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Rheological Properties of Fiber-Containing Drilling Sweeps at Ambient and Elevated Temperatures

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Abstract

Fiber-containing sweeps (fiber sweeps) are effective tools for wellbore cleaning in horizontal wells. It has been shown that adding fiber to traditional sweeps can result in an increase in cuttings removal and reduction in cuttings bed thickness, which reduces the amount of torque and drag in horizontal wells. Despite some reported successes in the field and favorable research results, the fluid and fiber properties that define and influence fiber sweep rheology are not fully understood.

The hole-cleaning capabilities of weighted sweeps, high- and low-viscosity sweeps, and tandem sweeps are well documented. However, these conventional sweep methods often result in an increase in equivalent circulating density (ECD). Fiber-containing sweeps, which have promise to overcome this ECD disadvantage, are becoming popular alternatives. However, little detail is known about the flow and cuttings-carrying properties of these slurries.

This article presents the rheological measurements carried out on fiber-containing sweep fluids. Tests were conducted using various unweighted and weighted water-based, mineral oil-based and internal olefin-based drilling fluids with concentrations of a monofilament synthetic fiber ranging up to 0.4 lb/bbl. The rheology was measured at ambient and 170°F. The study shows that fiber concentration has minimal effect on viscosity, indicating a negligible increase in ECD while providing improved sweep efficiency. These results can be useful for formulating sweep fluids utilized in deepwater applications.

Introduction

Poor hole cleaning can lead to an increase in non-productive time and costly drilling problems such as stuck pipe, premature bit wear, slow rate of penetration, formation fracturing, and high torque and drag (Ahmed and Takach 2008). A number of field-tested techniques have been introduced over the years to improve hole cleaning, cuttings transport, and prevent the formation of cuttings beds in the wellbore. Previous studies indicate that cuttings transport in directional wells is dependent on fluid rheology, wellbore inclination angle, rotary speed of the drillpipe, flow rate, wellbore geometry, and other drilling parameters (Valluri et al. 2006). Considering these factors, the most economical and easily employed procedures involve adding viscosifiers and weighting agents to the drilling fluid to increase the ability of the fluid to transport cuttings to the surface. Also, increasing the flow rate has the ability to re-suspend cuttings, with the maximum pump rate generally providing the best hole cleaning conditions. However, pressure losses and the equivalent circulating density (ECD) must be considered when increasing the flow rate. Although turbulent flow can produce optimal hole cleaning, turbulent flow also can erode the filter cake and borewall, as well as increase ECD. Therefore, using laminar flow at maximum flow rate, paired with fiber sweeps and mechanical agitation such as drillstring rotation and reciprocation is usually the preferred method for removing cuttings beds (Cameron et al. 2003). However, these methods often only slow the formation and buildup of cuttings beds and are not effective at removing cuttings beds. In response to these problems, drilling fluid sweeps are utilized. The sweeps remove cuttings that cannot be transported to the surface during normal fluid circulation while drilling and provide additional vertical lift to the cuttings. Sweeps can be performed in all well inclinations from vertical to horizontal, as required by wellbore conditions. In deviated, highly inclined, and extended reach drilling (ERD) wells, sweeps are an essential tool to facilitate wellbore cleaning.

In highly deviated wellbores and especially ERD wells, the cuttings transport performance of a drilling fluid generally diminishes. Some highly shear-thinning fluids, such as are used in milling operations, are an exception; even in horizontal wells, the strong viscous coupling between the rotating drillstring and fluid can bring up even metal shavings and fist-sized rock. In highly deviated wellbores, the fluid velocity has little vertical component, reducing the ability of the drilling fluid to suspend and carry the cuttings. The increased wellbore length results in higher ECD that limits the flow rate and provides more opportunity for the cuttings to form a bed on the low side of the wellbore. Also, the drillpipe rests on the low side of the wellbore in horizontal sections, forcing the majority of the fluid to the high side, reducing the flow on the low side which further encourages the formation of cuttings beds. Inadequate hole cleaning is common with ERD wells.

Sweeps containing traditional fibrous lost circulation materials (LCM) have been shown to decrease cuttings and silt beds, as well as reduce torque and drag and improve the rate of penetration (Cameron et al. 2003). These materials generally refer to organic fibers or plant-derived abrasive substances. Experimental studies (Ahmed and Takach 2008) and field applications (Bulgachev and Pouget 2006) have shown that specially designed sweeps containing synthetic monofilament fibers show improved hole cleaning efficiency over comparable non-fiber sweeps. While these and other cases demonstrate favorable results when utilizing fiber sweeps, the method for designing these sweeps is still not fully developed. Visually observing shaker screens to determine whether cuttings transport rate is constant or changing and plotting these trends versus the sweep volume and fiber concentration are the predominant methods of monitoring hole-cleaning efficiency.

When fully dispersed in the sweep fluid, fibers form a stable network structure that tends to support cuttings due to fiber-fiber and fiber-fluid interactions. The fiber-fiber interactions can be by direct mechanical contact and/or hydrodynamic interference among fiber particles. Mechanical contact among fibers improves the solids-carrying capacity of the fluid (Ahmed and Takach 2008).

Mechanical contact between the fibers and cuttings beds aid in re-suspending cuttings deposited on the low-side of the wellbore. As the fibers flow through annulus, mechanical stresses develop between the settled cuttings and the fibers. These mechanical stresses result in a frictional force which helps to re-suspend the cuttings, while the fiber networks carry the solids to the surface. Also aiding in the solids transport is the fiber-fiber interaction that enables the fiber network to move as a single phase. This fiber network can separate from the fluid phase. Therefore, at the surface of the cuttings bed the fiber may have a higher velocity than the fluid phase, which is typically very low. These fast moving fibers can therefore transfer more momentum to the deposited solids, overcoming the static frictional forces and initiating movement.

This study was undertaken to determine the effect of a fiber on drilling fluid rheology. This monofilament synthetic material is used in hole-cleaning sweeps throughout the industry. Tests were conducted of various unweighted and weighted water-based, mineral oil-based and internal olefin-based drilling fluids with a range of fiber concentrations. The rheology was measured at ambient and 170°F. The results are expected to be useful for formulating sweep fluids in deviated and deepwater applications.

Literature Review

Hole-cleaning sweeps may be classified as high-viscosity; high-density; low-viscosity; combinations; and tandem (Hemphill and Rojas 2002). Factors that govern sweep selection include hole angle, fluid density, lithology, cuttings diameter, drillpipe rotation and fracture gradient (Power et al. 2000). In deepwater and deviated wells, the drilling window between the fracture gradient and pore pressure generally narrows with increasing depth and hole angle, respectively, reducing the available options for hole cleaning sweeps. In addition, long horizontal departures are common in order to reduce the environmental impact. This, combined with the marginal operating window, necessitates a strict adherence to a manageable ECD. To properly manage the ECD, drilling fluid rheology must be optimized for the conditions, and the wellbore must be as free of cuttings as possible.

Surface torque and the ability of the rig to overcome it is an important factor when deciding the feasibility of drilling a well, especially an ERD well. The friction generated between the wellbore and the drillstring in long horizontal sections creates the surface torque. Hole tortuosity in ERD wells further reduces the ability of the drilling fluid to adequately carry cuttings to the surface. Leaving cuttings behind adds resistance to the drillstring, which proportionately increases wellbore friction and surface torque (Maehs et al. 2010).

The incorporation of fibrous LCM in the drilling fluid proved a major factor in reducing torque 25% on ultra-extended reach wells (Cameron 2001). In drilling an extended reach well in Abu Dhabi, the incorporation of fibrous hole cleaning sweeps resulted in a dramatic decrease in torque and drag and increased the rate of cuttings return to the surface by 50% (Cameron et al. 2003). While drilling Wytch Farm extended reach wells, it was observed that the addition of fibrous LCM impacted the measurable torque and drag (Robertson et al. 2005). In this case, the LCM was added both to the whole mud system and supplemented with sweeps. It is thought that the sweeps initiated the decrease in torque, and the LCM in the drilling fluid maintained the reduced torque levels. The mechanism by which the fibrous LCM decreased the torque was believed to be better hole cleaning and increased lubricity. The manner in which these mechanisms developed and operated is not fully understood, but one explanation is that the fibers intertwined to form a mesh, which scoured the wellbore. The fibers could also have acted as little roller bearings, increasing the lubricity of the drillstring, further reducing torque (Robertson et al. 2005).

