement were achieved in transition and turbulent flow conditions. Conclusively, the results obtained for the R-index indicated that the two fluids (OBM and Spacer) were compatible as the R-index value at any given shear rate was less than 40 based on guidelines for compatibility evaluation of the fluids.

Keywords Rheological Properties, Cement Placement, Compatibility, Zonal Isolation.

1. Introduction

Hydrocarbon is a major player in the energy market, because energy is a very important commodity in the day-to-day life of every nation. Therefore, hydrocarbon is a necessity and companies participate in the oil and gas trade to profit from the venture.

Drilling is the only known method used to produce oil and gas resources to the surface to make them available at trading points and it is a capital-intensive venture. Hydrocarbon production is seen as a profitable venture because the average life of oil and gas wells is between 20 and 30 years, after the initial huge investment, the cost of production continues to reduce while the selling price is mostly at profitable regimes and the market for the product is readily available.

The term drilling is used to describe several inter-related operations necessary to construct oil and gas wells [1]. Casing cementing is one of these key operations that determine the success of a drilling venture. Effective fluid displacement during drilling operations will result in high-quality cementing jobs that guarantee good zonal isolation and a solid bond between the cement and the casing and formation. Poor cement placements caused by insufficient mud removal have the potential to cause numerous significant operational issues and substantial environmental risks. Further, failed cement operations account for huge losses leading to over spending and sometimes, avoidable accidents and loss of wells during drilling operations. Thus, due to the strategic importance of casing cementing in the life of a well, high importance is placed on the selection of drilling fluid, its properties, and flow regimes.

Spacer fluid is a type of fluid that is used in drilling operations to separate two different fluids, like drilling fluid and cement, or to clean the wellbore before a new fluid is introduced [2]. The deployment of an efficient spacer will account for good hole cleaning and a water-wet environment. This will lead to cost effective cement jobs and optimization in an oil and gas well drilling operation.

2. Materials and Methods

The American Petroleum Institute (API) requirements and the American Standard for Testing Materials (ASTM) are two examples of internationally accepted standards that served as the foundation for the study's approach.

The main selection criteria and additives were made in order to best fit the particular requirements of the task at hand. Performance tests have shown to be the most successful in predicting a slurry's behavior in particular well conditions [2].

Table 1: List of Materials [Spacer]

Item	Materials	Weight/Volume	Functions
	Fresh Water		Material used for spacer fluid as a continuous phase
1	Barite	416.5 ml	Inert solid used as weighting agent
2	Pac-R	250 g	Material used as a viscosifier
3	Primary	2.0 g	Poly aminated fatty acid used to emulsify water into oil in oil
4	Emulsifier	9.53 ml	based drilling fluid
5	Secondary	9.53 ml	A blend of poly aminated fatty acid and aliphatic hydrocarbon
	Emulsifier		used to enhance the performance of primary emulsifier

Table 2: List of Materials Oil based Mud (OBM)]

Item	Materials	Weight/Volume	Functions
1 2 3 4 5 6 7 8	Base oil Lime Organophilic clay Primary Emulsifier Secondary Emulsifier Soltex Calcium chloride Barite	206.56 ml 3.90 g 2.0 g 10.75 ml 2.43 ml 5.00 g 34.30 g 41.11 g	Material used in oil based fluid as a continuous phase pH control Viscosifier Poly aminated fatty acid used to emulsify water into oil in oil based mud A blend of poly aminated fatty acid and aliphatic hydrocarbon used to enhance the performance of primary emulsifier To enhance filter cake properties Used as weighting agent, also calcium ion inhibits clay swelling, dispersion and migration

Table 3: List of Equipment Used

Item	Equipment/Apparatus	Type/Model	Function
1	Hamilton Batch Mixer	Model 7000	With two preset constant speeds of 4,000 and 12,000 no-load RPM, the Constant Speed Mixer offers variable speed mixing from 100 to 21,000 no-load RPM

			
2	Mud balance	 Chandler model 3530	The instrument used to determine the drilling fluid and cement slurry densities.
3	Viscometer	 MT-2000	used to gauge drilling fluid and cement slurry viscosity and gel strength.
4	Weighing balance	 Chandler model 1200	The weights of measured materials are read with this equipment. When measuring at 10g or more, balances must be accurate to within +/-0.01%, and when measuring at less than 10g, they must be accurate to within +/-1%.
5	Atmospheric Consistometer		Slurry conditioning

2.1 Test Procedure:

1. The Spacer was prepared by adding the materials according to the sequence and quantity listed in Table 1.
2. The oil-based mud (OBM) was prepared by adding the materials according to the sequence and quantity listed in Table 2.
3. The spacer fluid weight was determined using mud balance.
4. The oil-based mud weight was determined using mud balance.
5. The rheological properties of the spacer and the oil-based mud was determined, using fann viscometer for 800F, 1000F,1200F and at the bottom hole temperature (1510F) at various speeds of Θ3, Θ6, Θ100, Θ200, Θ300, and Θ600.
6. The spacer and the mud were conditioned to various temperatures of 800F, 1000F,1200F and 1510F in an atmospheric consistometer for 30 minutes respectively.

7. The spacer and the mud were mixed after the conditioning, at various ratios of 25/75, 50/50, and 25/75, and the rheological properties of the mixture were determined to test for the compatibility and wettability.
8. The wettability test was performed by dipping a glass rod into the mud/spacer mixtures and placed under a slow running tap the surface of the glass rod was observed.
9. Results were discussed.

2.1.1 Oil based mud (OBM) and Spacer fluid Preparation

Oil based mud and Spacer fluid systems were formulated based on well objectives and requirements. For this study, the following drilling fluid and spacer fluid systems were used in conducting the required experimental tests at four different temperatures of 80°F, 100°F, 120°F, 151°F (bore hole temperature).

2.1.2 Oil Based Mud Preparation

206.56ml of base oil was introduced into the mixer, 15g of organophilic-clay weighed and gradually poured into the mixer with the mixer, on, after 10 minutes, 10.75ml of primary emulsifier was introduced using syringe, subsequently 2.43 ml of secondary emulsifier was added followed by 34.3g calcium chloride powder, 88.55ml of fresh water, 3.9g of lime, 5g of soltex and 41.11g of barite. They were allowed to homogenously mix for 30 minutes. The mud density is measured using mud balance and the viscosity of the mud is also measured with the aid of Viscometer. Dial reading of the formulated drilling fluid was recorded at 600, 300, 200, 100, 6, and 3 rpm with the help of the viscometer.

2.1.3 Spacer Fluid Preparation

416.5ml of fresh water was introduced into the mixer, 2g of Pac-R was weighed and gradually poured into the mixer with the mixer, on, after 10 minutes, 250g of barite was weighed and gradually introduced into the mixer with mixer still running, 9.53ml of primary emulsifier was added using syringe, subsequently another 9.53 ml of secondary emulsifier was added. They were allowed to homogenously mix for 15 minutes. The spacer fluid density was measured to be 11.76ppg using mud balance and the viscosity of the spacer was also measured with the aid of Viscometer. Dial reading of the formulated spacer fluid was recorded at 600, 300, 200, 100, 6, and 3 rpm with the help of the viscometer

2.2. Viscosity measurement using a direct-indicating viscometer

The rotating devices known as "direct-indicating viscometers" were driven by an electronic motor. The yield point (YP) and plastic viscosity (PV) were ascertained using this technique. The speed rheometer was used to test these parameters in the manner described below:

Plastic Viscosity

First, the fluid samples were placed at the container and the rotor sleeve and immersed until the line scribed

1. The sleeve rotated at 600 rpm and after few seconds the readings were taken at the steady value.
2. The sleeve rotated at 300 rpm and after few seconds the readings were taken at the steady value.

