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Proppant Transport Using High-Viscosity Friction Reducer Fracture Fluids at High-Temperature Environment

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Summary

The stimulation of unconventional reservoirs to improve oil productivity in tight formations of shale basins is a key objective in hydraulic fracturing treatments. Such stimulation can be made by reliable fracture fluids that have a high viscosity and elasticity to suspend the proppant in the fracture networks. Recently, due to several operational and economic reasons, the oil industry began using high-viscosity friction reducers (HVFRs) as direct replacements for linear and crosslinked gels. However, some issues can limit the capability of HVFRs to provide effective sand transport, including the high fluid temperature during fracture treatment inside the formations. This may lead to unstable fracture fluids caused by a decrease in the interconnective strength between the fluid chains, which results in reduced viscosity and elasticity. This study comprehensively investigated HVFRs in comparison with guar at various temperatures. An HVFR at 4 gallons per thousand gallons of water (gpt) and guar at 25 pounds per thousand gallons of water (ppt) were selected based on fluid rheology tests and hydraulic fracture execution field results. The rheological measurements of both fracture fluids were conducted at different temperature values (i.e., 25, 50, 75, and 100°C). Static and dynamic proppant settling tests were also conducted at the same temperatures. The results showed that the HVFR provided better proppant transport capability than the guar. The HVFR had better thermal stability than guar, but its viscosity and elasticity decreased significantly when the temperature exceeded 75°C. An HVFR can carry and hold the proppant more deeply inside the fracture than liner gel, but that ability decreases as the temperature increases. Therefore, using conditions that mimic field conditions to measure the fracture fluid rheology, proppant static settling velocity, and proppant dune development under a high temperature is crucial for enhancing the fracture treatment results.

Introduction

The main objective of hydraulic fracturing treatments is to create a high formation permeability to enhance oil productivity. This can be achieved by transporting and distributing the proppant farther into the fracture networks. In the past, several viscoelastic fracture fluids have been used to transport sand inside fractured formations in many basins in the United States. Additionally, oil recovery may be stimulated by fracture fluids that have high viscoelastic parameters. The traditional method of using crosslinked gel provides an acceptable performance in high-temperature formations (Baumgartner et al. 1983). Also, polysaccharide fluids, such as guar or crosslinked gel, may exhibit a good proppant-carrying capacity, especially at small sand sizes or at lower proppant concentrations. However, challenges during traditional hydraulic treatment and fracturing operations using guar or crosslinked fluids include needing more chemicals to enhance the proppant transport, more water, and more trucks, tanks, and hydrating units. The flowback process produces solid residues because the interaction between the polysaccharides (e.g., guar or crosslinked fluids) with the breakers results in damage to the formation permeability. This may negatively affect the productivity of wells in comparison to when using polyacrylamide (Prakash et al. 2014). In addition, Harris et al. (2009) investigated rheologically biopolymer fluids to transport proppant at various temperature values. Their results predicted a good rheology for biopolymer fluids at high temperatures. However, these fluids have not been evaluated using a dynamic fracture slot to estimate their capabilities to transport proppant. Some synthetic polymers or polyacrylamide materials were studied to investigate the changes in the rheological structure of the fluids at different temperatures (Almubarak et al. 2019). These fluids retained stable fluid properties (e.g., viscosity) even at high temperatures that exceeded 100°C. However, more work is needed to evaluate these polyacrylamide fluids in static and dynamic systems to mimic proppant transport during hydraulic fracture treatments.

HVFRs are a polyacrylamide product that have become widely used in several basins in North America because of their high viscosity and elasticity, which provides excellent proppant distribution compared to traditional treatments using guar or crosslinked gels. HVFRs reduce the amount of chemicals, minimize the required amount of water, and limit the footprint of equipment at the location's surface (Van Domelen et al. 2017; Dahlgren et al. 2018; Johnson et al. 2018). HVFRs show insignificant residue, which means that the formation permeability might be restored successfully. Several researchers have studied the rheology of this friction reducer to provide a comprehensive understanding of the effectiveness of its viscosity and elasticity to control the proppant's settling (Gaillard et al. 2013; Hu et al. 2015, 2018; Aften 2018; Shen et al. 2018; Ba Geri et al. 2019a). The rheology measurements demonstrated that the viscosity and elasticity parameters of the HVFR were higher compared to guar; however, most of the rheology investigations in the previously mentioned studies were conducted at room temperature and did not evaluate the impact of temperature on the rheology of HVFRs and guar.

The static settling velocity of a solid particle using viscoelastic fluids was investigated and was measured through a confined system, using various fluid types and particle sizes (Malhotra and Sharma 2012; Arnipally and Kuru 2018). The particle settling velocity decreased after improving fluid properties such as viscosity and elasticity; also, the settling velocity of a solid particle rose when the particle size increased. However, all these studies were conducted using viscoelastic fluids, such as Boger fluids. In addition, these measurements were made at room temperature, not at higher temperatures. The settling velocity of the proppant through creep regimes was evaluated in several studies. Sanders et al. (2016), Shen et al. (2018), and Ba Geri et al. (2019b) examined the settling velocity of proppant using HVFRs and guar, finding that HVFRs showed a greater suspension of sand compared to guar. Zhao et al. (2018) and Biheri and Imqam (2020) investigated the effect of increasing the proppant size on the settling velocity using different fluid concentrations of HVFR and guar; the results showed that increased sand sizes minimized the fluids' capacity to hold the proppant for a significant length of time, while the settling velocity of the proppant decreased as the fracture fluid concentration rose. Most HVFR studies that measured

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settling velocity in creep or static regimes were conducted using cylindrical laboratory glass and have not investigated the fracture walls; all of these works were also conducted at room temperature. Furthermore, the friction reducer was evaluated to suspend the proppant in the slot systems at different sand concentrations and friction reducer concentrations. Drylie et al. (2018), Hu et al. (2018), and Zhao et al. (2018) compared the capacity of an HVFR to distribute sand through a dynamic slot using various proppant sizes and fluid concentrations to guar linear fluids. Additionally, Dahlgren et al. (2018) and Biheri and Imqam (2020) conducted similar dynamic experiments on HVFRs and guar, measuring the effect of increasing the proppant concentrations. The dynamic experiments showed that HVFRs provided excellent distribution of the proppant across the fracture, much better than guar, even when the proppant sizes increased. However, no study has investigated the effect of temperature on the capacity of HVFRs and guar to transport proppant through fractures. In summary, there is a lack of knowledge about investigation of the capability of HVFR at high temperatures. Some of the previously mentioned works conducted limited evaluations of the effect of temperature on HVFRs in rheology measurements. All the experimental research on HVFRs' capability to govern proppant settling in static and dynamic slots was conducted at room temperature and did not investigate the impacts of increasing the temperature on HVFRs during proppant static and dynamic settling in fracture systems.

This work is the first of its kind to evaluate the efficiency of HVFRs in both static and dynamic fracture systems under various temperatures conditions. For comparison purposes, guar was studied with HVFRs to determine the capacity of viscoelastic fluids to transport proppant in fracture networks. In static or creep regimes, several spherical particle sizes were selected to measure the settling velocity between the confined parallel walls using various fracture widths. In the dynamic model, the proppant transport was investigated at different temperature values for both the HVFR and guar, as well as the proppant impact using different sand sizes and proppant concentrations.

Experimental Design

Experimental Materials. Fluid Characteristics. Two types of fracture fluids, anionic HVFR at 4 gpt and guar at 25 ppt, were tested at various temperature values (i.e., 25, 50, 75, and 100°C). The fracture fluids were mixed with deionized water. The anionic HVFR (FLOJET DRP 2340 X) samples were provided by SNF Holding Company. The raw materials for the synthesis of HVFR are acrylamide and acrylic acid, which are polymerized together. This polyacrylamide has a high effective molecular weight of approximately 22×10^6 daltons using pH 8.2. Also, the hydrolysis degree of HVFR is approximately 35% to 45%. The HVFR used is a dry anionic HVFR, which was converted to fluid form to investigate its viscosity and elasticity (Sanders et al. 2016). **Table 1** shows the required weight to create a mixture of 4 gpt and 25 ppt using 1,000 gal of water.

Product	Concentration	Water Used (gallons)	Pounds to Make the Mixture
Guar	25 ppt	1,000	25
HVFR	4 gpt	1,000	10.4

Table 1—Pound-to-pound comparison of the HVFR and guar.

Proppant and Particles Characteristics. In the static model, the settling velocity through the fracture fluids was measured using different spherical particle sizes (i.e., 2, 4, and 6 mm). The spherical particle densities were measured in the laboratory, and their densities were similar, with an average of 2.626 g/cm^3 . Spherical particles were selected because of their uniform shape, barring some that have rough and irregular surface features. Two US silica sand sizes (i.e., 30/50 and 40/70 mesh sizes) were used to evaluate the proppant distribution inside the dynamic fracture model.