Flexible fibers in suspension form three-dimensional networks which exhibit shear strength and viscoelastic properties as a result of the mechanical entanglement. At higher concentrations, the fiber suspension is capable of supporting a load and transmitting shear stress through the entire flow regime (Swerin 1997). The mechanical entanglement of the fiber networks can actually hold particles in suspension, preventing or slowing their segregation. As such, fiber fluid suspensions have been shown to be an effective transport mechanism for hydraulic fracturing proppant (Bivins et al. 2005). When fibers are not present, settling of proppant proceeds according to Stokes' law. With fibers, Stokes' law does not strictly apply, because the fibers interfere with the settling process. That generates additional drag, and a distinct liquid-particle boundary does not develop.

A slot test was conducted to evaluate the proppant transport capability and settling prevention property of the fiber. Proppant in the fiber slurry was stable, and all proppant remained in suspension during the test. Graphical data showed a decrease in settling velocity of greater than one order of magnitude, as compared to fluid with no fiber. Furthermore, under the test conditions, it was determined that the minimum fluid viscosity to ensure adequate proppant transport was about 100 cP at 100 s^{-1} shear rate (Bivins et al. 2005).

The addition of fiber to a fluid also delays the onset of turbulent flow, thus reducing drag and maintaining the flow in the laminar regime (Gupta et al. 2002). When fibers are added to a shear flow, the fiber particles orient themselves in the direction of the deformation tensor. This realignment enhances the fluid's ability to resist amplification of disturbances. The critical Reynolds number increases as well as the general stability of the fluid as the fiber volume fraction and aspect ratio increase (Gupta et al. 2002). It has also been shown that the presence of fiber or fiber flocs can reduce the intensity of turbulence and encourage plug flow (Xu and Aidun 2005). This property of fiber-laden fluids is beneficial for hole cleaning operations, as higher pump rates may be used while keeping the fluid in laminar flow. Turbulent flow, while beneficial for wellbore cleaning, can erode the filter cake, resulting in lost circulation or formation damage.

Fiber Fluid Rheology

Controlling the rheology of the drilling and sweep fluids is essential to maintain favorable wellbore hydraulics and hole cleaning efficiency. This is of utmost importance when drilling extended and ultra-extended reach wells in deepwater where the pressure window often requires a minimum overbalanced wellbore pressure condition. In such environments, the pressure and temperature ranges rise to levels that are difficult to emulate in laboratory experiments, making it difficult to precisely predict the rheology of the fluids downhole.

To predict the transport properties and performance of fiber fluid sweeps in downhole conditions, the basic rheology of the base fluid and suspension must be understood. The proposed formulations for such fiber sweeps will be most effective when the rheology has been accurately modeled and fine-tuned for specific wellbore eccentricities. To begin to grasp how the fluid behaves, the relationship between shear stress and shear rate must be known. This is denoted as the shear viscosity profile, which is an aspect of the rheology of a fluid that is thought to control laminar flows in pipes, annuli and other geometries. The most common shear viscosity models used to characterize non-Newtonian drilling fluids include:

Bingham-Plastic (BP)

$$\tau = YP + PV\cdot\gamma$$

Power Law (PL)

$$\tau = K\gamma^n$$

Yield Power Law (YPL)

$$\tau = \tau_y + K\gamma^n$$

where τ = shear stress at the wall, γ = shear rate, YP = yield point, PV = plastic viscosity, K = consistency index, n = power law index and τ_y = yield stress. It will be noted that thixotropic effects like gel strength are not included in these treatments.

As cuttings carrying capacity is a desirable trait of drilling fluid, a measurable yield stress must be present to hold the cuttings in suspension. The classic viscosity model used for drilling fluids is the Bingham-Plastic or pseudoplastic model. Here the shear stress rises linearly with shear rate, with a slope given by PV. The intercept on the τ axis, YP, is often identified with the carrying capacity of the fluid. Most drilling fluids exhibit a non-linear shear stress-shear rate relationship, which is best described by the Yield Power Law model. The YPL model is useful in describing a wide range of polymer-based, oil-based and synthetic-based drilling fluids, from low shear rate to high shear rate. For fluids with yield stress (τ_y), such as the YPL fluid, a certain shear stress must be overcome before flow can initiate. Without yield stress, the fluid simply follows the PL model. The other two curve-fitting parameters describe the rheology of PL fluid. K is the viscosity of the fluid at a shear rate of 1.0 s^{-1}, therefore providing an effective description of fluid viscosity at low shear rates. The flow behavior index, "n", indicates the shear-thinning tendency of the fluid. In Newtonian fluids, where viscosity is constant, "n" is equal to one. Reducing "n" creates a fluid that is shear-thinning, which decreases the effective annular viscosity and flattens the annular velocity profile, increasing the overall hydraulic efficiency.

Recently, the viscosity profiles of synthetic-based drilling fluids were measured from 80 to 280°F and from 0 psig to 5000 psig (Demirdal et al. 2007). The study showed the rheology to be extremely sensitive to downhole conditions, with the yield stress and consistency index drastically changing with varying temperature and pressure. The overall trend was that these parameters decreased with increasing temperature, and increased with increasing pressure. The evaluation also showed that the Yield Power Law model continued to described the shear stress-shear rate relationship at all pressure and temperature conditions. Another study developed a simulator to determine the cuttings transport efficiency of drilling fluid under high-temperature and high-pressure conditions (up to 200°F and 2,000 psi). The experimental trend showed that higher temperatures diminished the cleaning efficiency of the fluid (Yu et al. 2007). Recent experiments studied water-based drilling foam and the effect of temperature on the cuttings concentration in a horizontal wellbore (Zhu 2005). The results showed that cutting concentration in the annulus generally increased as the fluid temperature increased.

Previous studies (Demirdal et al. 2007; Yu et al. 2007) show that temperature significantly alters the rheology of drilling fluids and influences the cuttings transport efficiency. As the rheological properties change, so too does the fluid's ability to exert viscous and drag forces on the cuttings and the fiber. As the fluid become thinner with elevated temperature, the amount of momentum transferred to the cuttings is diminished. The thinner fluid also loses its ability to maintain a uniform fiber concentration while flowing in the annulus.

This separation decreases the hole-cleaning ability of the fiber.

In designing a fiber-fluid formulation for wellbore cleaning sweeps, certain rheological parameters give a good indication of how well the sweep will perform. The yield stress and yield point of the fluid represent the amount of force required to move the fluid. At the same time, if the fluid possesses adequate yield stress to prevent the natural buoyancy of the fiber, the fiber will not separate. The yield stress indicates how well the sweep will maintain uniformity when circulating up the annulus.

Experimental Investigations

The current investigation involves experimental studies of the rheology of fiber-containing sweep fluids. Several base fluids were chosen to simulate the various drilling and sweep fluids utilized in the field (**Table 1**). A specially processed 100% virgin synthetic monofilament fiber was supplied for this research (**Table 2**), and was mixed with the base fluids at varying concentrations.

The water-based fluids included fluids prepared with xanthan gum (XG) at two mud weights, polyanionic cellulose (PAC), partially hydrolyzed polyacrylamide (PHPA) and mixtures of XG and PAC. Formulations were prepared with a broad range of concentrations of these polymers. Also tested were weighted mineral oil-based and internal olefin-based drilling fluids.

Experimental Setup and Procedure

The shear viscosity experiments were conducted using stand mixers (**Fig. 1**), rotational viscometers (Chandler 35 and Fann 35A, **Fig. 2**), thermocup, mud balance, and a laboratory oven. The Chandler 35 rotational viscometer has 12 speeds, and was modified to include a 1/5 spring. The weaker spring allows for more sensitive and accurate measurements in the low-shear-rate range, and reports all dial readings 5x higher than actuality. Both viscometers were calibrated and tested using multiple fluids to ensure readings were comparable.

The steps required to prepare the samples and record measurements are as follows:

Step 1. **Preparation of Base Fluid:** Bulk base fluid samples were prepared by mixing water, polymeric viscosifiers and barite. Immediately after mixing, all water-based fluids were covered and left undisturbed for a minimum of 24 hours to ensure full hydration. The fluids were then re-agitated, and a uniform sample was obtained to determine the specific gravity using the mud balance.