Calculation of Plastic Viscosity (PV):

Plastic viscosities (PV) of the drilling fluid were calculated using equation (1)

$$PV\ (cP) = (\theta_{600} - \theta_{300}) \quad (1)$$

$$YP\ (\frac{Ib}{100ft^2}) = \theta_{300} - PV \quad (2)$$

Where θ = the dial reading @ 300rpm

Shear rate (Sec^{-1}) =1.7023 × RPM, N (3)

Calculations for shear stress:

Shear stress (lb/100ft²) = 1.065× 1˚Faan (4)

2.3 Measurement of Fluid Density

Procedure:

1. Prior to testing the dry cup with mud and rotating it until it seated, the instrument was first leveled.
2. Then, the fill was cleaned.
3. The mud was swiped outside the cup and the beam was then positioned to hold the balance. It was made sure that the muds were released via the hole in the cap to release the trapped gas.
4. The reading was then obtained from the rider's side, in the direction of the knife-edge.

2.4 Measurement of Rheological Compatibility

$$R\ (RPM) = \emptyset_m - \emptyset_p \quad (5)$$

$\emptyset_m$ = highest dial reading among different mixture ratios at a given RPM

$\emptyset_p$ = highest dial reading among pure fluids at that RPM.

Furthermore, the rheological compatibility of the fluid at that RPM is evaluated based on the guideline shown in Table 4**.** The *R*-index values are based on the R1-B1 rotational viscometer readings, and thus the conversion factor of Pa = dial reading×0.511 (*API RP 10B-2* 2013) was used to modify it according to rheometer readings. The average of ramp up and ramp down shear stress values was used to calculate the *R*-index. The reason behind checking the friction pressure for certain *R*-index is to make sure that the mixed fluid in small annuli is not posing a risk to weak formation by increasing bottom hole pressure. Much attention should be paid to the *R*-index at shear rates of 100–200 s^{-1} because these shear rates commonly occur during primary cementing operations.

Table 4: Guideline to evaluate the Compatibility of Fluids with respect to *R*-index

R-Index (for Rheometer)	Comment
R < 0 (R< 0)	Compatible
0 < R < 40 (0 < R < 20.44)	Compatible (check friction pressure)
41 < R 70 (20.44 < R < 35.77)	Slightly incompatible (test for better formulation)
R > 71 (R > 35.77)	incompatible

2.6 Wettability Test

Wettability was performed using a glass rod method. A clean glass rod was dipped into the mud and placed under a slow running tap. If the glass rod is clean it shows wettability but if it remains oily, then it is oil wet. The glass rod was also dipped into the spacer at various spacer/ mud/ ratios.

2.7 Method of Data Analysis

1. Rheological values will be screened to see if there is a trend.
2. The values will be screened to see if point of inversion of rheological properties can be established.
3. The rheological values will be screened to see if compatibility can be established.
4. The rheological properties can also be screened for water wettability.
5. It is believed that for good hole cleaning the flow regime of the drilling fluid should be in turbulent region, [4], [5].
6. The flow regime was determined by calculating average velocity and Reynolds number of the fluid using the equations:

The **average fluid velocity** through the annular space was determined using the equation:

$$\text{OR } V=\frac{17.16(OP\ bbls/min)}{(dh^2-dp^2)} \quad (6)$$

OR

$$V=\frac{OP(gpm)}{2.45(dh^2-dp^2)} \quad (7)$$

OR

$$V=\frac{3.06\ (OP)ft^3/min}{dh^2-dp^2} \quad (8)$$

Where:

V = average fluid velocity, ft/sec

OP = pump output; bbl/min, gpm, or ft^3/min

dp = outside diameter of pipe, inches

dh = hole diameter, inches.

Reynolds Number:

Reynolds number is a dimensionless quantity used to establish the patterns of fluid flow. If values of fluid are applied to the Reynolds equation,

$$R_{Na} = \frac{928\ x\ (dh-dp) x\ V\ x\ \ell}{PV} \quad (9)$$

Where

R_{Na}=Reynolds number for annulus (dimensionless)

dh = hole diameter (inches)

dp= outside diameter of pipe (inches)

V= Average velocity (ft/sec)

ℓ = Density of fluid (lbm/gal)

Note: if Reynolds number, $R_{Na} < 2000$ – Laminar flow,

$2000 < R_{Na} < 4000$ – Transition flow

$R_{Na} > 4000$ – Turbulent flow

In this design, we determined the annular flow pattern by calculating average velocity and Reynolds number of the spacer fluid, if the calculated Reynolds number, (R_{Na}) of spacer fluid < 2000, it means the spacer fluid is in a laminar flow regime, if the Reynolds number, (R_{Na}) of spacer fluid is $2000 < R_{Na} < 4000$, then it is transition flow. But when the calculated result of $R_{Na} > 4000$, it means the spacer fluid is in a turbulent flow regime.

3. Results and Discussion

3.1 Results and Analysis

The various results of the experiments on oil-based mud (OBM) with a density of 9.2 ppg and spacer fluid density of 11.76 ppg were presented in this section. Also, the effect of temperature on the rheological properties of the fluids, compatibility, and wettability of the the OBM and Spacer formulated were investigated, and the impact of flow rate on cutting removal was discussed.

3.1.1 Effect of Temperature on Rheological Properties of the Formulated Spacer and Oil-Based Mud

The effects of temperature on the PV and YP were shown in Figures 1, 2 and 3, 4 as well as in Appendix A1 to A 4 respectively.