Rheology Measurement Description. The viscosity and elasticity parameters of the HVFR and guar samples were measured using an advanced rheometer. The plate diameter was 50 mm, while the gap was 0.5 mm, and the fluid viscosity was investigated at low and high shear rates (i.e., 0.1 to $1,000 \text{ s}^{-1}$) to evaluate how the fluids governed the proppant transport. The analysis of the fracture fluids rheology was conducted at several temperatures, including 25, 50, 75, and 100°C. The rheometer was designed to measure the temperature effect to 200°C. To have the results as accurate as possible, a manufactured cover was used to reduce the fluid evaporation at high temperatures (e.g., 100°C).

Proppant Settling in Static and Dynamic Fracture Models. Solid Particle Static Settling Velocity Measurements. Each fracture fluid was mixed at the desired concentration with deionized water using a magnetic blender at 300 rev/min. After that, the fracture fluid was poured into the confined fracture model (**Fig. 1**) to investigate the capability of the fracture fluids to suspend solid particles. The confined fracture model was created using two fracture widths: 7 and 10 mm. The fracture fluid was poured inside the confined model and left for almost 24 hours to ensure there were no bubbles in the fracture fluids that might affect the solid settling velocity measurements. After that, the fracture model was placed inside a large, visible glass container filled with water to allow measurement of the settling velocity at temperatures of 25, 50, and 75°C. Using a thermostat, the water was heated until it reached the proper temperature. The objective of heating the water was to transfer heat to the fracture fluids inside the fracture model and to ensure that the temperature was distributed as equally as possible into every corner of the glass container using a small pump that moved the water from the bottom to the top of the container.

The settling velocity of the solid particles was measured by dropping particles inside the fracture model from the top at the desired temperature. The dropping of particles should be close to the fracture model inlet at the top to prevent air from contacting the spherical particles. The particle settling velocities were recorded with a video camera located in front of the fracture model, as shown in **Fig. 2**. The experimental measurements were made using three spherical particle sizes (i.e., 2, 4, and 6 mm). To obtain accurate results, each experiment was repeated at least three times. The recorded videos of the settling velocity were analyzed using an advance tracker software (Brown et al. 2021).

Proppant Transport inside the Dynamic Fracture Model. **Fig. 3** shows the dynamic transport fracture model that was built to mimic proppant slurry transport in hydraulic fracturing treatments. A laboratory fracture model $2 \text{ ft} \times 2 \text{ ft}$ was constructed as a slot model with a gap of 0.25 in. Four injection points representing four perforations of 0.25-in. diameter were made perpendicular to the fracture slot. Each injection point was merged to a pressure indicator. Only one of the four perforations (at the bottom of the model)

was used to conduct the proppant transport. A heat jacket controlled the fracture fluids' temperature at one of three temperatures (i.e., 25, 50, and 75°C). A flow rate meter was joined to a pump, and a valve was placed between the pump and flowmeter to control the flow rate to obtain the desired fluid velocity as the temperature increased.

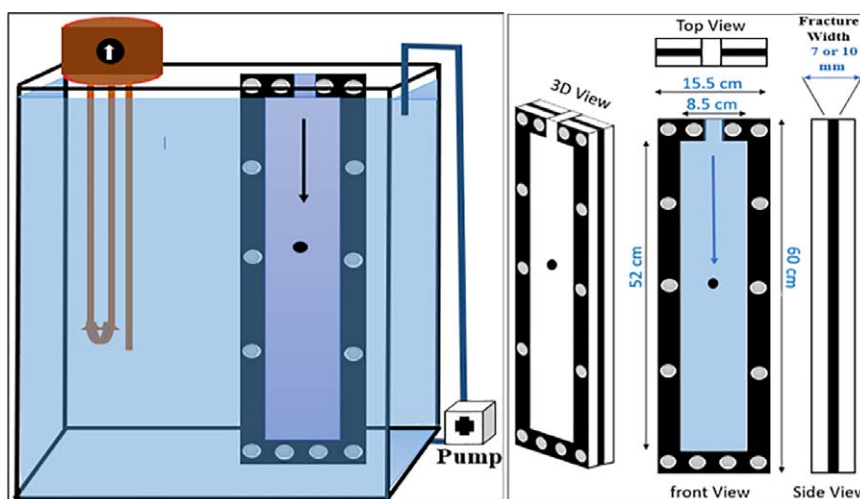


Fig. 1—Static model to measure the spherical particle settling velocity.

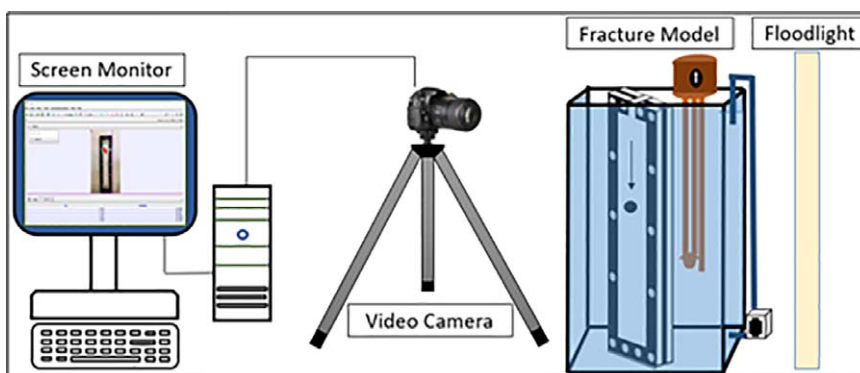


Fig. 2—Solid settling velocity measurements.

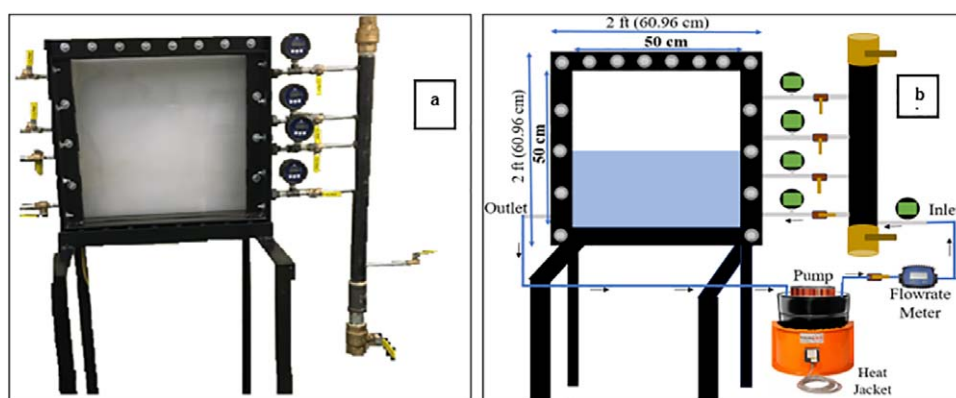


Fig. 3—Dynamic fracture model. (a) Real dynamic model. (b) Dynamic sketch setup.

The fracture fluids were prepared using a mechanical blender at the required concentration (HVFR at 4 gpt and guar at 25 ppt), and the fracture fluids were left for 1 day to ensure there were no air bubbles in the fluid. To mimic an HVFR stimulation treatment in a reservoir, the fracture fluid initially filled the fracture slot, as shown in Fig. 3. After the fluid level inside the dynamic model became stable, the video camera began filming. The fracture slot apparatus was illuminated with an LED vapor tight fixture (4,000 lumens, 2 ft × 2 ft) to add extra light during recording. Two sand mesh sizes (i.e., 30/50 and 40/70) were used, and the slurry of proppant and fracture fluid was prepared at the proper proppant concentration and injected into the dynamic fracture model using a submersible pump. The pumping of the slurry continued for 1 hour to allow adequate time to evaluate the capability of the HVFR and guar to suspend the proppant. All of the experiments were conducted using a constant pumping rate of 1 gal/min. Because the dynamic model

width was known (i.e., 0.25 in. or 0.635 cm), the volume of the proppant inside the fracture was measured regularly over time using SketchAndCalc (2021), a computer program that calculates area.

Results and Analysis of Rheology Measurements

Viscosity Measurements. Figs. 4a and 4b exhibit the viscosity curve for the HVFR and guar at different fluid concentrations at 25°C. The results show that the viscosity decreased as the shear rate rose for both fracture fluids (i.e., HVFR and guar). Also, the power-law properties, such as the consistency index (k) and flow behavior index (n), were investigated using the HVFR and guar at different concentrations. The results imply that the consistency index k increases as the fluid concentration increases. The consistency index of the HVFR was 0.11, 0.31, 0.79, and 1.93 for 1, 2, 4, and 8 gpt, respectively, whereas the consistency index of guar was 0.02, 0.09, and 0.31 using 15, 25, and 35 ppt, respectively. However, the flow behavior index (n) of the HVFR did not demonstrate a crucial difference in value even when the concentration increased from 1 to 8 gpt. The flow behavior index was 0.49, 0.38, 0.31, and 0.26 using 1, 2, 4, and 8 gpt, respectively. On the other hand, the flow behavior index for guar decreased as the concentration increased, with flow behavior indices of 0.84, 0.74, and 0.63 for 15, 25, and 35 ppt, respectively. Because of the chemical structure of the HVFR, which has a high molecular weight of approximately 22×10^6 daltons, the friction reducer may provide better viscosity and elasticity compared to guar, which has the lower molecular weight of approximately 1×10^6 daltons. This low molecular weight of guar may lead to a poor interconnection between the molecules, which might lead to shorter molecular chains.