Step 2. **Preparation of Samples:** After fluids were mixed and hydrated (if necessary), individual samples were weighed and organized according to the polymer and fiber concentration (**Fig. 3**). Fiber was added to the samples at weight concentrations of 0.02%, 0.04%, 0.06%, and 0.08%. For the unweighted water-based fluids, 0.08% corresponded to 0.28 lb/bbl fiber, whereas for the 12-lb/gal water-based and non-aqueous fluids, it corresponded to 0.4 lb/bbl fiber.

Step 3. **Viscosity Measurements at Ambient Temperature:** After all the samples were prepared, the shear viscosity profiles of the base fluids were measured using two rotational viscometers (Chandler 35 and Fann 35A). If the viscosity of the fluid being measured exceeded the spring capacity of the Chandler 35, the Fann 35A was utilized for the higher shear rate measurements.

Step 4. **Viscosity Measurements at Elevated Temperature:** Samples were placed in an oven for heating. The oven was set at approximately 180°F, and samples were agitated every 15 minutes to ensure uniformity. Once a sample was heated to 170°F as confirmed by a mercury thermometer, the sample was removed from the oven and mixed for 30 seconds using a stand mixer. This mixing time was deemed adequate to achieve uniform re-dispersion of the fibers. Immediately after mixing, a portion of the sample was poured into the thermocup. Using a mercury thermometer, the thermocup temperature was adjusted to achieve a constant fluid temperature of 170°F. The viscometer measurements were taken using the procedure described in Step 3.

Results

The shear stress of each fluid was measured from 1 rpm to 600 rpm at ambient and elevated temperature. When circulating through the annulus, most parts of the fiber sweep are in the plug flow regime. Therefore, the low-shear-rate range is more significant when analyzing and predicting the behavior of these fiber sweeps under downhole conditions. However, to provide a general understanding of fiber sweeps, **Figs. 4** to **9** show the results of the viscometer measurements for the entire shear rate range.

Experiments were conducted with four (4) increasing levels of fiber concentration (Step 2). For the majority of the fluids tested, the trends were consistent as fiber concentration increased. To reduce data clutter, only the intermediate (0.14-lb/bbl) and high (0.28-lb/bbl) fiber concentrations were included in the figures for the water-based drilling fluids.

Effect of Fiber Concentration

One goal of the research was to determine the effects that adding fiber and increasing the fiber concentration have on the rheology of the fluid. As it has been shown in previous studies (Ahmed and Takach 2008), adding fiber to fluid has an insignificant effect on the flow behavior of the fluid. According to field results and supporting theories stated previously, adding fiber to the fluid may actually improve the hole cleaning performance without affecting the rheological properties of the fluid. After analyzing the results of the viscometer experiments we have found that the fiber has no predictable influence on the fluid rheology. In most cases, the addition of fiber to the base fluid resulted in a slight increase in shear stress (**Figs. 5a, 6c, 8b**). Other times, the base fluid exhibited a higher shear stress than the fiber fluid (**Fig. 7c**). Despite these deviations from the base fluid, the magnitude of their departure from the baseline was relatively insignificant. Careful observation of these figures will show that at shear rates less than 10 s^{-1}, the shear stress values for the majority of cases were nearly identical (**Figs. 7c** and **8b**).

In another case, two similar polymeric fluids showed contradicting trends. The high-temperature, weighted fiber fluid mixed with 0.87-lb/bbl XG polymer (**Fig. 7a**) showed the most common characteristic, with the shear stress increasing with fiber concentration. This is apparent in the low-shear-rate range, though the influence of fiber concentration is much less in the high-shear-rate range. Conversely, the high-temperature, weighted fiber fluid mixed with 1.75-lb/bbl XG mud (**Fig. 7b**) shows an opposing trend, with fiber concentration reducing shear stress throughout the shear rate range measured. Despite this peculiarity, the change in shear stress in the region of interest (low shear rate) is of little consequence. At the shear rate 51.09 s^{-1}, the difference in shear stress between the base fluid and 0.4 lb/bbl fiber fluid (**Fig. 7a**) is 15%.

Another important point is the remarkably minor influence that fiber concentration has on shear stress in the oil-based and synthetic-based muds. Even at low shear rates, the change in shear stress ranges from 4% to 6% for most cases, with the most extreme difference of 8.8% at 51 s^{-1} (Fig. 9a). This finding is encouraging, as it implies that fiber may be added to sweeps to enhance hole cleaning without increasing the ECD. Oil-based and synthetic-based muds are often used in harsh, not-easily-accessible environments where there is concern for shale interaction and environmental impact. These well locations often require high-angle wells to reduce the footprint and target multiple formations. Fiber sweeps might be employed to reduce the cuttings beds in these extended reach horizontal wells where pressure loss along the annulus is a major concern.

In every case, the addition of fiber had no significant impact on the general shape of the shear stress vs. shear rate plots. The data obtained for the base fluid accurately describes the behavior of the fiber fluid at both ambient and elevated temperatures.

In a study conducted by Ahmed and Takach (2008), the hole-cleaning efficiency of fiber sweeps was compared to base fluid (viscous) sweeps. The experiments were carried out in a flow loop with varying inclination angles, measuring the cuttings bed height and frictional pressure loss during sweep circulation. For the same annular velocity, the fiber sweeps generally showed a reduced bed height in the flow loop annulus. Annular pressure loss was recorded as a function of time for various flow rates. The results indicate that frictional pressure loss is approximately equal for the base fluid and fiber sweep. In one instance, the fiber sweep pressure loss was less than that exhibited by the base fluid.

Pipe viscometer experiments were also conducted comparing flow curves of the base fluid and fiber sweep. Viscometer pressure loss was measured as a function of flow rate. At low flow rates (laminar, plug flow regime), pressure loss for the base fluid and fiber sweep were equal and the flow curves were similar. A similar conclusion was drawn from a previous study (Xu and Aidun 2005) comparing velocity profiles as a function of fiber concentration. The inclusion of a small amount of fiber had minimal effect on the velocity profile at low Reynolds number flow.

Effect of Temperature

In order to reproduce the behavior of the fiber fluid under downhole conditions, the ambient temperature experiments were repeated at high temperature, as shown in **Fig. 4** to **Fig. 9**. The general trend exhibited in all the fluids studied is that the fluid's ability to flow increases with temperature. The warmer temperature creates a "thin" fluid that is more easily deformed. This enhanced tendency for deformation diminishes the fluid's ability to project its inherent flow resistance.

An important trend becomes apparent when analyzing how temperature influences viscosity at different fiber concentrations. As mentioned previously, adding fiber or increasing fiber concentration shows a general tendency for slightly higher viscosity measurements at ambient temperature, when compared to the base fluid. In most cases, this same trend is observed in the high-temperature measurements (**Figs. 6c** and **6d**). However, in some fluids, the increased temperature nullified the influence of fiber concentration (**Fig. 4b**). In these instances, adding fiber to the fluid resulted in an increase in viscosity at ambient temperature. However, when taking measurements of the same fluid at high temperature, the fiber showed little or no influence on the viscosity.

The oil-based and synthetic-based muds show remarkable behavior at ambient and elevated temperature. Regardless of temperature, the fiber has an insignificant influence on viscometric measurements. Throughout the entire shear rate range, the percentage difference between base fluid and fiber fluid remains low and relatively constant. None of the water-based fluids tested showed this level of control over the entire shear rate range at both temperatures.

The temperature of the fluids was altered to provide a closer representation to actual downhole conditions. However, elevated pressure conditions in the wellbore were not considered in this study, partly as a consequence of the operational capability of the equipment available for these experiments. Previous studies have investigated the effect of elevated pressure on the rheology of various fluids. Zhou et al. (2004) conducted experiments to investigate aerated mud cuttings transport in an high-pressure, high-temperature (HPHT) flow loop. The effect of elevated pressure (up to 500 psi) was found to have minimal influence on cuttings concentration. Another study (Alderman et al. 1988) investigated the influence of high temperature and high pressure on water-based mud. The viscous behavior of the fluids in the HPHT conditions reflected the characteristics of their respective continuous phases: a weak pressure dependence and an exponential temperature dependence. It was also shown that the fluid yield stress was essentially independent of pressure, but highly influenced by temperature. Other studies concentrating on the pressure and temperature effects on cement slurry rheology gave similar results. The plastic viscosity of the cement slurry showed little increase with increasing pressure (up to 5000 psi) in relation to the significant effect of increased temperature up to 260°F (Ravi and Sutton 1990).