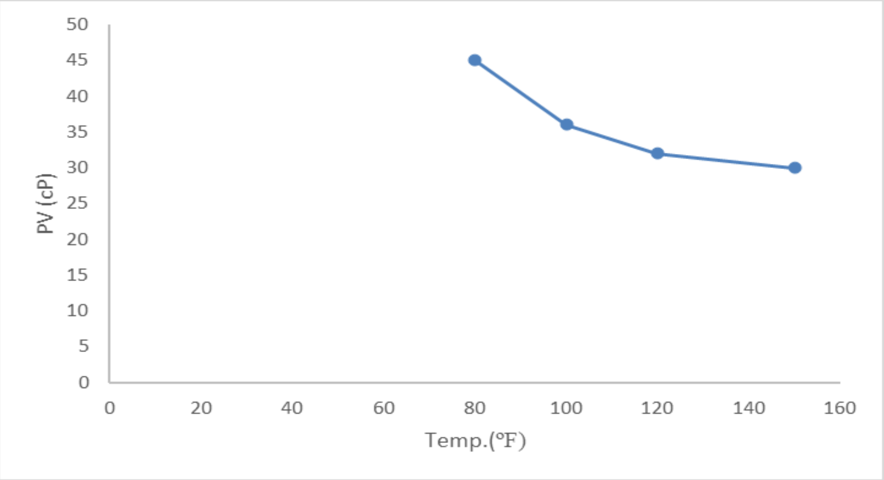

Figure 1: PV Variation with Temperature in OBM

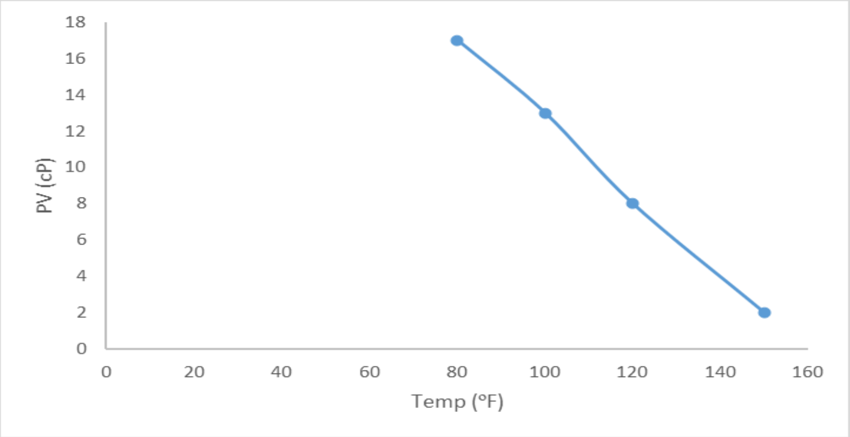

Figure 2: PV variation with Temperature in Spacer

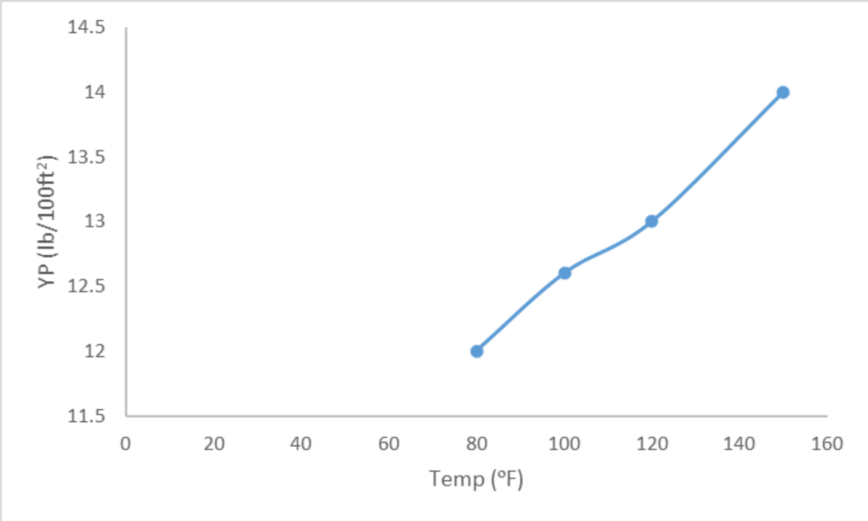

Figure 3: YP Variation with Temperature in Spacer

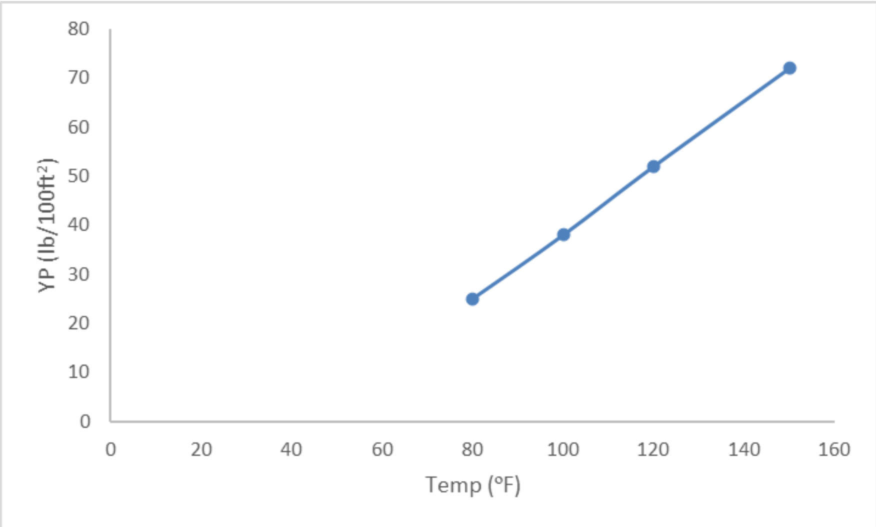

Figure 4: Effect of Temperature on the YP in OBM

3.1.2 Compatibility between Formulated Spacer and OBM

The compatibility of OBM and spacer were shown in figure 5 - 10. The flow curves were used to indicate level of compatibility of the two fluids (OBM and spacer).

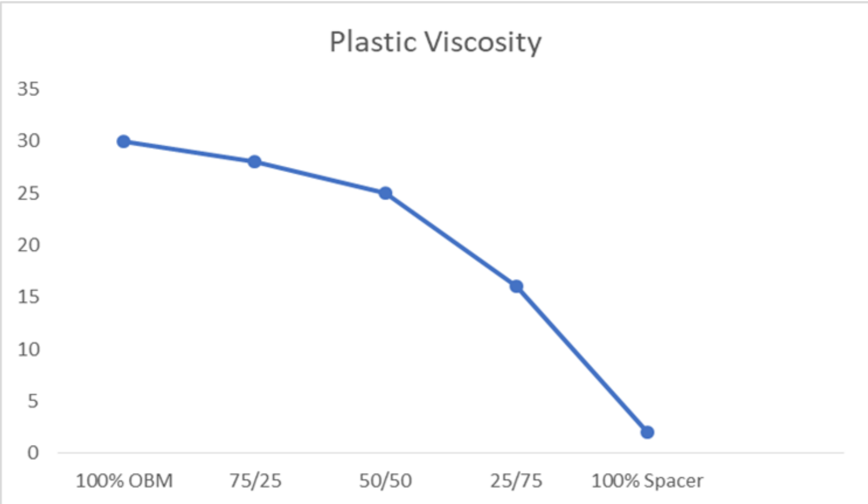

Figure 5: Plastic viscosity for Percent Mixtures of Oil-based Mud and Spacer Fluid