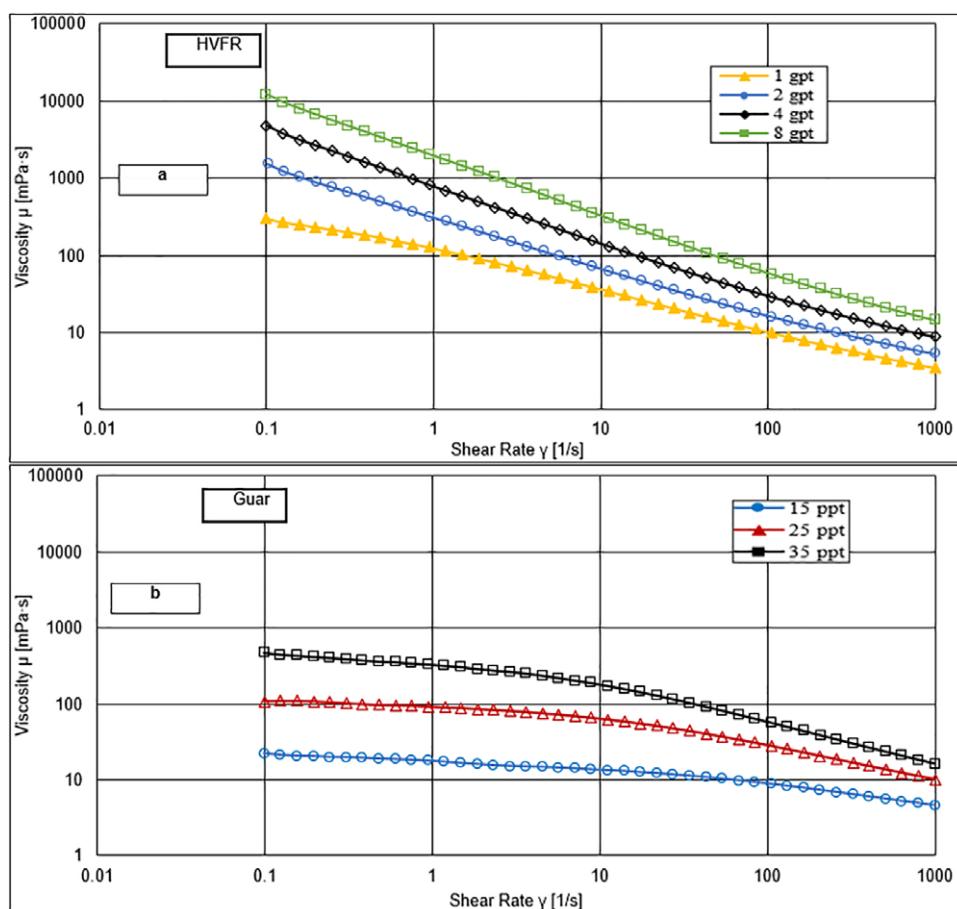


Fig. 4—Viscosity curves for (a) HVFR and (b) guar using various concentrations and measured at 25°C.

Based on the literature and the previously described experimental laboratory results and field case studies during hydraulic fracture treatments, the fluid concentrations of HVFRs were typically in the range of 2 to 5 gpt, whereas guar was mainly used at 20 to 30 ppt (Aften 2018; Dahlgren et al. 2018; Drylie et al. 2018; Hu et al. 2018; Johnson et al. 2018; Shen et al. 2018; Zhao et al. 2018; Ba Geri et al. 2019a; Biheri and Imqam 2021). Accordingly, HVFR at 4 gpt and guar at 25 ppt were selected to investigate the impact of temperature in the remainder of this study.

The effect of temperature on viscosity was evaluated using both fracture fluids at various temperatures. It can be seen from Figs. 5 and 6 that the viscosity decreased with an increase in temperature. However, the HVFR exhibited more resistance to higher temperatures than guar, especially at low shear rate values. At 10 s^{-1} , the viscosities of the HVFR were 136, 133, 90, and $3.42 \text{ mPa}\cdot\text{s}$ at 25, 50, 75, and 100°C , respectively, whereas the viscosities of guar at 10 s^{-1} were 69, 44, 30, and $0.71 \text{ mPa}\cdot\text{s}$, respectively, at the same temperatures. Nevertheless, at high shear rates, the viscosities of both the fracture fluids were similar. At a shear rate of 100 s^{-1} , the HVFR viscosities were 31, 24, 16, and $0.36 \text{ mPa}\cdot\text{s}$, compared to the guar viscosities of 31, 20, 12, $0.03 \text{ mPa}\cdot\text{s}$ at 25, 50, 75, and 100°C , respectively. Also, it was observed that the viscosities of both fracture fluids decreased tremendously when the shear rate was greater than or equal to 100 s^{-1} . This suggests that the fracture fluid may not be able to maintain an appropriate viscosity near the wellbore, where a high shear rate is expected to occur.

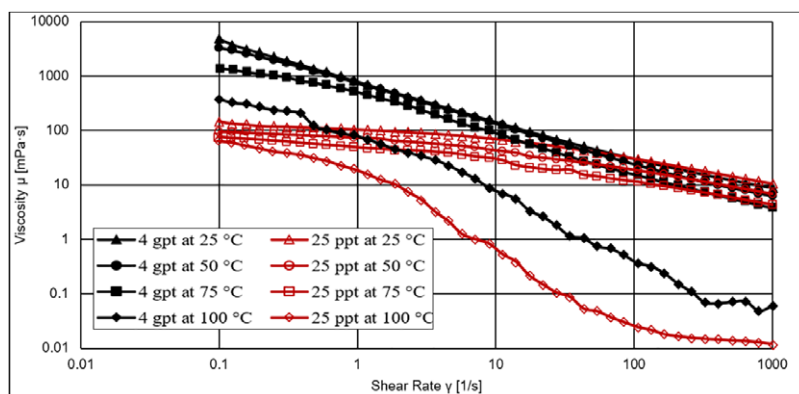


Fig. 5—Viscosity measurements of the HVFR and guar at different temperatures.

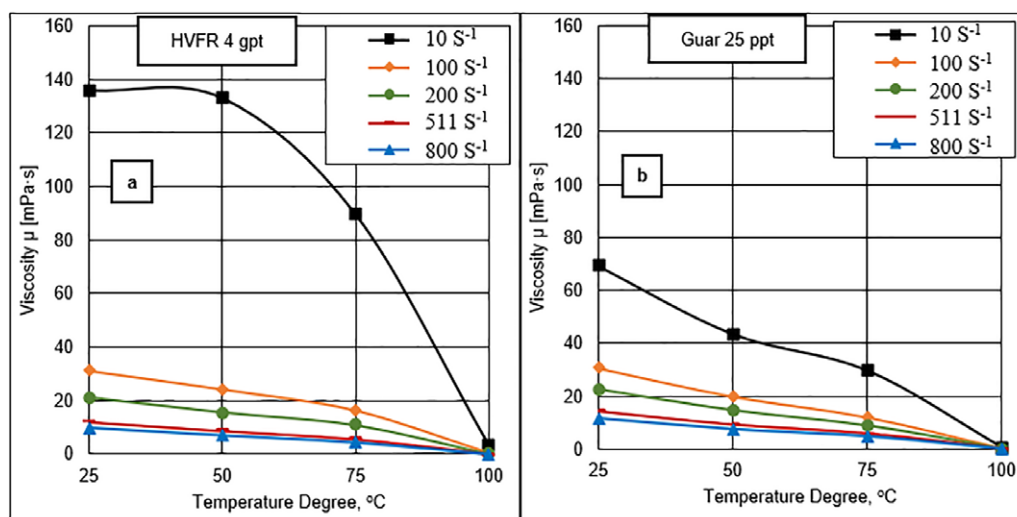


Fig. 6—Shear rate impact on the viscosities of (a) HVFR and (b) guar at various temperatures.

Also, the power-law properties, such as the consistency index (k) and flow behavior index (n), were investigated using the HVFR and guar at different temperatures. At 25°C, the consistency index (k) of the HVFR was higher compared to that of guar. Also, when the temperature was increased to 50°C, the HVFR was able to resist being affected and retained a good consistency index. However, increasing the temperature to 75°C led to a sharp drop in the HVFR consistency index because the friction reducer was adversely affected by the temperature at 75°C. Although the guar's consistency index did not provide any resistance to the change in temperature, it decreased directly once the temperature reached 50°C, and the consistency index continued to decrease with an increase in the temperature to 75°C. **Tables 2 and 3** show the fluid parameters, such as the flow behavior index (n) and consistency index (k) at different temperatures. The consistency index of the HVFR was 0.79, 0.71, 0.41, and 0.07 at 25, 50, 75, and 100°C, respectively, whereas the guar's consistency index was 0.09, 0.05, 0.02, and 0.01, respectively, at the same temperatures. The rheology measurements of the flow behavior index (n) of the HVFR did not show significant changes even when the temperature was increased, in contrast with the guar's flow behavior index, which exhibited increasing values as the temperature rose. The HVFR flow behavior indices were 0.31, 0.28, 0.31, and 0.35, whereas those of guar were 0.74, 0.78, 0.86, and 0.89 for 25, 50, 75, and 100°C, respectively. At 100°C, it was hard to measure the viscosity of both fracture fluids because the fluids exhibited a kind of evaporation compared to lower temperatures.