Shear Viscosity Parameters

The first step in analyzing the fiber fluid shear viscosity was to record all the viscometer shear stress measurements. Least-squares regression was performed to determine the rheological parameters for all fluid-fiber-temperature formulations (**Tables 3 through 8**). The coefficient of determination, R^2, represents how well the measured shear stress values correlate with the values predicted by the Yield Power Law model. An R^2 value of 1.00 represents an exact match of experimental data with the predictive model data. The vast majority of the experimental data points fit the regression model extremely well.

As discussed previously, the shear viscosity models are mathematical relations that approximately represent the measured data using curve-fitting parameters. Some properties believed to exist in some polymers do not always manifest themselves. For instance, XG fluids typically exhibit a yield stress only at high concentrations. At low concentrations, XG fluids best fit the regular Power Law model without a yield stress. This yield stress value increases as polymer concentration increases and the fluid becomes more viscous at low temperature (**Table 3**). However, at high temperature (170°F) even the higher concentration fluids do not show a yield stress value. Regardless, neither PAC (**Table 4**) nor PHPA (**Table 7**), by contrast, is expected to show a yield stress. Indeed that is the case, except for a couple of PHPA cases. However, the uncertainty in the yield stress in all of these cases is expected to be approximately 1 lb/100 ft^2.

When using the regression analysis, the yield stress necessary to allow for the best curve fit may be infinitesimally small, while other times the data fits best with a zero yield stress. Such was the case with XG and PAC fluids. As discussed previously, at high polymer concentration, the XG fluid analysis resulted in zero yield stress, while the PAC fluids showed a yield stress less than one. However, plotting the data provides a more realistic picture of which fluids obey the PL or YPL model. **Fig. 10** clearly shows that at identical conditions and polymer concentration, the XG fluid exhibits a true yield stress.

Conclusions

This study was conducted to investigate the effects of temperature and fiber concentration on the rheology of fiber-containing sweeps. Rheology experiments were conducted using rotational viscometers to measure the rheology of base fluids and fiber-containing fluids at ambient temperature and 170°F. The shear viscosity profiles of fiber sweep fluids were compared using graphical and curve-fitting regression analyses. Based on the experimental results and data analysis, the following conclusions can be made:

- Fiber sweeps may well be utilized to increase cuttings removal from the wellbore with no effect on the ECD, unlike traditional high density and high viscosity sweeps, whose usefulness is limited in extended reach wells due to their tendency to increase the ECD.

- The addition of fiber up to 0.08 wt% has a minor effect on the fluid's shear viscosity profile, whether at ambient temperature or 170°F. Some instances showed slight increases in viscosity, while others showed a decrease with increasing fiber concentration.

- In most cases, as fiber concentration increased, the viscosity showed increasingly non-Newtonian behavior; with the Yield Power Law model, n decreased while K and τ_y increased.

- Neither oil-based nor synthetic-based fluids exhibited any significant shear viscosity sensitivity to fiber concentration at ambient temperature or 170°F. It may be possible for oil-based or synthetic-based drilling fluid sweeps to be utilized in the field with no significant increase in ECD.

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Nomenclature

BHA = *Bottomhole Assembly*
BP =*Bingham Plastic*
PAC = *Polyanionic Cellulose*
PHPA = *Partially-Hydrolyzed Polyacrylamide*
PL =*Power Law*
XG = *Xanthan Gum*
YPL =*Yield Power Law*
τ = *Shear stress (lbf/100 ft^2)*
τ_y = *Yield stress (lbf/100 ft^2)*
K = *Consistency index (lbf-s^n/100 ft^2)*
N = *Flow behavior index*
γ = *shear rate (s^{-1})*
μ = *Viscosity*
ppg = *Pounds per gallon (lb/gal)*
ECD = *Equivalent circulating density*

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Table 1 – Test Matrix of Rotational Viscometer Measurements

	Base Fluid (lb / bbl)	Weighting Agent	Fiber Concentration (lb / bbl)
Water-Based Mud [WBM]	**XG** (0.35, 0.87, 1.75, 2.62)	None 8.33 ppg	0.00, 0.14, 0.28
	PAC (0.35, 0.87, 1.75, 2.62)	None 8.33 ppg	0.00, 0.14, 0.28
	XG / PAC [50%/50%] (0.35, 0.87, 1.75, 2.62)	None 8.33 ppg	0.00, 0.14, 0.28
	XG (0.87, 1.75, 2.62)	*Barite* *12.1 ppg*	0.00, 0.20, 0.40
	PHPA (0.17, 0.35, 0.52)	None 8.33 ppg	0.00, 0.14, 0.28
OBM	**Mineral Oil-base** [VERSACLEAN® System]	*Barite* *12.2 ppg*	0.00, 0.20, 0.40
SBM	**Internal-Olefin-base** [NOVAPLUS® System]	*Barite* *12.1 ppg*	0.00, 0.20, 0.40

Table 2 – Fiber Properties

Material = Polypropylene
Spec. Grav. = 0.91
Length = 0.40 in (10 mm)
Diameter = 0.004 in (100 μm)
Melting Point = 325°F – 350°F

Table 3 – Rheological Parameters of XG Drilling Fluid with Varying Fiber Concentration at 72°F and 170°F

Composition		Rheological Properties							
		72°F				170°F			
Fluid	Fiber Conc. (lb / bbl)	τ_y	k	n	R^2	τ_y	k	n	R^2
		lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
XG 0.35 lb/bbl	0.00	0	0.04	0.76	1.00	0	0.09	0.61	0.99
	0.14	0	0.08	0.65	0.99	0	0.06	0.68	1.00
	0.28	0	0.08	0.65	0.99	0	0.06	0.67	0.99
XG 0.87 lb/bbl	0.00	0	0.80	0.48	1.00	0	0.34	0.53	1.00
	0.14	0	0.75	0.50	1.00	0	0.34	0.54	1.00
	0.28	0	0.77	0.50	1.00	0	0.40	0.51	1.00
XG 1.75 lb/bbl	0.00	4.75	5.06	0.33	1.00	0	4.41	0.31	1.00
	0.14	6.24	4.38	0.35	1.00	0	2.69	0.36	0.99
	0.28	6.34	4.27	0.36	1.00	0	4.03	0.32	1.00
XG 2.62 lb/bbl	0.00	13.33	8.76	0.31	1.00	0	10.83	0.25	1.00
	0.14	14.33	8.97	0.31	1.00	0	9.04	0.28	1.00
	0.28	16.15	8.08	0.33	1.00	0	10.43	0.25	1.00

Table 4 – Rheological Parameters of PAC Drilling Fluid with Varying Fiber Concentration at 72°F and 170°F

Composition		Rheological Properties							
		72°F				170°F			
Fluid	Fiber Conc. (lb / bbl)	τ_y	k	n	R^2	τ_y	k	n	R^2
		lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
PAC 0.35 lb/bbl	0.00	0	0.03	0.84	0.99	0	0.05	0.61	0.97
	0.14	0	0.03	0.85	0.99	0	0.06	0.60	0.99
	0.28	0	0.04	0.77	0.99	0	0.08	0.57	0.98
PAC 0.87 lb/bbl	0.00	0	0.09	0.82	1.00	0	0.02	0.92	0.99
	0.14	0	0.10	0.82	1.00	0	0.04	0.84	0.99
	0.28	0	0.11	0.81	1.00	0	0.04	0.85	0.99
PAC 1.75 lb/bbl	0.00	0	0.44	0.74	1.00	0	0.16	0.77	1.00
	0.14	0	0.56	0.70	1.00	0	0.15	0.78	1.00
	0.28	0	0.61	0.69	1.00	0	0.15	0.78	1.00
PAC 2.62 lb/bbl	0.00	0	1.22	0.68	0.99	0	0.28	0.76	1.00
	0.14	0	1.36	0.67	0.99	0	0.32	0.75	1.00
	0.28	0	1.52	0.65	0.99	0	0.27	0.79	1.00

Table 5 – Rheological Parameters of XG/PAC (50%/50%) Drilling Fluid with Varying Polymer and Fiber Concentration at 72°F & 170°F