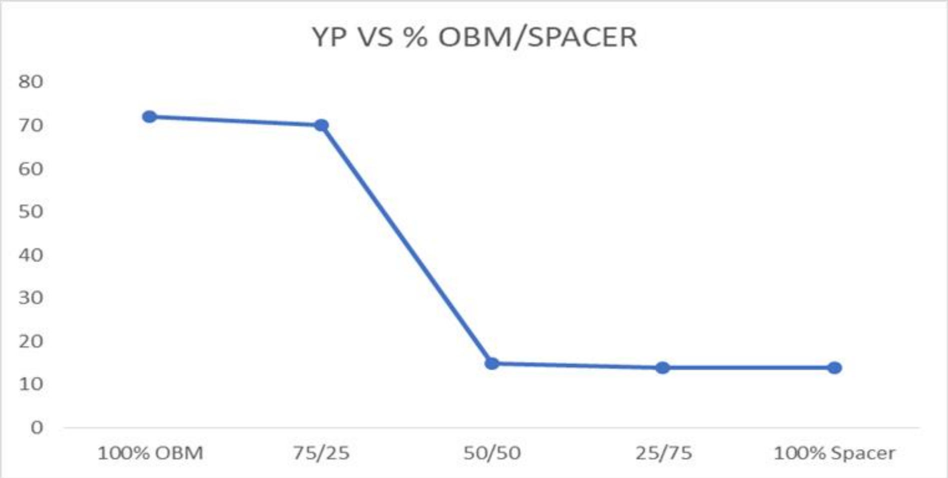

Figure 6: Yield Point versus Percent Mixtures of Oil based Mud and Spacer Fluid

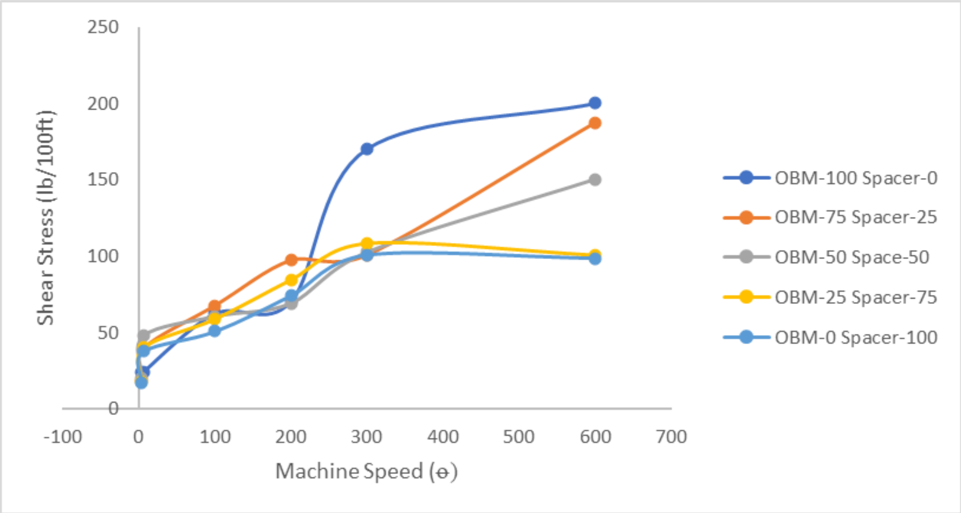

Figure 7: Rheology for OBM, Spacer and Mixture of Spacer and OBM at 80°F

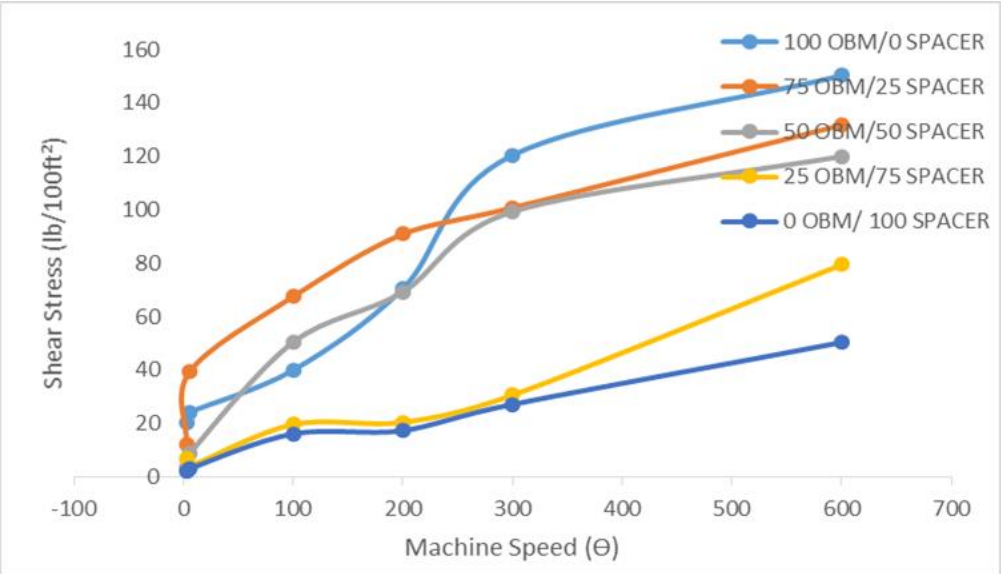

Figure 8: Rheology for OBM, Spacer and Mixture of Spacer and OBM at 100°F

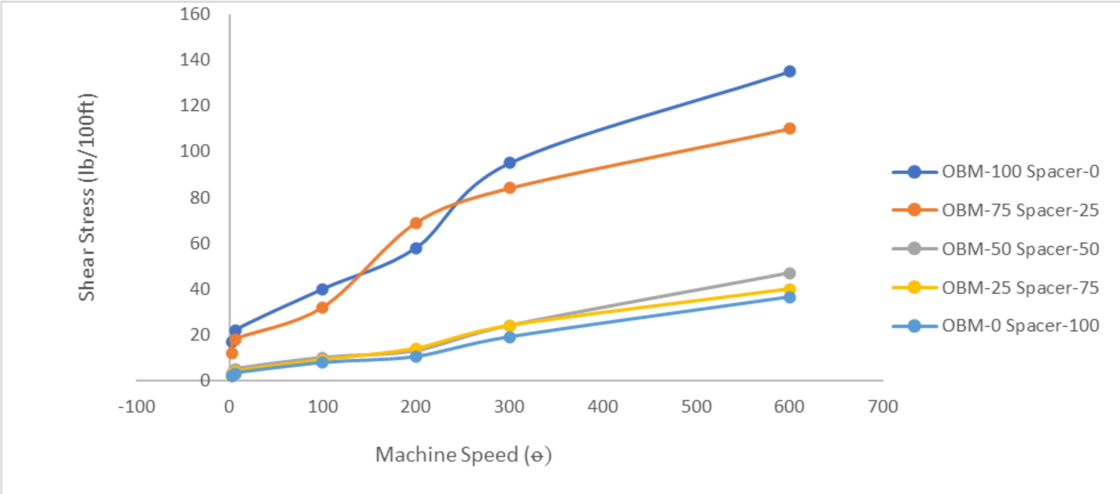

Figure 9: Rheology for OBM, Spacer and Mixture of Spacer and OBM at 120°F

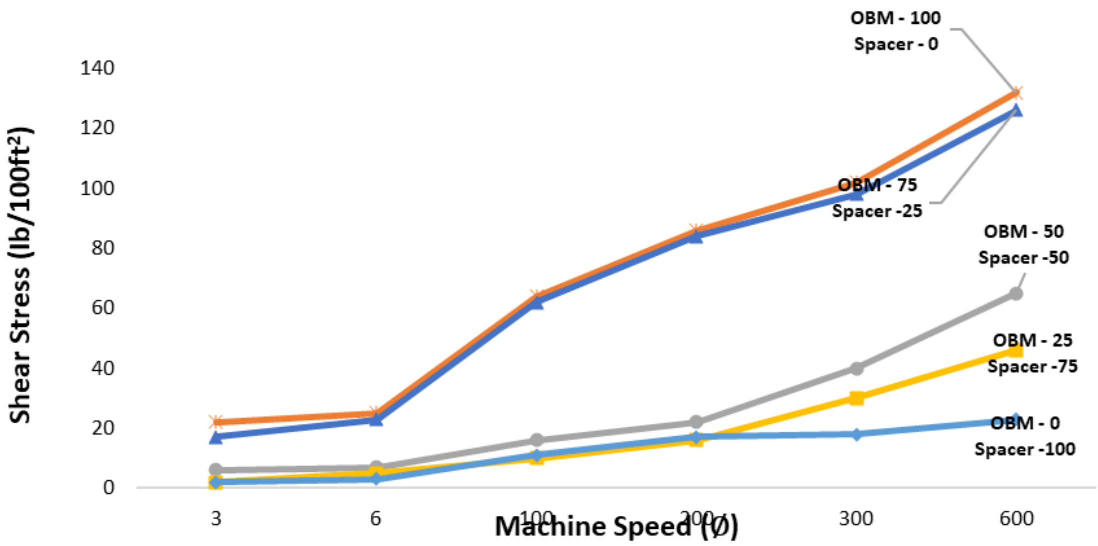

Figure 10: Rheology for OBM, Spacer and Mixture of Spacer and OBM at 151°F

3.1.3 Relationship between Shear Rate, Shear Stress and R-index

Tables 5 – 8 showed the values of R-index for the OBM/Spacer Admixtures.

The results on the tables showed R-index for each of the fluid combination which include: 100 OBM/0 spacer, 75 OBM/25 spacer, 50 OBM/50 spacer, 25 OBM/75 spacer and 0 OBM /100 spacer.

Table 5: Results of Shear Stress (lb/100ft2) and Shear Rate (Sec-1) OBM, Spacer, Mixtures of Spacer and OBM at 80°F

Shear Rate (Sec^{-1})	Shear Stress ($lb/100ft^2$)										
	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	
	100	0	75	25	50	50	25	75	0	100	R-index
4051.3	200.20		187.50		150.45		100.97		98.60		2.37
800.90	170.4		100.70		102.60		108.65		100.7		7.95
400.60	70.5		97.24		69.10		84.79		74.20		10.58
240.30	62.50		67.50		60.45		59.00		50.76		8.24
200.25	24.40		39.5		47.80		40.25		37.65		2.6
12.99	24.30		18.65		20.40		17.50		16.96		0.54

Table 6: Results of Shear Stress (lb/100ft2) and Shear Rate (Sec-1) OBM, Spacer, Mixtures of Spacer and OBM at 100°F

Shear Rate (Sec^{-1})	**Shear Stress (lb/100ft^2)**										
	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	
	100	0	75	25	50	50	25	75	0	100	R-index
3061.38	150.2		131.7		120		79.45		50.4		29.05
710.90	120.45		100.79		99.30		30.7		27.23		3.47
400.60	70.5		90.90		69.20		20.5		17.4		3.1
230.30	40		67.50		50.45		19.7		16.20		3.5
12.25	24.20		39.5		8.9		4.2		3.2		1
5.99	20.30		12		3.7		6.9		2		4.9

Table 7: Results of Shear Stress (lb/100ft2) and Shear Rate (Sec-1) OBM, Spacer, Mixtures of Spacer and OBM at 120°F

Shear Rate (Sec^{-1})	**Shear Stress (lb/100ft^2)**										
	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	OBM	Spacer	
	100	0	75	25	50	50	25	75	0	100	R-index
2021.38	135		110		47		40		36.5		3.5
610.90	95		84		24		24		19		5
440.60	58		69		13		14		10.4		3.6
180.30	40		32		10		9		7.75		1.25