Temperature (°C)	HVFR			Guar		
	Concentration (gpt)	τ	R^2	Concentration (ppt)	τ	R^2
25	1	$0.11\gamma^{0.49}$	0.99	15	$0.02\gamma^{0.84}$	0.99
25	2	$0.31\gamma^{0.38}$	0.99	25	$0.09\gamma^{0.74}$	0.98
25	4	$0.79\gamma^{0.31}$	0.98	35	$0.31\gamma^{0.63}$	0.99
25	8	$1.93\gamma^{0.26}$	0.99			

Table 2—Power-law parameters of HVFR and guar at different concentrations and temperatures.

Tables 2 and 3 show the power-law parameters, such as the flow behavior index (n) and consistency index (k) of the HVFR and guar at various concentrations and temperatures.

Temperature (°C)	4 gpt HVFR		25 ppt Guar	
	τ	R^2	τ	R^2
25	$0.79\gamma^{0.31}$	0.98	$0.09\gamma^{0.74}$	0.98
50	$0.71\gamma^{0.28}$	0.99	$0.05\gamma^{0.78}$	0.99
75	$0.41\gamma^{0.31}$	0.97	$0.02\gamma^{0.86}$	0.99
100	$0.07\gamma^{0.35}$	0.98	$0.01\gamma^{0.89}$	0.98

Table 3—Power-law parameters of HVFR and guar at different temperatures.

Time-Dependent Effect of Temperature on the Viscosity. The impact of time on both the fracture fluids was evaluated to determine whether the fracture fluids' viscosity at different temperatures would be affected over time. All rheological measurements started after reaching the desired temperature. **Figs. 7a and 7b** illustrate the influence of increasing the temperature using an HVFR concentration of 4 gpt and guar concentration of 25 ppt; each experiment was conducted separately and was started after reaching the desired temperature. The results show that at 25°C, both the fracture fluids at 10 s^{-1} shear rates demonstrated a stable viscosity, even after 5,000 seconds (1 hour and 23 minutes). As the temperature was increased to 50°C, the HVFR still provided excellent resistance to temperature, but its viscosity began to decrease slightly after approximately 2,100 seconds. This occurred for two reasons: (1) because the HVFR started to evaporate slightly, which caused the viscosity to decrease, and (2) because the temperature affected the strength of the fluid molecules. On the other hand, guar did not provide any resistance to the temperature at 50°C because its viscosity started to drop directly after a short time. At 75°C, the HVFR exhibited a large reduction in viscosity, which started to decrease after approximately 450 seconds. However, the viscosity value of the HVFR was still higher than that of guar at 75°C. After 5,000 seconds and at a shear rate of 10 s^{-1} , the viscosities of the HVFR were 138, 113, and 14 mPa·s at 25, 50, and 75°C, respectively, whereas the guar viscosities were 67, 21, and 3 mPa·s, respectively, at the same temperatures. In addition, the impact of increasing the shear rates with time on the fracture fluid viscosities was studied for the HVFR and guar. At 25°C, both fracture fluids had almost the same viscosities at the high shear rate of 100 s^{-1} . At 100 s^{-1} , the viscosities of the HVFR were 32, 26, and 5 mPa·s, whereas the guar's viscosities were 30, 12, and 2 mPa·s at 25, 50, and 75°C, respectively. In addition, at 100°C, both fracture fluids decreased directly and exhibited unstable viscosities, so using this HVFR at temperatures equal to or greater than 100°C may not be recommended.

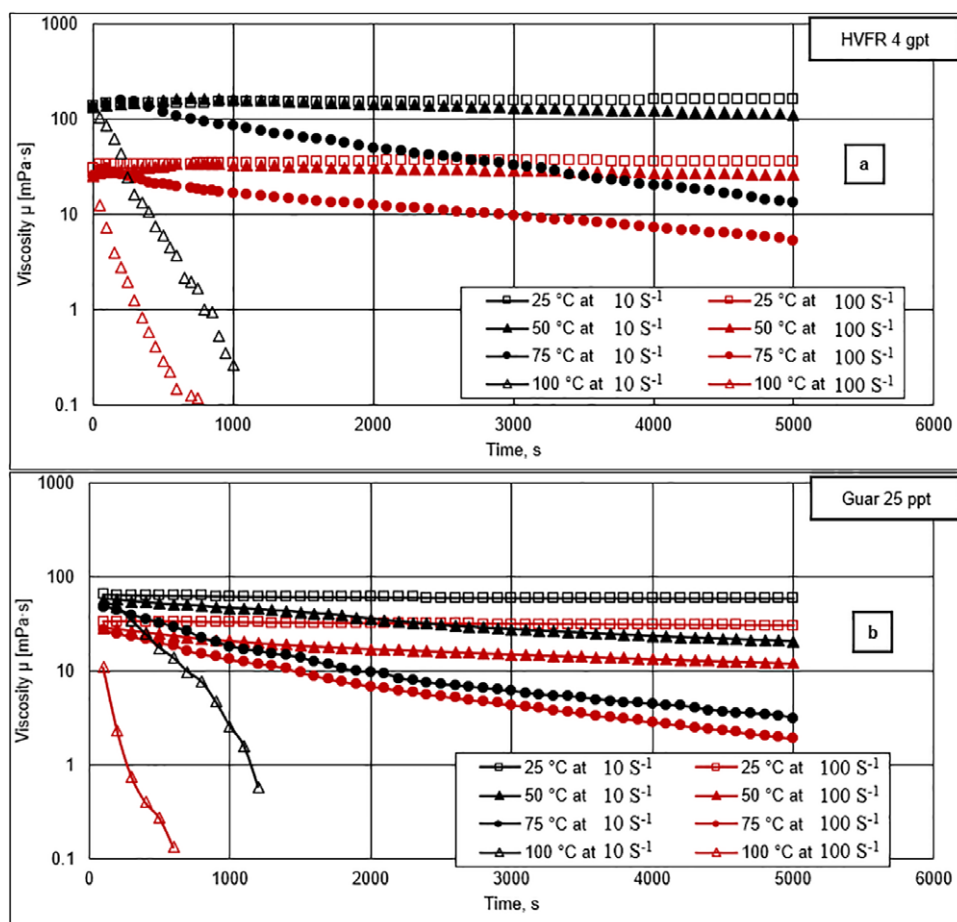


Fig. 7—Time-dependent temperature effect on the viscosity of (a) HVFR and (b) guar using various temperatures.

Elasticity Measurements. Determining the elastic properties of fracture fluids is crucial to using them where they could have a significant impact on the transport of proppant in fracture networks. **Figs. 8a and 8b** compare the elasticity of the HVFR at a 4 gpt concentration to guar at a 25 ppt concentration at various temperatures. The relaxation time (crossover frequency of the loss modulus G'' and

storage modulus G') was measured to establish the elasticity of the fluid. A long relaxation time indicates that the fluid has greater elastic properties compared to a fluid with a short relaxation time. The results showed that at 25°C, the HVFR had better elasticity compared to guar. Increasing the temperature to 50°C caused a reduction in the elastic properties of both fracture fluids; however, the HVFR still provided better elasticity than guar. At higher temperatures (greater than 50°C), the HVFR's elasticity decreased so sharply that it might not significantly aid in the transport of proppant. In contrast, with guar, there were almost no elastic properties at a high temperature (greater than 50°C), because there was no crossover frequency between G'' and G' .

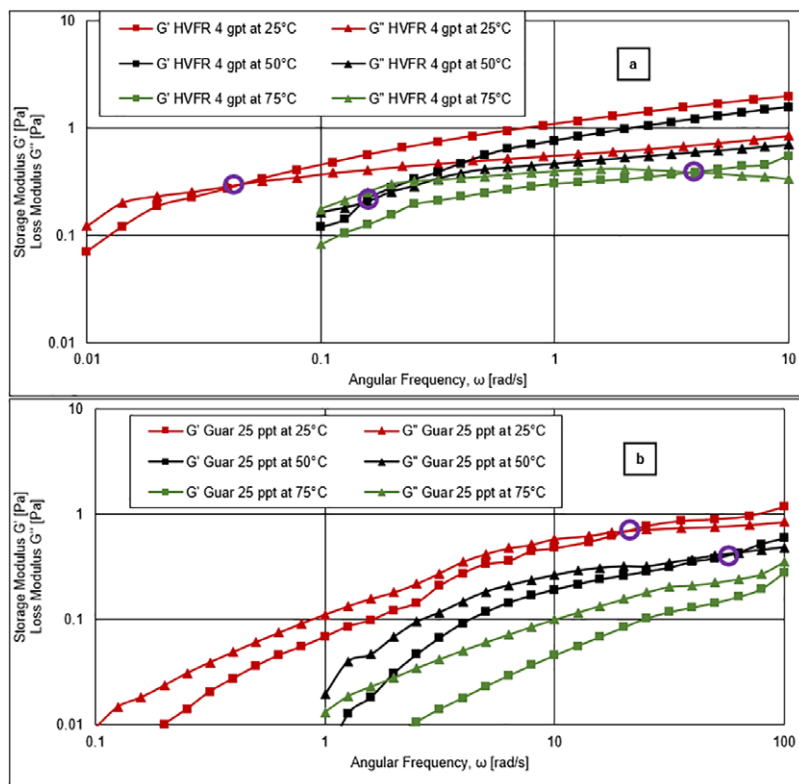


Fig. 8—Elastic properties of (a) HVFR and (b) guar at various temperatures.