Composition		Rheological Properties							
		72°F				170°F			
Fluid	Fiber Conc.	τ_y	k	n	R^2	τ_y	k	n	R^2
	(lb / bbl)	lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
XG/PAC 0.35 lb/bbl	0.00	0	0.05	0.71	0.98	0	0.06	0.60	0.97
	0.14	0	0.05	0.72	0.99	0	0.06	0.60	0.97
	0.28	0	0.05	0.74	0.99	0	0.05	0.62	0.97
XG/PAC 0.87 lb/bbl	0.00	0	0.19	0.69	1.00	0	0.08	0.66	0.99
	0.14	0	0.25	0.65	1.00	0	0.07	0.71	0.99
	0.28	0	0.29	0.63	1.00	0	0.08	0.71	1.00
XG/PAC 1.75 lb/bbl	0.00	0	0.66	0.62	1.00	0	0.38	0.66	1.00
	0.14	0	0.98	0.56	1.00	0	0.53	0.62	1.00
	0.28	0	0.98	0.57	1.00	0	0.66	0.59	1.00
XG/PAC 2.62 lb/bbl	0.00	0	2.17	0.53	0.99	0	0.61	0.64	1.00
	0.14	0	2.48	0.51	1.00	0	1.09	0.56	1.00
	0.28	0	2.64	0.50	1.00	0	1.36	0.53	1.00

Table 6 – Rheological Parameters of XG+Barite (12-lb/gal) Drilling Fluid with Varying Fiber Concentration at 72°F and 170°F

Composition		Rheological Properties							
		72°F				170°F			
Fluid	Fiber Conc.	τ_y	k	n	R^2	τ_y	k	n	R^2
	(lb / bbl)	lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
XG+Barite	0.00	0.52	0.55	0.62	0.99	0	1.05	0.46	0.99
0.87 lb/bbl	0.20	0.84	0.50	0.64	1.00	0	0.95	0.47	0.99
12 ppg	0.40	1.09	0.77	0.58	0.99	0	1.07	0.46	0.99
XG+Barite	0.00	7.06	4.23	0.45	0.99	3.48	5.78	0.34	0.99
1.75 lb/bbl	0.20	8.02	4.07	0.46	1.00	3.64	5.78	0.32	0.99
12 ppg	0.40	9.20	3.91	0.46	1.00	1.07	6.93	0.29	1.00
XG+Barite	0.00	16.91	10.14	0.36	1.00	7.64	16.37	0.22	1.00
2.62 lb/bbl	0.20	17.03	10.31	0.36	1.00	9.59	13.35	0.24	0.99
12 ppg	0.40	17.09	10.25	0.36	1.00	6.64	15.07	0.23	0.99

Table 7 – Rheological Parameters of PHPA Drilling Fluid with Varying Fiber Concentration at 72°F and 170°F

Composition		Rheological Properties							
		72°F				170°F			
Fluid	Fiber Conc.	τ_y	k	n	R^2	τ_y	k	n	R^2
	(lb / bbl)	lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
PHPA 0.17 lb/bbl	0.00	0	0.17	0.55	0.99	0	0.06	0.56	0.99
	0.14	0	0.16	0.56	0.99	0	0.06	0.56	0.99
	0.28	0	0.10	0.64	0.99	0	0.07	0.55	0.99
PHPA 0.35 lb/bbl	0.00	0	0.34	0.54	1.00	0	0.30	0.47	1.00
	0.14	0	0.31	0.56	1.00	0	0.35	0.45	1.00
	0.28	0.51	0.22	0.62	1.00	0	0.38	0.45	0.99
PHPA 0.52 lb/bbl	0.00	1.05	0.40	0.58	1.00	0	0.59	0.44	1.00
	0.14	1.07	0.46	0.56	1.00	0	0.61	0.43	1.00
	0.28	0	0.61	0.69	0.99	0	0.72	0.42	1.00

Table 8 – Rheological Parameters of OBM and SBM with Varying Fiber Concentration at 72°F and 170°F

Composition		**Rheological Properties**							
		72°F				170°F			
Fluid	Fiber Conc. (lb / bbl)	τ_y	k	n	R^2	τ_y	k	n	R^2
		lbf/100 ft^2	lbf-s^n/100 ft^2			lbf/100 ft^2	lbf-s^n/100 ft^2		
OBM (12.2 ppg)	0.00	6.92	1.03	0.72	1.00	5.09	0.69	0.63	1.00
	0.20	7.63	0.93	0.74	1.00	5.35	0.79	0.61	1.00
	0.40	7.61	0.96	0.73	1.00	5.32	0.83	0.61	1.00
SBM (12.1 ppg)	0.00	7.21	0.88	0.69	1.00	4.15	0.52	0.62	0.99
	0.20	7.84	0.86	0.70	1.00	3.97	0.51	0.62	0.99
	0.40	7.86	0.85	0.70	1.00	3.96	0.50	0.63	1.00


Fig. 1 – Stand mixers


Fig. 2 – Rotational viscometers

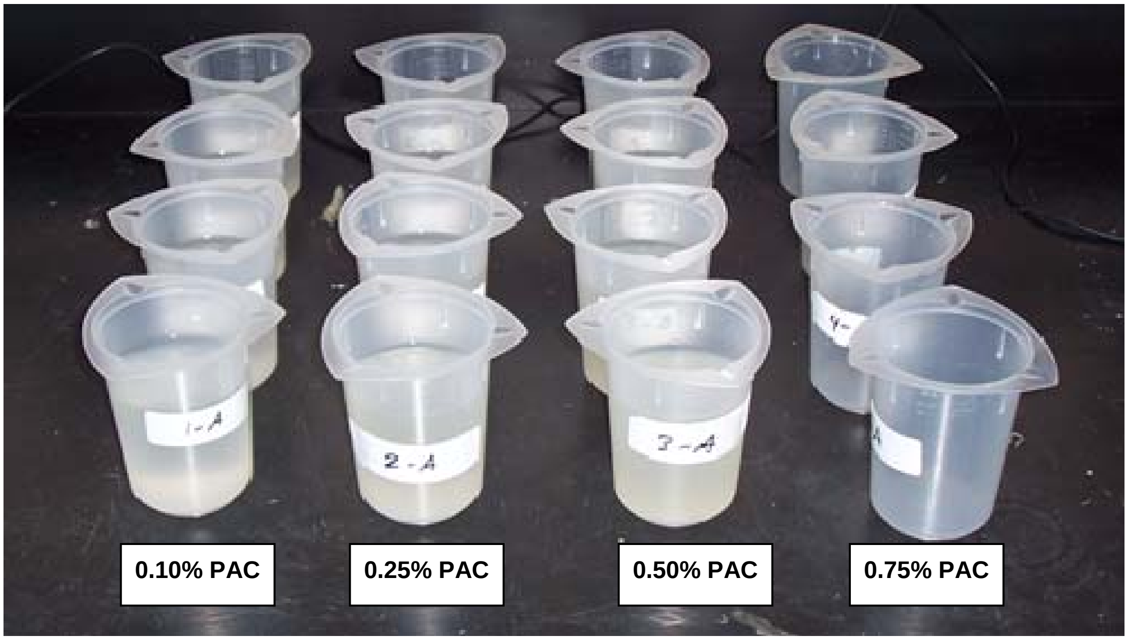
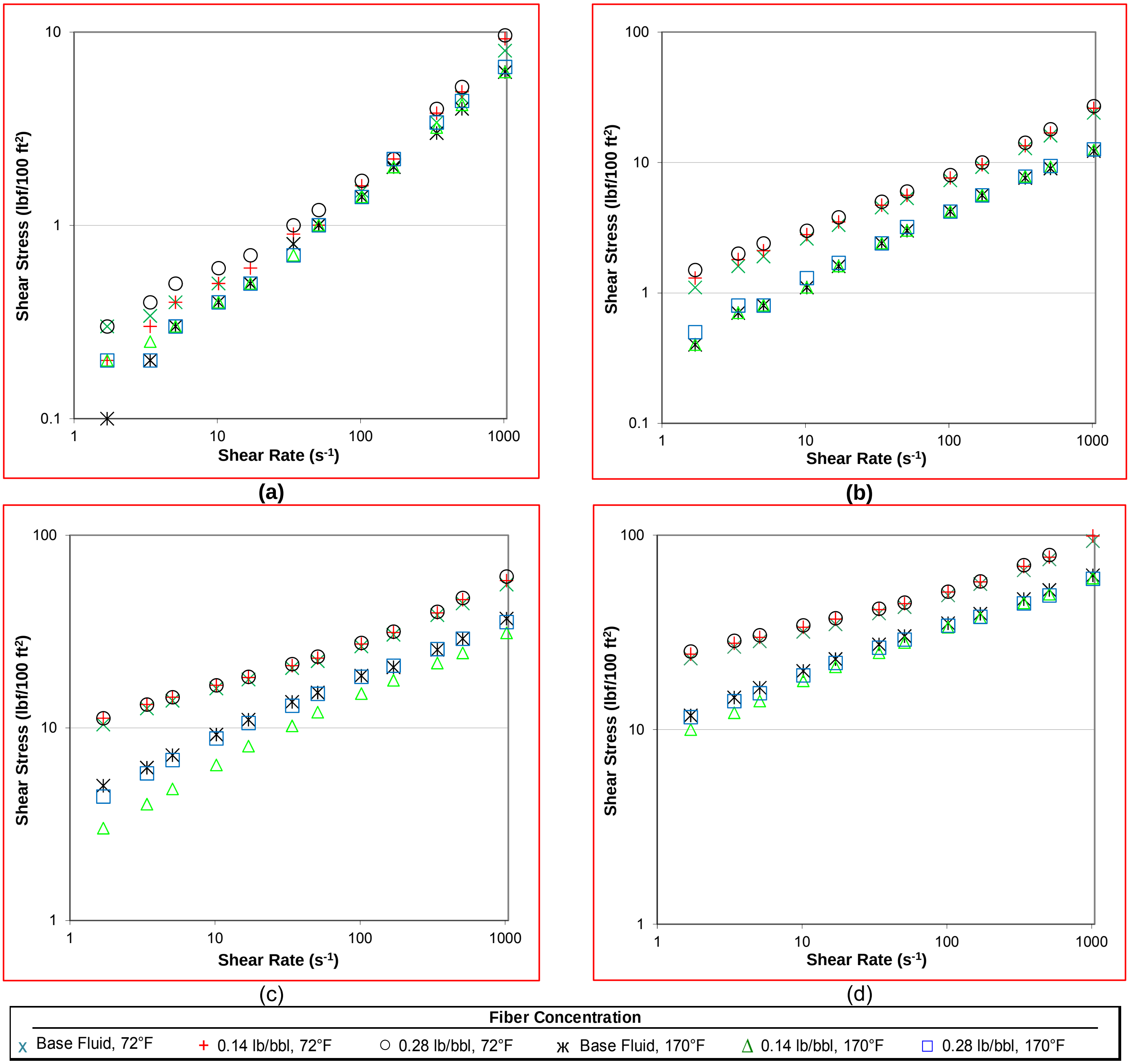