20.22	22		18		5		4		3.2		0.8
7.11	17		12		3		2		2		0

Table 8: Results of Shear Stress (lb/100ft^2) and Shear Rate (Sec^{-1}) OBM, Spacer, Mixtures of Spacer and OBM at 151°F

Shear Rate (Sec^{-1})	**Shear Stress (lb/100ft^2)**										
	OBM	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**	
	100	**0**	**75**	**25**	**50**	**50**	**25**	**75**	**0**	**100**	**R-index**
1021.38	141		134		69		49		24		25
510.90	101		104		43		31		19		12
340.60	92		89		23		17		18		-1
170.30	68		66		17		11		12		-1
10.22	27		24		7		55		3		52
5.11	23		18		6		2		2		0

3.1.4 Impact of Flow Rate on Hole Cleaning

The impact of flow rate on hole cleaning was presented in Table 9

Table 9: Results for the Mathematical Modeling of the Impact of Flow Rate on the Flow Regimes.

Well Number	**Average Velocity (ft/sec)**	**Flow Rate (BPM)**	**Reynolds Number**	**Flow Regime**	**Cement Integrity**
Pilot Spacer	2.39	8	34,234	Turbulent	Good
1	3.00	10	12528	Turbulent	Good
2	2.39	8	3206	Transition	Good
3	3.58	12	1857	Laminar	Failed
4	3.00	10	1961	Laminar	Failed
5	3.00	10	1865	Laminar	Good

6	2.70	9	15875	Turbulent	Good
7	3.00	10	29232	Turbulent	Good
8	2.39	8	34932	Turbulent	Good
9	3.00	10	2932	Transition	Good
10	2.70	9	2828	Transition	Good

3.2 Discussion

3.2.1 Effect of Temperature on Rheological Properties of the Formulated Spacer and Oil Based Mud

Figures 11 and 12 showed the rheological properties (PV) of the formulated spacer fluid and oil-based mud decreasing progressively with increasing temperatures of 80°F, 100ºF, 120ºF 151°F. The results showed that the increase in temperatures has a similar impacts on both the formulated spacer and OBM. This finding was also presented in Appendices A1 to A4.

However, the yield points for both spacer and oil-based mud showed a reversal effect with an increase in temperature. As the temperature increased, the yield point (YP) experienced a resultant rise. (Figures 3 and 4).

These results showed there was a corresponding decrease in plastic viscosity at higher rotational speed with increasing temperature for oil-based mud and Spacer figures 1 and 2. The spacer and oil-based mud exhibited thixotropic behavior meaning the viscosity of slurry thinned when subjected to constant shear force, that is, the longer the fluid is under shear stress, the less, its viscosity, and this is in line with the findings of Mercer and Weymann, [7].