Fig. 9 shows the effect of increasing the temperature on the relaxation time of the HVFR and guar. The HVFR demonstrated better elastic properties than guar, even when the temperature increased. The HVFR's relaxation time was 21.32, 5.95, and 0.2 seconds at 25, 50, and 75°C, respectively, whereas the relaxation time of guar was 0.044 and 0.02 seconds, respectively, at 25 and 50°C. At 75°C, guar did not exhibit any relaxation time because there was not a crossover frequency. These results suggest that the elasticity of guar might not allow it to effectively transport the proppant to distribute the sand into the fractures, whereas the elastic property of the HVFR showed that it can provide quality proppant transport at less than 75°C.

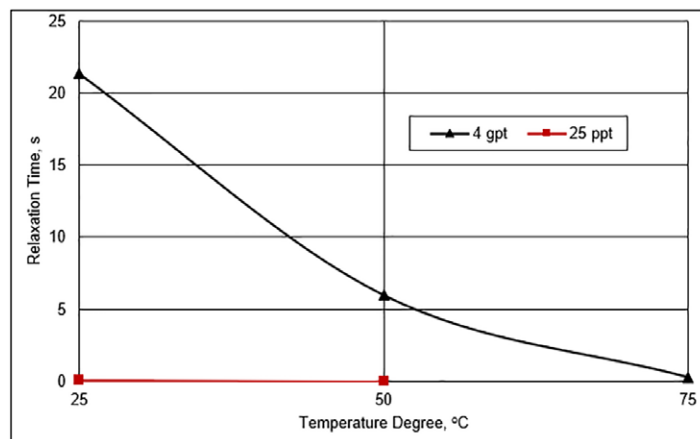


Fig. 9—Relaxation time of the HVFR and guar at various temperatures.

Loss Factor. The loss factor describes two portions of the viscoelastic behavior. Figs. 10a and 10b depict the loss factor ($\tan \theta$) of the fracture fluids, which represents the relationship of the loss modulus (G'' , viscous property) to the storage modulus (G' , elastic property). The results showed that the loss factor of both fracture fluids (HVFR and guar) increased as the temperature rose from 25 to

75°C. Additionally, the loss factor (G''/G') of the HVFR and guar revealed the relevant factors that can govern proppant transport. The HVFR had a lower loss factor compared to guar. This means that guar has weak elasticity, so it might have to depend almost solely on its viscosity to transport proppant.

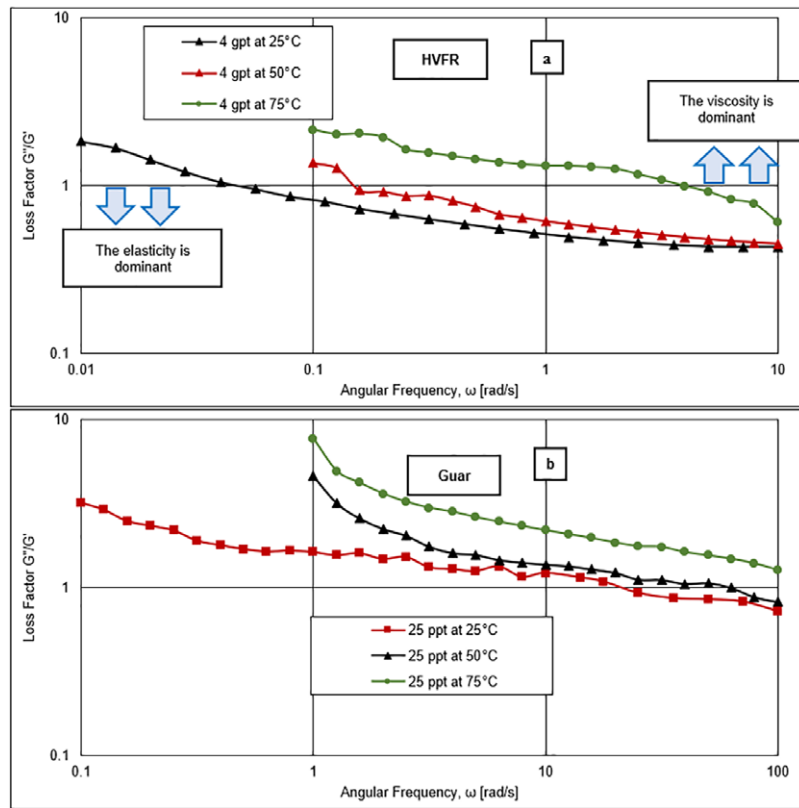


Fig. 10—Loss factor of (a) HVFR and (b) guar at various temperatures.

Spherical Particles Settling Velocity in a Static Model

The spherical particles static settling velocity was measured to understand the impact of the fluid temperature, fracture width, particle size, and ratio of the particle size to the fracture width.

Effect of Temperature. The effect of temperature on the settling velocity of the spherical particles was investigated using three temperature values (i.e., 25, 50, and 75°C). Fig. 11 exhibits the effects of temperature in creep regimes using two fracture fluids (i.e., HVFR and guar). The measurements were made at a 10-mm fracture width and 6-mm spherical particle size. The settling velocity of the particles increased as the temperature increased. This was due to a reduction in the viscous and elastic properties of the fracture fluids, which negatively affected the capacity of the fracture fluids to suspend the particles. However, the HVFR still demonstrated a higher capacity to hold the spherical particles for a significantly longer time than guar, even at higher temperatures. The average terminal settling velocities in the HVFR were 0.042, 0.16, and 0.19 m/s at 25, 50, and 75°C, respectively, whereas the spherical particle velocities through guar were 0.21, 0.24, and 0.28 m/s at 25, 50, and 75°C, respectively.

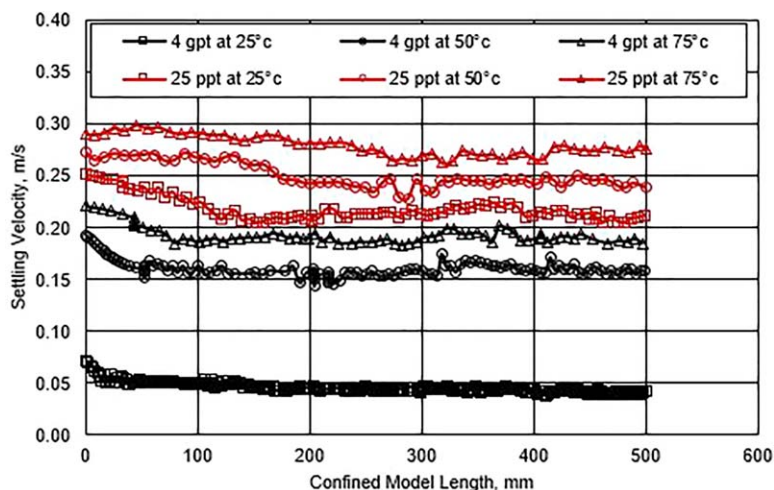


Fig. 11—Particle settling velocity through the HVFR and guar using a 6-mm particle size and 10-mm fracture width.

Effect of Fracture Width. Fig. 12 shows the impact of different fracture widths (i.e., 7 and 10 mm) on the particle settling velocity using both fracture fluids. The measurements were carried out using a 6-mm particle size at 25°C. The settling velocities of the spherical particles in both the fracture fluids were faster in a 10-mm fracture width because the friction between the spherical particles and the parallel walls was lower, compared to a 7-mm width, where the friction was higher and slowed the particle settling velocities. However, the HVFR demonstrated a higher capacity than guar to suspend the particles. The settling velocities into the HVFR were 0.031 and 0.042 m/s for particles of 7 and 10 mm, respectively, whereas they were 0.16 and 0.21 m/s for the same-sized particles, respectively, using guar.

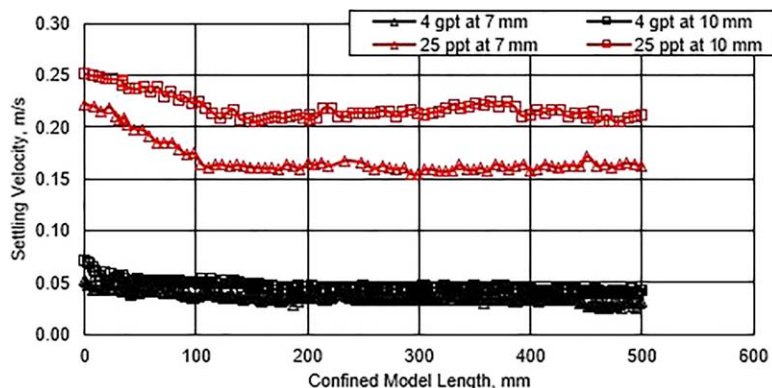


Fig. 12—Particle settling velocity through the HVFR and guar using different fracture widths.