Fig. 3 – Fluid samples organized by polymer and fiber concentration



(a) (b) (c) (d)

Fig. 4 Rheology of XG drilling fluid at 72°F and 170°F with varying fiber and polymer concentrations: a) 0.35-lb/bbl XG; b) 0.87-lb/bbl XG; c) 1.75-lb/bbl XG; and d) 2.62-lb/bbl XG

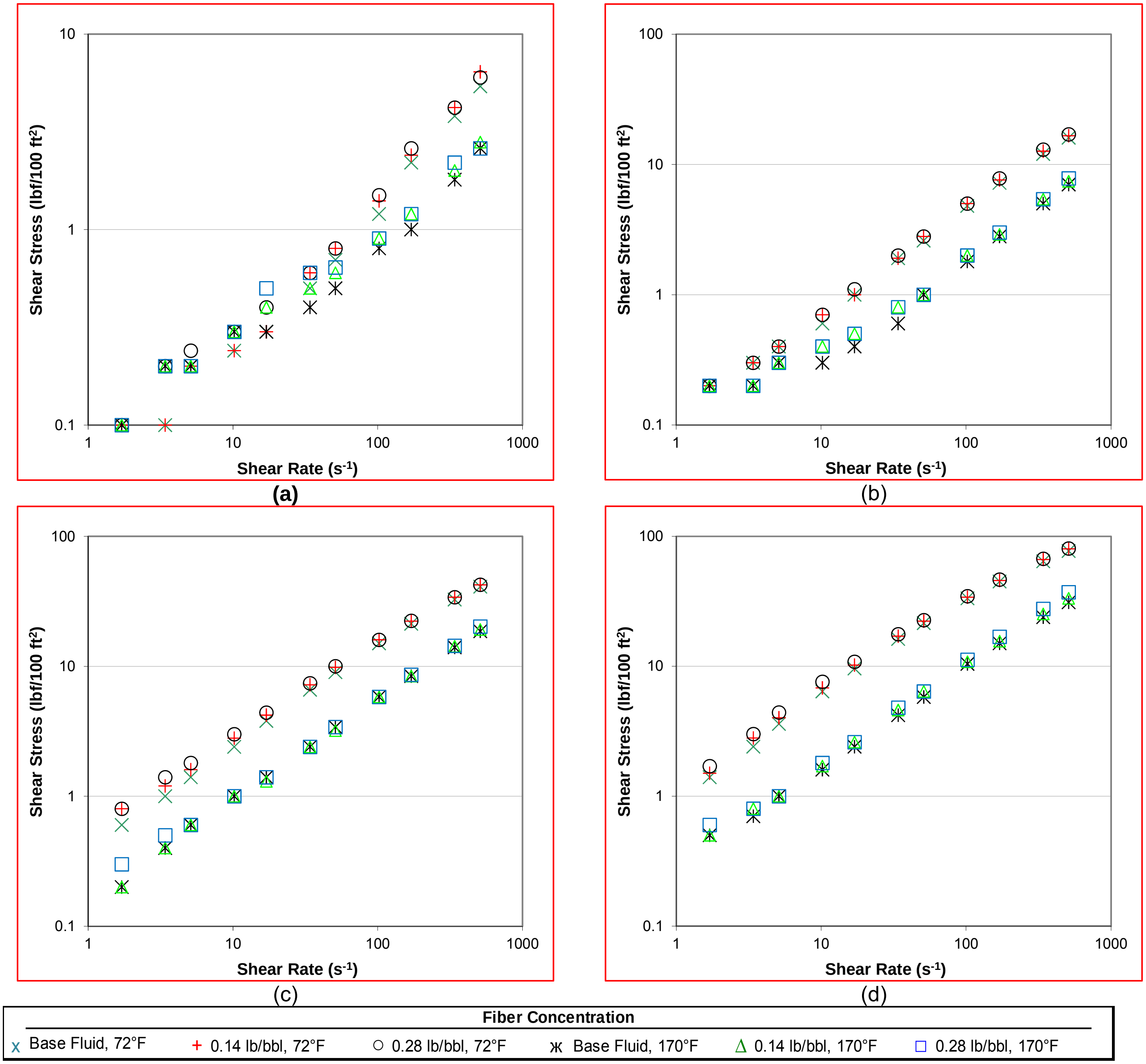


**Fig. 5 Rheology of PAC drilling fluid at 72°F and 170°F varying fiber and polymer concentrations:
a) 0.35-lb/bbl PAC; b) 0.87-lb/bbl PAC; c) 1.75-lb/bbl PAC; and d) 2.62-lb/bbl PAC**