3.2.2 Compatibility between Formulated Spacer and OBM

The compatibility of the spacer and OBM is a very important factor in ensuring a successful cementing operation. The spacer must be able to completely displace the drilling mud before cement slurries will be pumped in to avoid the presence of entrained mud. From the results obtained, the shear stress increased as the machine speed increased at different OBM/Spacer ratios – 100 OBM/0 Spacer, 75 OBM/25 Spacer, 50 OBM/50 Spacer, 25 OBM/75 Spacer and 0 OBM/100 Spacer at 80°F, 100°F, 120°F and 151°F. The flow curves of the admixtures lay between the flow curves of the pure fluids (OBM and Spacer) as shown in figures 6 –10, confirming compatibility. The result indicated that at the point where OBM and spacer were 100%, the shear stress trends were the same, which means they are compatible and the spacer can completely flush out the drilling mud (OBM). As a result, if the rheological characteristics of the admixture do not significantly differ from those of the individual fluids—OBM and spacer, for example—then the two fluids are considered compatible. Any significant rise in the flow curve indicates that the admixture has gelled, which is an unmistakable sign that the fluids are unwanted and incompatible. However, it indicates that the two fluids are compatible when the admixtures' flow curves fall between the pure fluid's (OBM or spacer) flow curves. A significant increase in the mixture's flow curve signals an unfavorable rise in the bottom hole pressure needed for the spacer to push the mixing zone out of the way. The formation may fracture as a result of this increased pressure. Mud displacement may also be impacted by the mixture's flow curve values increasing. For efficient displacement, the frictional pressure gradient exerted by the displacing fluid (spacer) should be at least 20% higher than that of the displaced fluid (mixed), according to the effective laminar flow rule system proposed by Couturler et al. [9].

Compatibility is also the capacity to produce a fluid mixture without encountering undesirable reactions [10]. In other words, there shouldn't be any noticeable gelation, sludge, solid gel, or phase separation between the spacer and mud mixture. In the worse scenario, gelation could block the annulus and prevent cement from being pumped, or it could result in excessive frication pressure, which is undesirable since it could mess up the formation. In order to ensure that there won't be any problems when the fluid combination is forced into the well bore, it is vital to assess how well the spacer and fluid mixture work together. Evaluating the compatibility of mud and spacer is possible by examining the increase in viscosity of a mud/spacer mixture over the range of 0-100% to 100-0% by volume. Excellent compatibility is achieved when the viscosity of the mixture at a given shear rate is smaller than the viscosity of the more viscous component at the same shear rate [11].

3.2.3 R-index and Compatibility of Formulated Spacer and OBM

R-index is important in the determination of the compatibility of surface and OBM. The results obtained showed different values for R-index (Tables 1–4). The compatibility of the two fluids is established if there is no significant change in the rheological properties of the admixture when compared with the rheological properties of the individual fluids which include OBM and spacer. R-index is a system developed by cement engineers to evaluate the compatibility of fluids in a well bore [12]. Tables 1 –4 showed the R-index of OBM and spacer at different 80°F, 100°F, 120°F and 151°F at different shear rates. Based on the results, the R-index value was less than less than 40 at every shear rate. Therefore, the OBM and spacer were compatible with the temperature range used for the study. However, the friction pressure must be monitored in this case. The deduction was based on the R-index guideline for the evaluation of the compatibility of fluids [12].

3.2.4 Wettability of Formulated Spacer

Tables 1 to 3 show the results of the rheological properties of the formulated spacer fluid and oil-based mud. These experimental results indicated that the surfactant used in the formulation of the spacer for displacement of the oil-based mud was very effective (Table 3 and Figures 5 and 7). Upon the mixture of 75:25, rheological readings suggested that interfacial inversion must have taken place. The overall rheological readings for all the spacer/mud mixtures fall between neat spacer and neat mud rheology, this showed that they are compatible.

The experimental result also showed that the rheological properties of plastic viscosity and yield point for the mixture of spacer fluid and oil-based mud are compatible. The values for the mixture fall between the values for the oil-wet, oil-based mud and that of the water-wet, spacer fluid (Figures 5 and 6).

Furthermore, comparing the investigative results obtained for both the plastic viscosity and the yield point in the appendix at Table A10 and A11 respectively, it was observed that at the point where there was 100% oil base mud, the plastic viscosity was 30cp while the yield point was 72 lb/100ft^2. However, this value sequentially dropped in a gradual process as the spacer and oil base mud composition was being altered in the other to get a stable behavior that would give better results in terms of well-cleaning efficiency and cement bonding capabilities. At a mixture of 75% oil base mud and 25% spacer fluid, the plastic viscosity gave 28cp sensitivity while the yield point gave a value of 70lb/100ft^2. This characteristic gradually reduced as the mixture of Oil base mud was further altered to 50% and spacer fluid also altered to a value of 50% composition. The resultant values were 25cp for plastic viscosity and 15 lb/100ft^2 for yield point respectively. A further alteration to a mixture of 25% OBM and 75% spacer fluid saw the plastic viscosity sharply drop to 16 cP while the yield point showed a slight drop to 14 lb/100ft^2. Also, one more change of the mixture to 100% spacer fluid without any mixture of oil base component showed another sharp drop of the plastic viscosity to 2cp while the yield point maintained a consistent value at 14lb/100ft^2. Again, it was clear that the rheological values of the OBM and spacer fluid mixture fall in the expected range of that of neat OBM and neat spacer fluid, thus confirming the compatibility of the spacer fluid with OBM (Table 3).

The maximum oil-wet situation was represented by the red curve. The maximum water-wet situation was represented by the light blue line. The deep blue curve (25 Spacer/75% OBM) showed the beginning of reversal from oil-wet to water-wet. We note that the reversal was rapid as even before we got to the 50%spacer/50% OBM curve the mixture had become completely water-wet (Figure 10). This confirms that the designed spacer fluid has effective hole-cleaning properties.

Further, a wettability test was carried out to confirm the status of the mixed fluid. The wettability test was done by dipping a glass rod into 100% OBM, and then in the various mud/spacer mixtures placing it under a slow-running tap, and observing the surface of the glass rod.

It was noticed that when the glass rod was dipped into the 100% OBM specimen and placed under slow-running water, the OBM could not be washed off. However, when the glass rod was dipped into the 25/75% Spacer/OBM specimen mixture and placed under slow-running water, the specimen was washed off but with some difficulty. On trying this experiment in the 50/50% specimen mixture, the glass rod was washed off with more ease. Subsequently, when the 75/25% Spacer/OBM specimen mixture was tested, the glass rod was easily washed off, showing that the spacer fluid effectively reversed the oil-wet surface to become water-wet.

From the mathematical modeling, and the results in Table 5, the freshly prepared spacer from the laboratory has turbulent flow using a modest flow rate of 8 BPM, which was similar to what was used in the field operations.

Wells 3, 2, 6, 7, and 8 were also in the turbulent flow regions. And well 9 and 10 are in transition flow regimes. While wells 3, 4, and 5 are in laminar regimes. Also, wells 3 and 4 had cement integrity problems after placements. However, all the other wells had no issues. The mathematical modeling showed that good hole cleaning and cement placement can be achieved in transition and turbulent flow conditions. So, while designing the hole cleaning program, it is desirable to have the flow regime in the transition and/or turbulent regions. Also, the wettability and compatibility qualities of the spacer fluid should be adequately considered.