Effect of Spherical Particle Size. Fig. 13 presents the effect of various particle sizes on the settling velocity through the fracture fluids at 25°C, with a fracture width of 10 mm. In both the HVFR and guar, the settling velocity of the particles was faster when using a larger size (e.g., 6 mm) because of its higher weight compared to smaller particle sizes, such as 2 mm. The settling velocities of the particles using 4 gpt were 0.0012, 0.026, and 0.042 m/s for 2, 4, and 6 mm, respectively. In contrast, the settling velocities of the spherical particles across the guar samples were 0.05, 0.16, and 0.21 for 2, 4, and 6 mm, respectively. Additionally, the settling velocity of the 2- and 6-mm particles in guar and HVFR, respectively, had similar settling velocities at approximately 0.05 m/s. Interestingly, these results imply that the HVFR had the ability to hold large, solid particles (6 mm), which is similar to guar's ability to hold smaller solid particle sizes (2 mm). Also, it was noted that the settling velocity initially seems to fall and then level a little before starting to be stable, especially when a bigger particle size such as 6 mm was used. This might happen because of particles dropped at the entrance of the model, so at this point the particles might not fully be controlled by the fluid's properties such as viscosity and elasticity, so the particles will have higher settling velocity at the short beginning of the experiment.

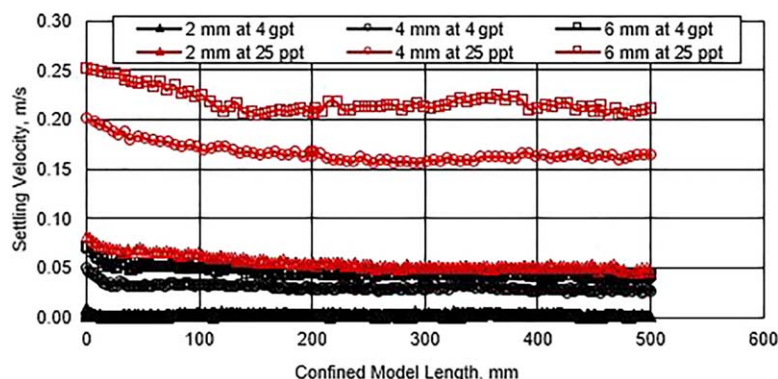


Fig. 13—Impact of particle sizes on the settling velocity using the HVFR and guar with different particle sizes.

Ratio of Particle Size to Fracture Width. The ratio of the particle size to the fracture width (r) was used to understand its impact on the solid settling velocity. Fig. 14 and Table 4 show the ratio of the particle size to the fracture width (r) using three particle sizes (i.e., 2, 4, and 6 mm) and two fracture widths (i.e., 7 and 10 mm) at different temperatures. These measurements were conducted using 4 gpt HVFR. At 25°C, the ratio (r) presented similar settling velocities for both the 7- and 10-mm fracture widths, especially at smaller particle sizes (smaller ratios). The settling velocities were 0.001, 0.02, and 0.031 m/s for the ratios of 0.29, 0.57, and 0.86, respectively, whereas the settling velocities were 0.0012, 0.026, and 0.042 m/s for the ratios of 0.2, 0.4, and 0.6, respectively. This might have occurred because the fluid properties did not change at 25°C, which may have created viscous layers that minimized the friction effect between the particles and fracture walls. However, increasing the temperature to 50°C produced a slight reduction in the fluid viscosity, as shown in Fig. 14 and Table 4, causing the settling velocity to increase in both fracture widths. At 75°C, a significant difference in the settling velocity was observed in both fracture widths, and the settling velocities were 0.016, 0.07, and 0.1 m/s for the ratios of 0.29, 0.57, and 0.86, respectively; the settling velocities were 0.024, 0.11, and 0.18 m/s for the ratios of 0.2, 0.4, and 0.6, respectively. This difference in the settling velocities might have occurred because the viscosity of the HVFR was reduced and could not create viscous layers to separate the particles from contacting the fracture's parallel walls. This resulted in a cap on the settling velocities between the two fracture widths with the same particle size. Table 4 summarizes the impact of the ratio of the particle size to the fracture width on the settling velocity at various temperatures.

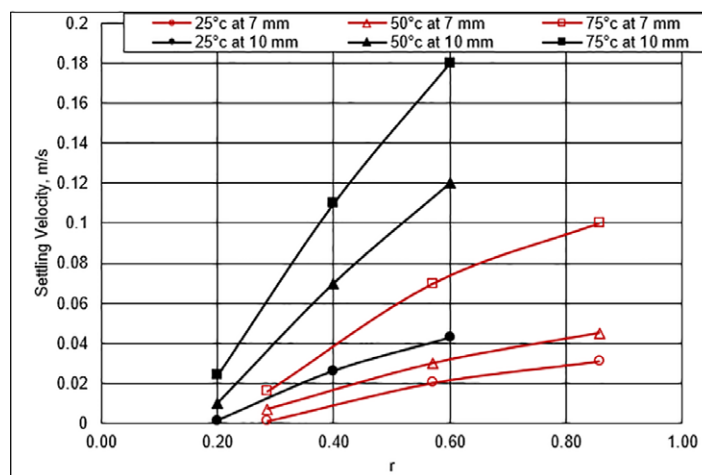


Fig. 14—Terminal settling velocity vs. the ratio of the particle size to the fracture width using 4 gpt HVFR.

Fracture Width (mm)	Particle Size Diameter, D_p (mm)	Ratio of Particle Size to Fracture Width	Terminal Settling Velocity, V (m/s)		
			25°C	50°C	75°C
7	2	0.29	0.001	0.007	0.016
	4	0.57	0.02	0.03	0.07
	6	0.86	0.031	0.045	0.1
10	2	0.2	0.0012	0.01	0.024
	4	0.4	0.026	0.07	0.11
	6	0.6	0.042	0.12	0.18

Table 4—Effect of the ratio of the particle size to the fracture width on the solid settling velocity at different temperatures.

Proppant Transport in a Dynamic Fracture Slot Model

Experiments investigating proppant transport inside fractures were conducted to understand the impact of the fluid temperature, proppant size, and proppant concentrations.

Effect of Temperature. Because insightful understanding of the improved temperature resistance of the HVFR is necessary, a dynamic slot fracture model was designed to study the impact of temperature on the HVFR's performance when transporting proppant. Fig. 15 shows that at a low temperature of 25°C, the HVFR provided an excellent proppant distribution in the fracture even after a long time of pumping, and a small sand bank was observed near the wellbore. Increasing the temperature to 50°C led to a slight reduction in the HVFR's ability to suspend the sand; however, the friction reducer still provided a good sand transport. At a higher temperature of 75°C, the viscosity and elasticity of the HVFR decreased noticeably, which negatively affected the sand distribution. The sand started to gather and created a large sand bank after approximately 10 minutes. In a similar experiment, guar was used to transport the proppant in the dynamic model at similar temperature values. Fig. 15 shows that guar's ability to hold the sand at a low temperature of 25°C was extremely weak compared to the HVFR; the sand bank started to build up faster inside the fracture model, and less sand was transported farther into the fracture. Increasing the temperature to 50 and 75°C reduced the guar's efficiency, because more sand was observed in the fracture. In oilfield applications, this may lead to operational issues, such as increased surface pressure. Based on the rheology measurements of the HVFR and guar discussed earlier, the viscosity of both fracture fluids was very low at high shear rates, which implies that the fluid viscosity may not contribute significantly to sand transport in comparison to elasticity. The elastic factor of the guar was weak, resulting in poor sand distribution in comparison to the HVFR. This may explain why guar cannot provide a good proppant suspension across the fracture networks compared to the HVFR. Fig. 16 displays the proppant distribution along the slot as a function of injection time, where the dune height data were digitized from Fig. 15. The HVFR held the proppant for a longer time without significant settling compared to guar, even when the temperature continued to increase. In comparison to guar, the HVFR provided a better sand transport capacity across the slot except at 75°C, where sand started to accumulate inside the slot, and the proppant dune height reached approximately 10 mm.

The volume of the sand inside the dynamic model was determined by measuring the area using the SketchAndCalc area calculation program. The fracture width of the fracture model was 0.25 in. (0.635 cm). Eq. 1 was used to calculate the proppant volume, whereas Eq. 2 expresses the measurements of the volume ratio.

$$\text{Proppant volume} = \text{sand area inside the dynamic model} \times \text{width of fracture model} \quad (1)$$

$$\text{Volume ratio} = \frac{\text{proppant volume}}{\text{total volume}} \quad (2)$$

Fig. 17 exhibits the volume ratio of the proppant that was presented in Fig. 15, where the proppant volume ratio is the ratio of the proppant volume to the total volume of proppant and the fracture fluid in the dynamic fracture system. At 25°C, the HVFR provided a lower sand volume ratio with increased pumping time compared to guar, in which the sand volume gathered rapidly. Increasing the temperature to 50°C did not affect the HVFR's ability to suspend and distribute the proppant, and the volume ratio of the sand in the

dynamic model was slightly larger than at 25°C, especially after 20 minutes. However, guar did not provide any resistance to the temperature at 50°C, when the sand volume ratio after 20 minutes was almost three times the volume ratio at 25°C. The effect of the temperature on the HVFR was clearly noted at 75°C, and the proppant volume ratio increased in a shorter time in comparison with the lower temperatures of 25 or 50°C. Appendix A contains the original data of the proppant volume ratio in Fig. 17.