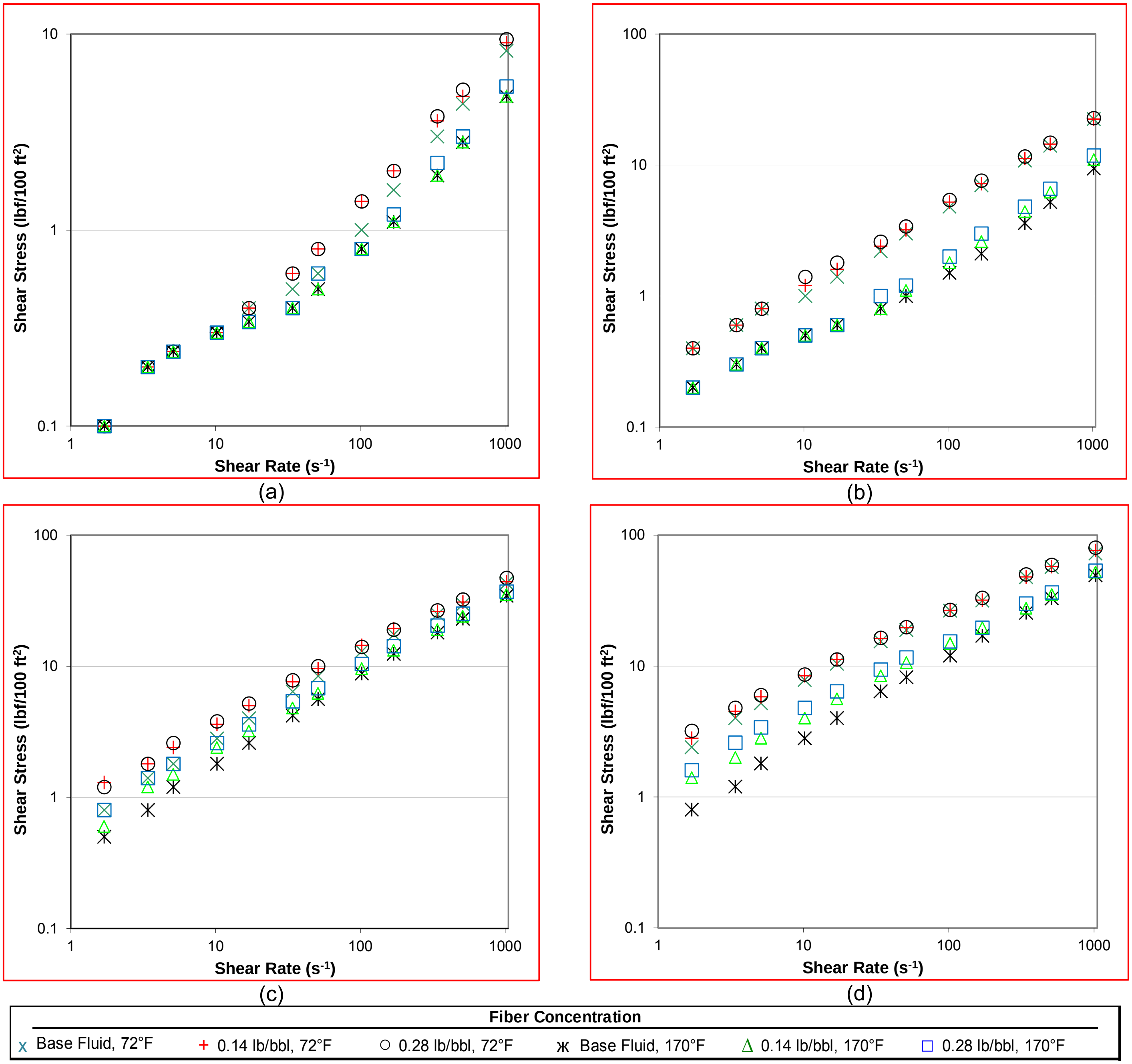
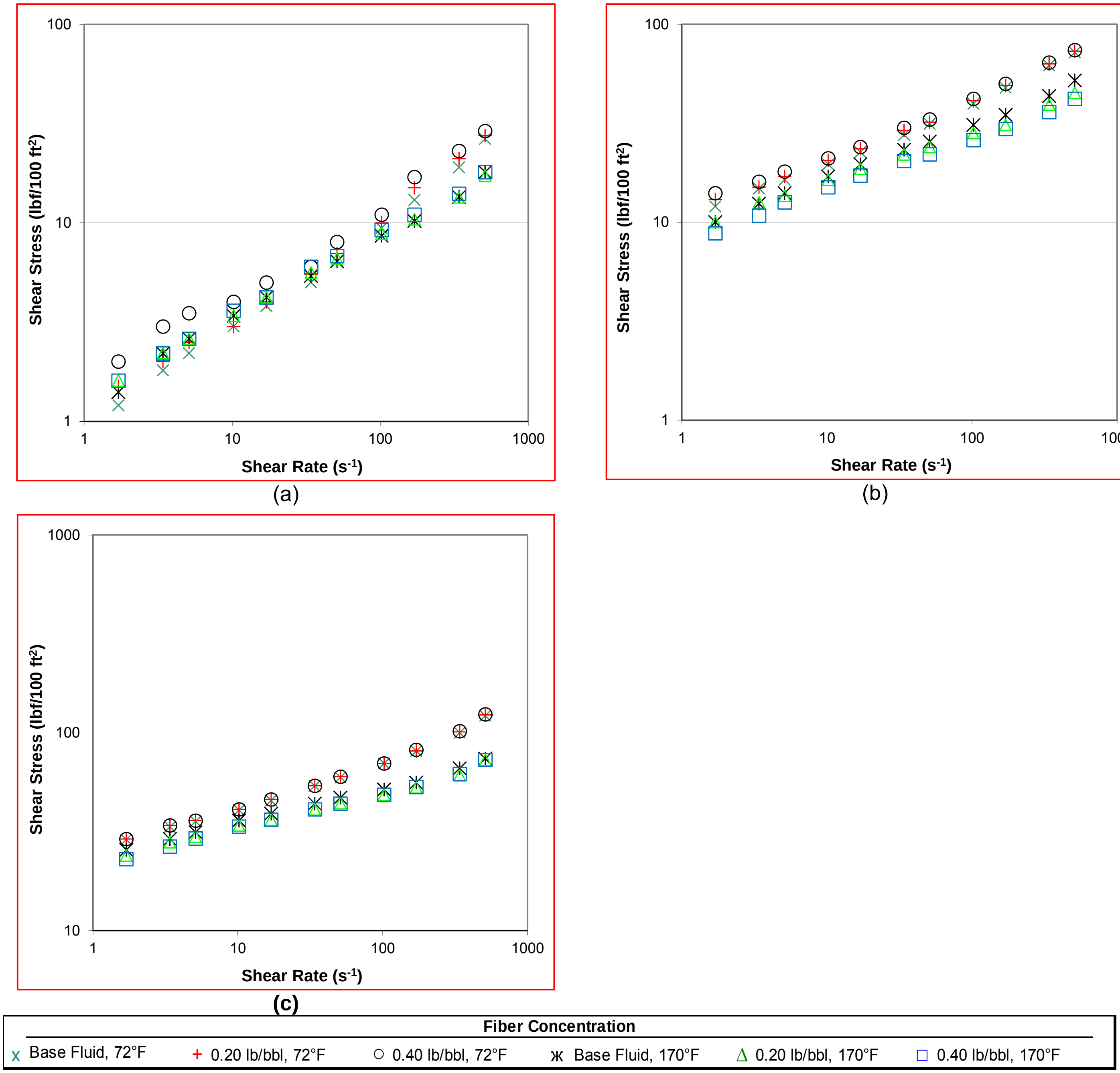


Fig. 6 – Rheology of XG/PAC (50%/50%) fluid at 72°F and 170°F varying fiber and polymer concentrations: a) 0.35-lb/bbl XG/PAC; b) 0.87-lb/bbl XG/PAC; c) 1.75-lb/bbl XG/PAC; and d) 2.62-lb/bbl XG/PAC