At the temperature of 151°F, an increase in the rotation per minute (RPM) when investigating the oil base mud (OBM) standard value brought about a corresponding increase in the shear stress which automatically translated to an increase in the shear rate and hence, systematically increased the flow rate. This was even evident when analyzing the individual response of the test carried out on shear stress against the shear rate at different RPMs. For instance, at 3RPM, the shear stress was 22 lb/ft^2 bringing about a shear rate of 37sec^{-1} which was relatively low based on the low RPM applied. As the speed of the rheometer was increased to 6RPM, the shear stress and shear rate simultaneously increased from 22 lb/ft^2 to 25 lb/ft^2 and from 37 sec^{-1} to 43 sec^{-1} respectively. A further increase of the speed to 100 RPM resulted in a higher and sequential increase of the shear stress to 64 lb/ft^2 and a shear rate increase to 109 sec-1 from the initial 25 lb/ft^2 shear stress and 43 sec^{-1} shear rate. As the rotary speed increased further upward to 200RPM, the shear stress increased to 86 lb/ft^2 resulting in an increase shear rate of 146sec^{-1}. Furthermore, at the 300 RPM rotary speed, the shear rate of the OBM mixture moved upward to 102 lb/ft^2 resulting to an additional increase of the shear rate flow to 174sec^{-1}. Finally, at 600 RPM rotary speed, the oil base mud (OBM) increased spontaneously from 102 lb/ft^2 shear rate value to 132 lb/ft^2 resulting to an increase of the shear stress from 174 sec^{-1} to 225 sec^{-1} shear rate value. This simply indicates that a higher shear stress at 151°F is supposed to induce an increase in flow rate of the oil base mud (OBM), which will in turn give a better hole cleaning that will lead to efficient cement bonding. But in practice this is not always true because of other factors that has to do with the inclination/ deviation of the hole.

Further comparative analysis, at a standard temperature of 80°F: From the table, A7, an increase in the rotation per minute (RPM) brings about a corresponding increase in the shear stress which automatically translates to an increase in the shear rate hence, systematically increases the flow rate. This is even evident when analyzing the individual response of a standard SPACER fluid mixture for shear stress values against shear rate at different RPM. For instance, at 3 RPM, the shear stress was 2 lb/ft^2 bringing about a shear rate of 3sec^{-1} which is relatively low based on the low RPM applied. As the speed of the rheometer was increased to 6RPM, the shear stress and shear rate simultaneously increased from 2 lb/ft^2 to 3 lb/ft^2 and from 3 sec^{-1} to 5sec^{-1} respectively. A further increase of the speed to 100 RPM resulted to a higher and sequential increase of the shear stress to 16 lb/ft^2 from 3 lb/ft^2 and 27sec^{-1} from the initial 5 lb/ft^2 shear rate. As the rotary speed increased further upward to 200RPM, the shear stress increase to 23lb/ft^2 resulting to an increased shear rate of 39sec^{-1}. Furthermore, at 300 RPM rotary speed, the shear rate of the spacer fluid and spacer moved upward to 29 lb/ft^2 resulting to an additional increase of the shear rate flow to 49sec^{-1}. Finally, at 600 RPM rotary speed, the spacer fluid increased spontaneously from 29 lb/ft^2 shear rate value to 46 lb/ft^2 resulting to an increase of the shear stress from 49 sec^{-1} to 78sec^{-1} shear rate value. This simply indicate that a higher shear stress at 80^{0}F brings about an increased flow rate of the spacer fluid, which is supposed to give a better cleaning of the well bore to ensure proper and efficient cement bonding. But, again a higher flow rate does not always mean a better hole cleaning, if other indices like pipe rotation, fluid rheology, cutting size and inclination are not duly considered, [4].

Moreover, looking at the various components of the spacer fluid–OBM mixtures at different ratios, both at 151^{0}F and you will observe that the results obtained in the experiment followed the same trend. For instance, with reference to table A12, at a ratio of 25% spacer and 75% OBM, it was observed that the values of the shear stresses of the spacer and OBM mixtures when testing at 3rpm, 6rpm, 100rpm, 200rpm, 300rpm, 600rpm respectively, increased steadily from 17($lb/100ft^2$), 23($lb/100ft^2$), 62($lb/100ft^2$), 84($lb/100ft^2$), 98($lb/100ft^2$), 126($lb/100ft^2$), respectively which resulted in the corresponding increase of the shear rate (flow rate) from 29sec^{-1}, 39 sec^{-1}, 106 sec^{-1}, 143 sec^{-1}, 167 sec^{-1}, to 214sec^{-1} respectively.

Similarly, looking at the various components of the spacer fluid–OBM mixtures at different ratios, and at 151^{0}F it was observed that the results obtained in the experiment followed the same trend. For instance, with reference to table A13, at a ratio of 50% spacer and 50% OBM, it was observed that the values of the shear stresses of the spacer and OBM mixtures when testing at 3rpm, 6rpm, 100rpm, 200rpm, 300rpm, 600rpm respectively, increased steadily from 6(lb/100ft^2), 7(lb/100ft^2), 16(lb/100ft^2), 22(lb/100ft^2), 30(lb/100ft^2), 95(lb/100ft^2), respectively which resulted in a corresponding increase of the shear rate values (flow rate) from 10sec^{-1}, 12 sec^{-1}, 27 sec^{-1}, 37sec^{-1}, 51sec^{-1} to 162sec^{-1} respectively.

The same experience was also observed, looking at the various components of the spacer fluid–OBM mixtures at different ratios, both at 151^{0}F you will observe that the results obtained in the experiment followed the same trend. For instance, with reference to table A14, at a ratio of 75% spacer and 25% OBM, it was observed that the values of the shear stresses of the spacer and OBM mixtures when testing at 3rpm, 6rpm, 100rpm, 200rpm, 300rpm, 600rpm respectively, increased steadily from 2(lb/100ft^2), 3(lb/100ft^2), 10(lb/100ft^2), 16(lb/100ft^2), 20(lb/100ft^2), 40(lb/100ft^2), respectively which resulted in a corresponding increase of the shear rate values (flow rate) from 3sec^{-1}, 5sec^{-1}, 17sec^{-1}, 27sec^{-1}, 34sec^{-1} to 68sec^{-1} respectively.

Finally, it was also observed, looking at the various components of the spacer fluid mixtures at different ratios, both at 151^{0}F you will observe that the results obtained in the experiment followed the same trend. For instance, with reference to table A15, at a ratio of 100% spacer without any mixture of OBM, it was observed that the values of the shear stresses of the spacer and OBM mixtures when testing at 3rpm, 6rpm, 100rpm, 200rpm, 300rpm, 600rpm respectively, increased steadily from 2(lb/100ft^2), 3(lb/100ft^2), 11(lb/100ft^2), 17(lb/100ft^2), 21(lb/100ft^2), 23(lb/100ft^2), respectively which resulted in a corresponding increase of the shear rate values (flow rate) from 3sec^{-1}, 5sec^{-1}, 19sec^{-1}, 29sec^{-1}, 36sec^{-1} to 39sec^{-1} respectively (Figures 7 and 8).

4. Conclusion

Based on the results of the experimental study the following conclusions were made

1. The study proved the mud / spacer admixture Compatibility and ability of the Spacer to create interfacial inversion to make the hole water-wet. This is in tandem with recent work works (Shantanu, et al., 2020).
2. It was found that temperature increment brought about the corresponding decrease in the plastic viscosity of both the spacer and oil-based mud.
3. The mathematical model part of this work showed that turbulent flow regime or transient flow regime was the suitable for proper hole cleaning for better cementing job.
4. Spacer and oil-based cement responded in a similar manner to the change in temperature; hence it proved they were compatible.
5. The R-index values showed that the OBM and spacer were compatible at the selected temperature range.