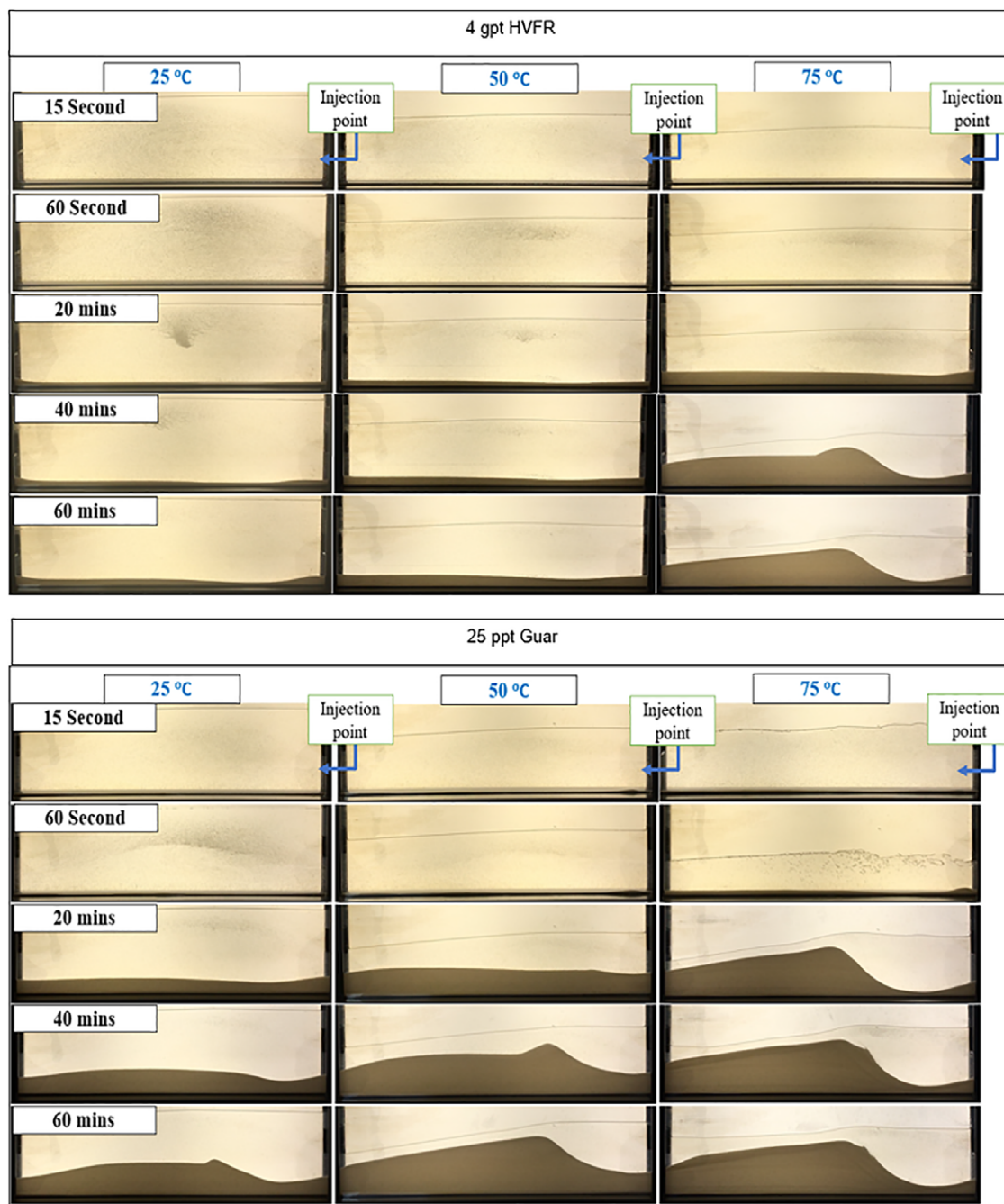


Fig. 15—Photographs of the proppant distribution across the dynamic fracture model using the HVFR and guar at various temperatures.

Effect of Proppant Sizes. Figs. 18 and 19 exhibit the proppant transport in the dynamic model using the HVFR at a 4 gpt concentration at 25°C. Two proppant sizes (i.e., 30/50 and 40/70 mesh sizes) were used to investigate the HVFR's ability to suspend proppant for a significant time. At a 40/70 mesh size, the HVFR provided a high degree of suspension for the sand over a longer slurry injection time and distributed the proppant well across the entire fracture, as shown in Fig. 19. Increasing the proppant size to 30/50 did not reduce the HVFR's effectiveness, because the proppant was distributed in a similar manner to the low mesh size (40/70); however, a small sand bank was observed at the higher mesh size of 30/50.

Fig. 20 displays the sand volume ratio that was presented in Fig. 18 using different sand sizes. The HVFR was more efficient in distributing the proppant, even when the sand size was increased from 40/70 to 30/50. However, almost twice the sand volume ratio was noticed when using 30/50 mesh instead of 40/70; after 1 hour, the proppant volume ratio was approximately 0.036 with 40/70 mesh, whereas it was 0.072 with 30/50 mesh. Appendix B contains the original data of the proppant volume ratio in Fig. 20.

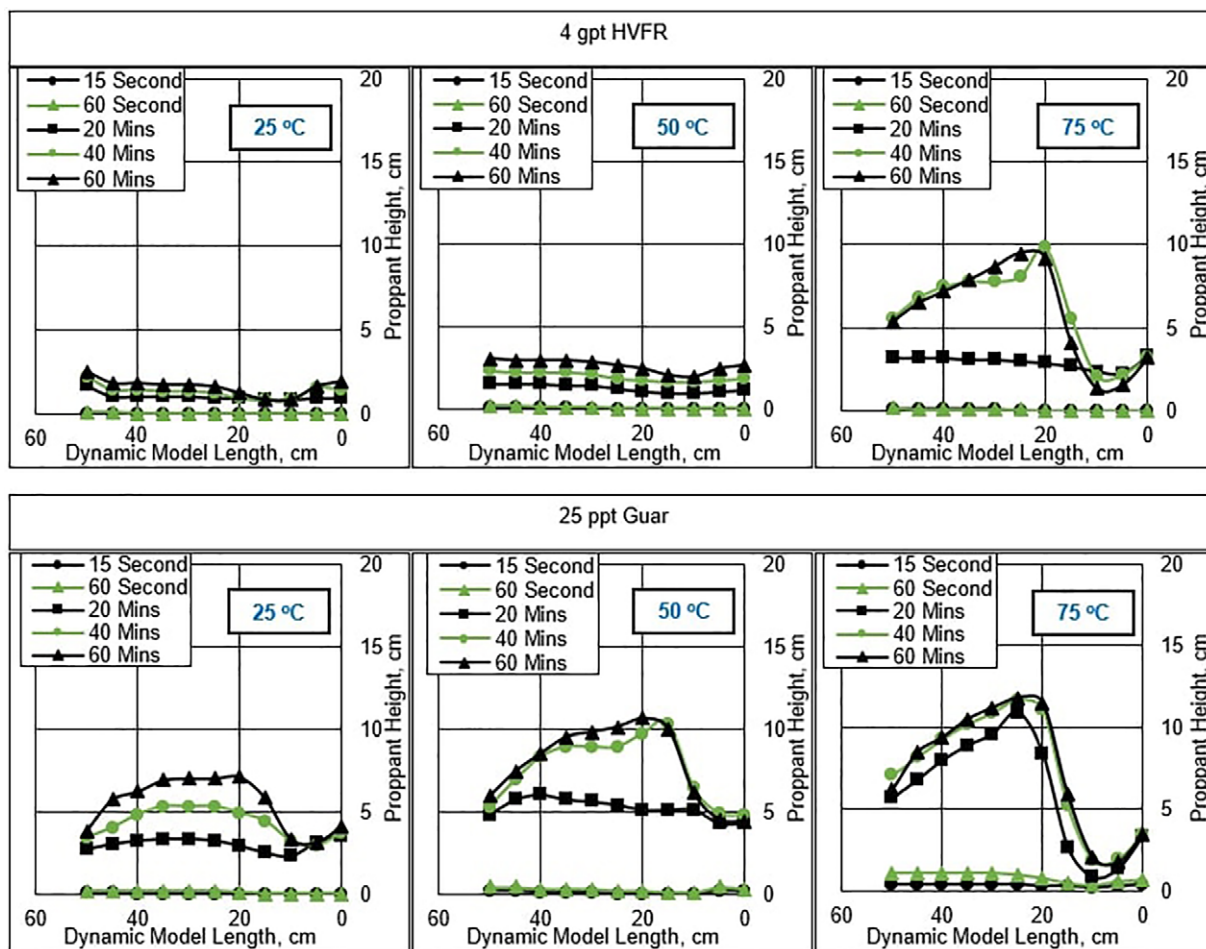


Fig. 16—Proppant distribution along the fracture slot using the HVFR and guar at various temperatures.