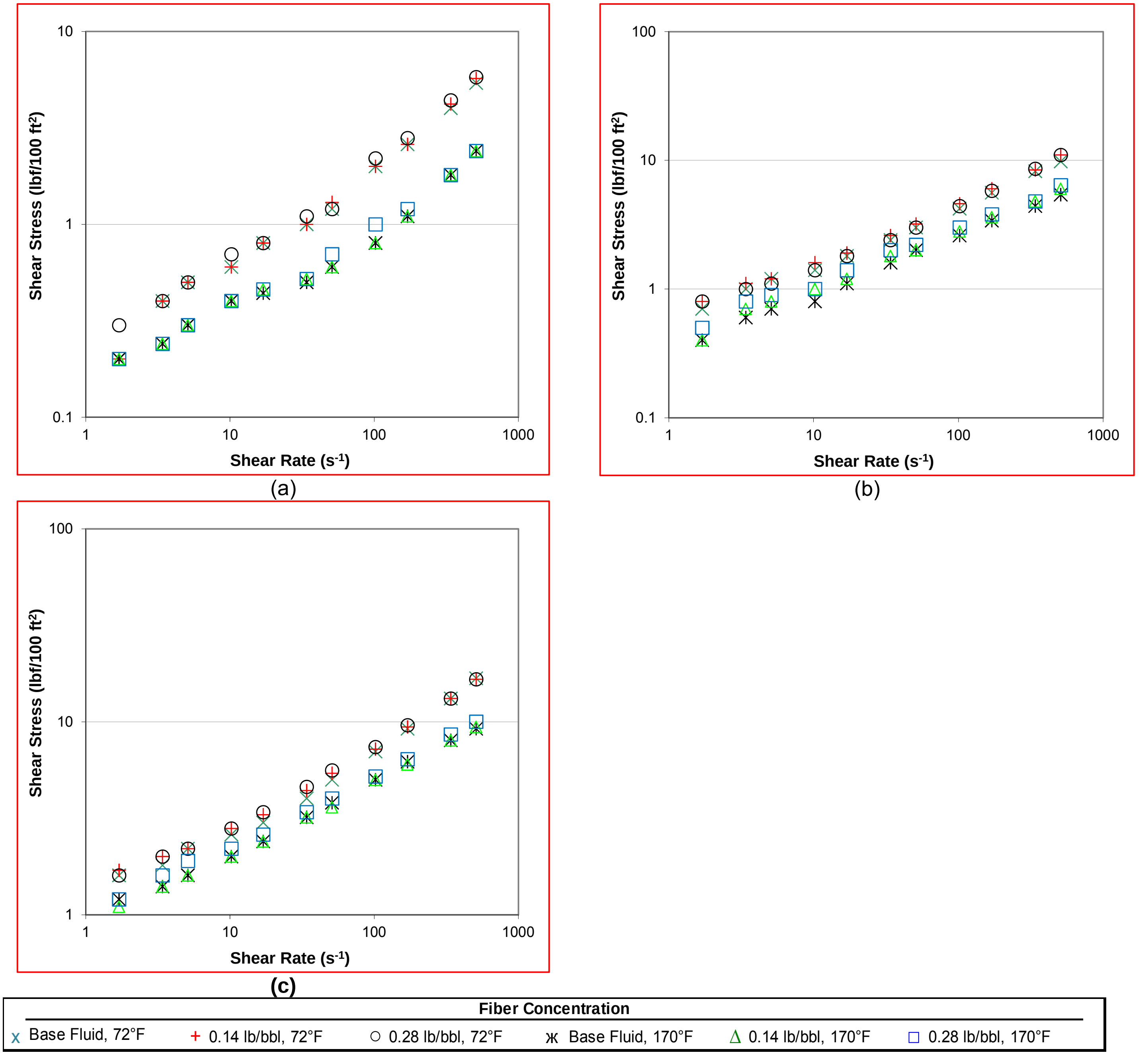


(a)

(b)

(c)

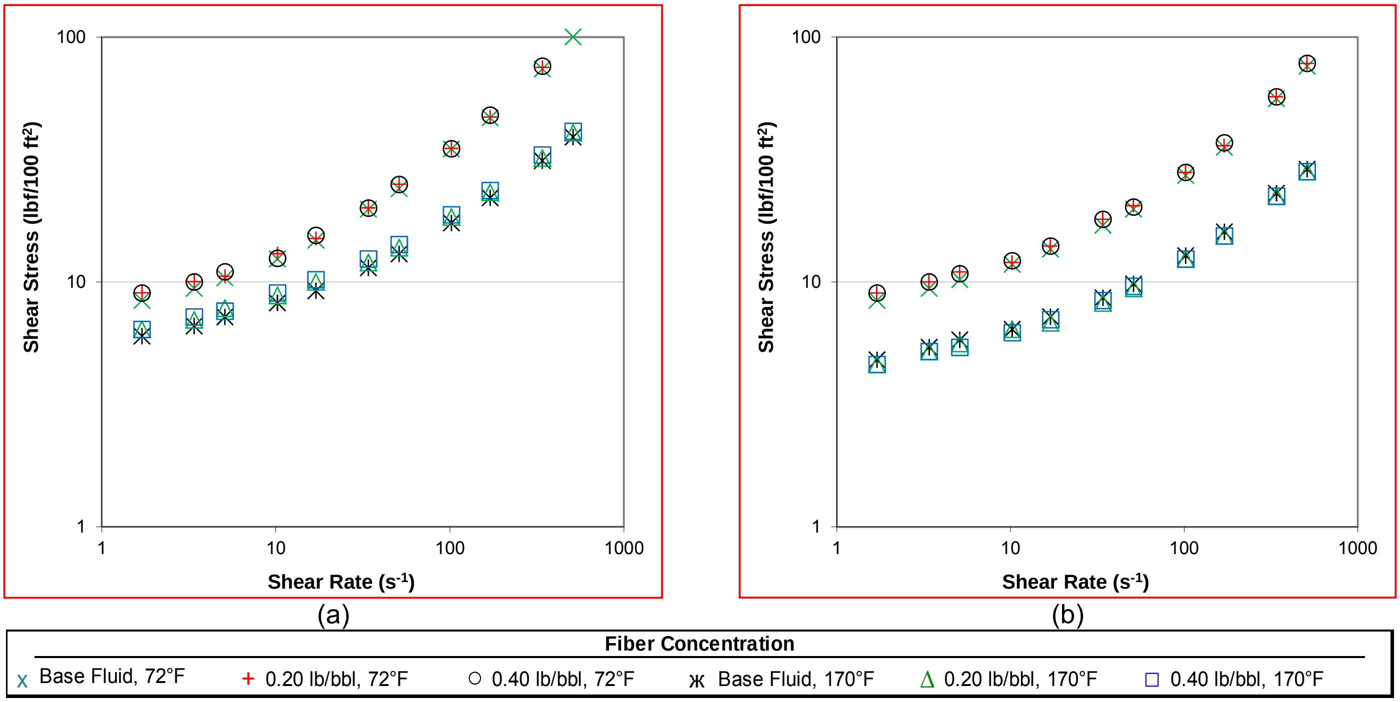
Fig. 7 – Rheology of 12-lb/gal XG fluids at 72°F and 170°F varying fiber and polymer concentrations: a) 0.87-lb/bbl XG; b) 1.75-lb/bbl XG; and c) 2.62-lb/bbl XG



(a) (b)

(c)

Fig. 8 – Rheology of PHPA fluids at 72°F and 170°F varying fiber and polymer concentrations: a) 0.17-lb/bbl PHPA; b) 0.35-lb/bbl PHPA; and c) 0.52-lb/bbl PHPA



(a)

(b)

Fig. 9 Rheology of invert fluids at 72°F and 170°F varying fiber concentrations: a) OBM; and b) SBM

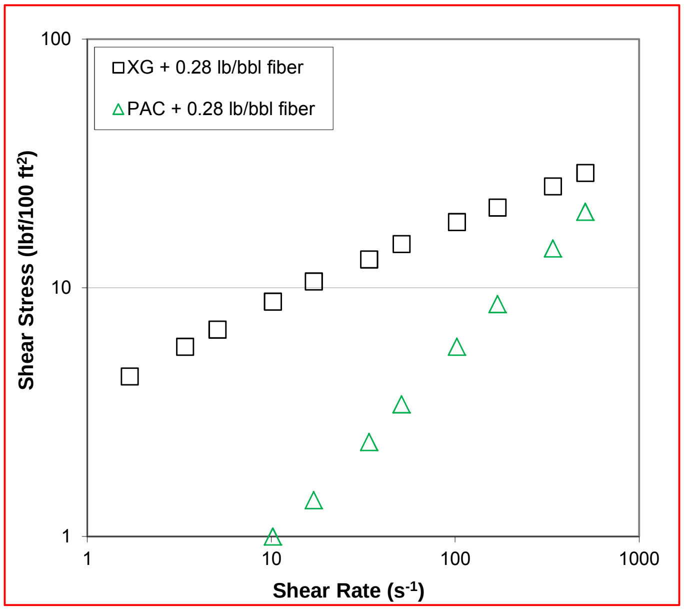


Fig. 10 – Rheology of weighted (12-lb/gal) polymeric fluids with XG and PAC concentrations of 2.62 lb/bbl