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Appendices

Table A1: Effect of Temperature on Plastic viscosity for Spacer

PV	Temperature
17	80
13	100
8	120
2	151

Table A2: Effect of Temperature on Plastic viscosity for Oil based mud

PV	Temperature
45	80
36	100
32	120
30	151

Table A3: Effect of Temperature on Yield Point for Spacer

YP	Temperature
12	80
12.6	100
13	120
14	151

Table A4: Effect of Temperature on Yield Point for Oil Based Mud

YP	Temperature
25	80
38	100
52	120
72	151

Table A5 Rheological Tests for OBM and Spacer at 80°F

Rotational Speed	Dial Readings	
(rpm)	Oil Based Mud	Spacer
600	115	46
300	70	29
200	53	23
100	35	16
6	12	3
3	10	2
PV (cP)	45	17
YP (lb/100ft^2)	25	12

Table A6 Rheological Tests for OBM and Spacer at 150°F

Rotational Speed	Dial Readings	
(RPM)	Oil Based Mud	Spacer
600	132	23
300	102	18
200	86	17
100	64	11
6	25	3
3	22	2
PV (cP)	30	2
YP (lb/100ft^2)	72	14

Table A7 Results of Shear Stress (lb/100ft^2) and Shear Rate (Sec^{-1}) for OBM and Spacer at 80°F

Shear Rate (Sec^{-1})	Shear Stress (lb/100ft^2)	
	Oil Based Mud	Spacer
1021.38	122.0	49
510.90	115.5	31

340.60	56	25
170.30	38.	17
10.22	13	3
5.11	11	2

Table A8: Results of Shear Stress ($lb/100ft^2$) and Shear Rate (Sec^{-1}) OBM and Spacer at 150°F

Shear Rate (Sec^{-1})	Shear Stress ($lb/100ft^2$)	
	Oil Based Mud	Spacer
1021.38	154	25
510.90	109	19
340.60	92	17
170.30	\68	12
10.22	27	3
5.11	23	2

Table A9 Investigation of Compatibility of Spacer with OBM using PV of the mixture

Plastic Viscosity (cp)	Mixture (%)
30	100% OBM
28	75/25
25	50/50
16	25/75
2	100% Spacer
0	0

Table A10 Investigation of Compatibility of Spacer with OBM using Yield Point of the mixture

Yield Point ($lb/100ft^2$)	Mixture (%)
72	100% OBM
70	75/25
15	50/50
14	25/75
14	100% Spacer

Table A11: Investigation of the Wettability of the Spacer fluid using Shear stress /shear rate for 100% Spacer at 151°F.

RPM(ϴ)	Shear stress ($lb/100ft^2$)	Shear rate (Sec^{-1})
3	2	3
6	3	5
100	11	19
200	17	29
300	21	36
600	23	39

Table A12 Investigation of the Wettability of the Spacer fluid using Apparent Viscosity for 100% OBM at 151°F

100% OBM @151°F		
RPM (ϴ)	Shear stress ($lb/100ft^2$)	Apparent Viscosity (cp)
600	132	66
300	102	51
200	86	43
100	64	32

6	25	12.5
3	22	11

Table A13: Investigation of the Wettability of the Spacer fluid using Apparent Viscosity for 25% Spacer/ 75% OBM at 151°F

25%Spacer75% OBM @151°F		
RPM (Ɵ)	**Shear stress (lb/100ft²)**	**Apparent Viscosity (cp)**
600	126	63
300	98	49
200	84	42
100	62	31
6	23	11.5
3	17	8.5

Table A14 Investigation of the Wettability of the Spacer fluid using Apparent Viscosity for 50% Spacer/ 50%OBM at 151°F.

50%Spacer/50% OBM @151°F		
RPM (Ɵ)	**Shear stress (lb/100ft²)**	**Apparent Viscosity (cp)**
600	95	47.5
300	30	15
200	22	11
100	16	8
6	7	3.5
3	6	3

Table A15 Investigation of the Wettability of the Spacer fluid using Apparent Viscosity for 75% Spacer/ 25%OBM at 151°F.

75% Spacer/25% OBM @151°F		
RPM (Ɵ)	**Shear stress (lb/100ft²)**	**Apparent Viscosity (cp)**
600	40	20
300	20	10
200	16	8
100	10	5
6	3	1.5
3	2	1

Table A16 Investigation of the Wettability of the Spacer fluid using Apparent Viscosity for 100% Spacer at 151°F.

100% Spacer @151°F		
RPM (Ɵ)	**Shear stress (lb/100ft²)**	**Apparent Viscosity (cp)**
600	23	11.5
300	21	10.5
200	17	8.5
100	11	5.5
6	3	1.5
3	2	1

Table A17 Compatibility Tests for OBM and Spacer at 151°F

Rotational Speed	**OBM**	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**	**OBM**	**Spacer**
RPM	**100**	**0**	**75**	**25**	**50**	**50**	**25**	**75**	**0**	**100**

600	132	126	65	46	23
300	102	98	40	30	18
200	86	84	22	16	17
100	64	62	16	10	11
6	25	23	7	5	3
3	22	17	6	2	2
PV	30	28	25	16	2
YP ($lb/100ft^2$)	**72**	**70**	**15**	**14**	**14**

Table A18 Compatibility Tests for OBM and Spacer at 120°F

Rotational Speed RPM	**Shear Stress ($lb/100ft^2$)**									
	OBM 100	Spacer 0	OBM 75	Spacer 25	OBM 50	Spacer 50	OBM 25	Spacer 75	OBM 0	Spacer 100
600	135		110		47		40		36.5	
300	95		84		24		24		19	
200	58		69		13		14		10.4	
100	40		32		10		9		7.75	
6	22		18		5		4		3.2	
3	17		12		3		2		2	

Table A19 Compatibility Tests for OBM and Spacer at 100°F

Rotational Speed RPM	**Shear Stress ($lb/100ft^2$)**									
	OBM 100	Spacer 0	OBM 75	Spacer 25	OBM 50	Spacer 50	OBM 25	Spacer 75	OBM 0	Spacer 100
600	150.2		131.7		120		79.45		50.4	
300	120.45		100.79		99.30		30.7		27.23	
200	70.5		90.90		69.20		20.5		17.4	
100	40		67.50		50.45		19.7		16.20	
6	24.20		39.5		8.9		4.2		3.2	
3	20.30		12		3.7		6.9		2	

Table A20 Compatibility Tests for OBM and Spacer at 80°F

Rotational Speed RPM	**Shear Stress ($lb/100ft^2$)**									
	OBM 100	Spacer 0	OBM 75	Spacer 25	OBM 50	Spacer 50	OBM 25	Spacer 75	OBM 0	Spacer 100
600	200.20		187.50		150.45		100.97		98.60	
300	170.4		100,70		102.60		108.65		100.7	
200	70.5		97.24		69.10		84.79		74.20	
100	62.50		67.50		60.45		59.00		50.76	
6	24.40		39.5		47.80		40.25		37.65	
3	24.30		18.65		20.40		17.50		16.96	