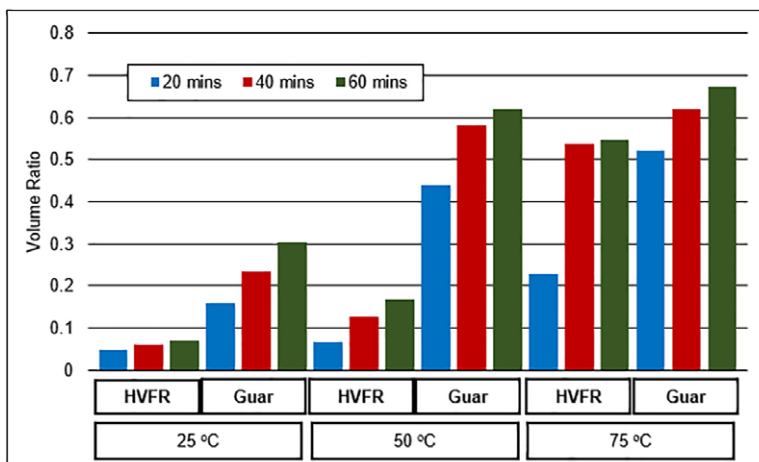


Fig. 17—Volume ratio over time using the HVFR and guar at various temperatures.

Effect of Proppant Concentrations. Figs. 21 and 22 illustrate the impact of the proppant concentration on the HVFR's ability to suspend and distribute sand inside the fractures using two proppant concentrations, 0.5 and 1 ppg. The HVFR effectively transported the proppant even when the sand concentration was increased. However, after 1 hour, the sand bank almost doubled in size when the proppant concentration was increased from 0.5 to 1 ppg.

Fig. 23 estimates the measurements of the proppant volume ratio (presented in Fig. 21) for different sand concentrations using the SketchAndCalc area calculation program. After 1 hour, at the higher sand concentration of 1 ppg, the sand volume ratio was approximately twice as much sand as the proppant volume ratio using 0.5 ppg. The sand volume ratio was 0.072 using a 0.5 ppg concentration, while increasing the proppant concentration to 1 ppg produced a volume ratio of approximately 0.137. Appendix C contains the original data of the proppant volume ratio in Fig. 23.

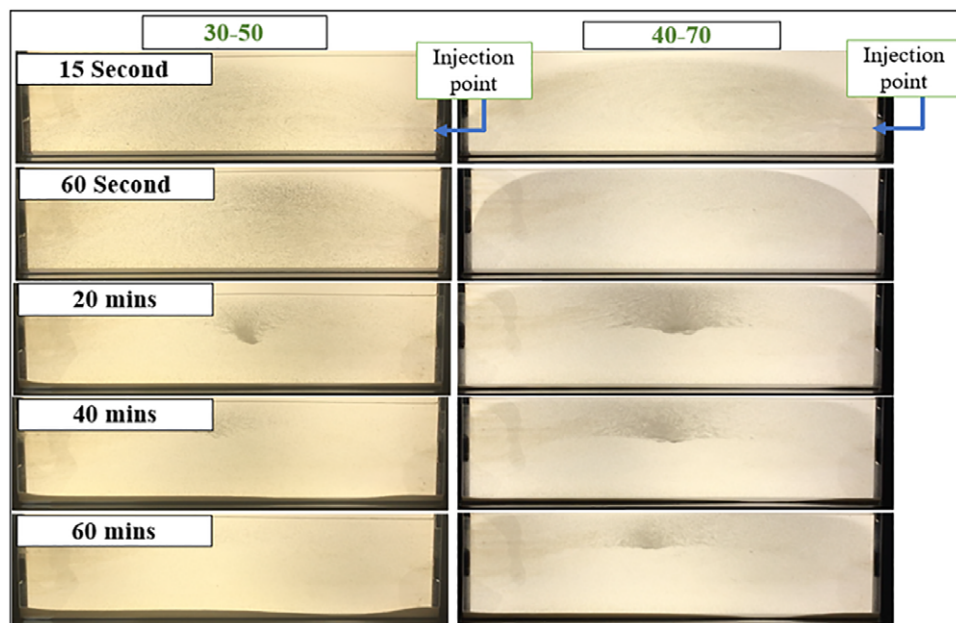


Fig. 18—Photographs of the proppant distribution across the dynamic fracture model using different sand sizes at 25°C.

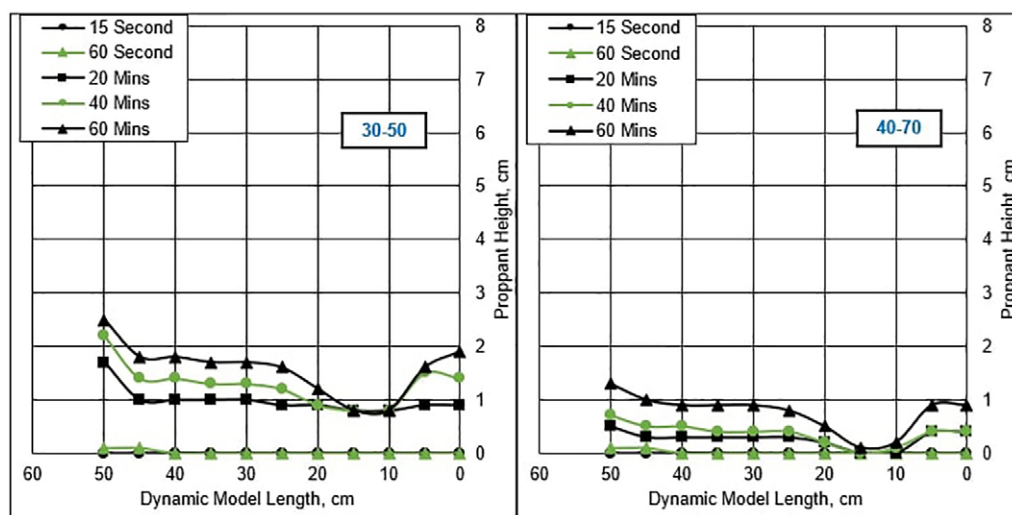


Fig. 19—Proppant dune height with time using different sand concentrations at 25°C.

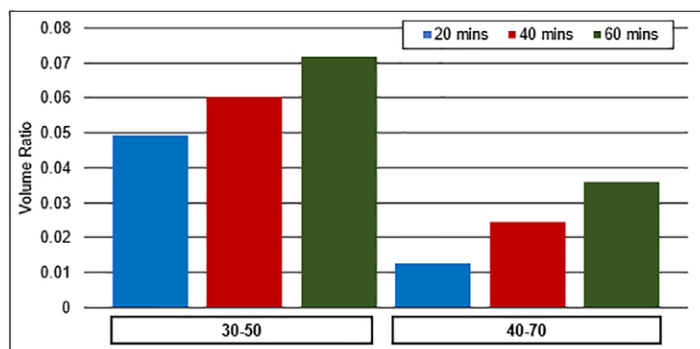


Fig. 20—Volume ratio over time using different sand sizes at 25°C.

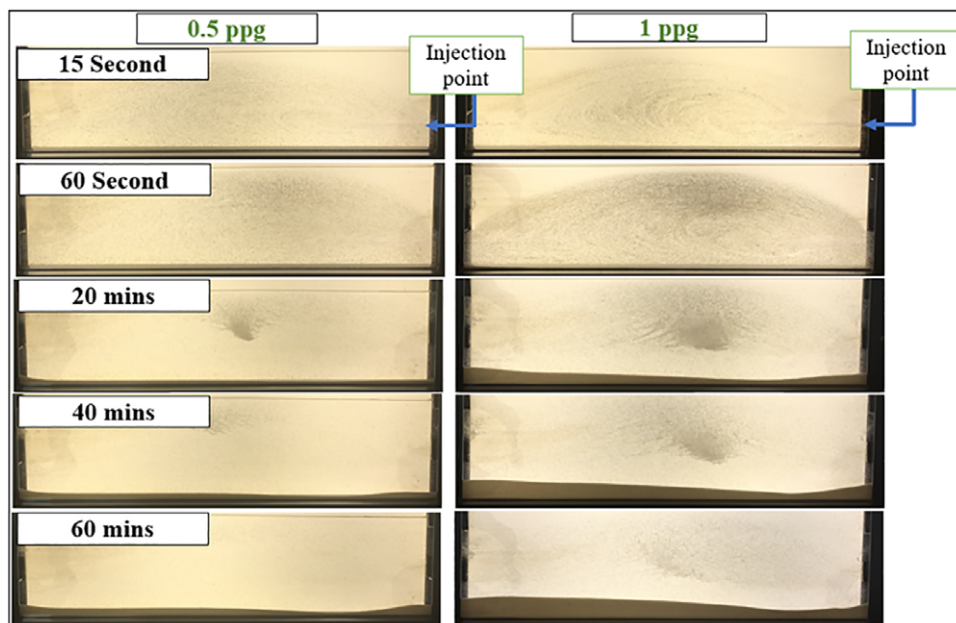


Fig. 21—Photographs of the proppant distribution across the dynamic model using different sand concentrations at 25°C.

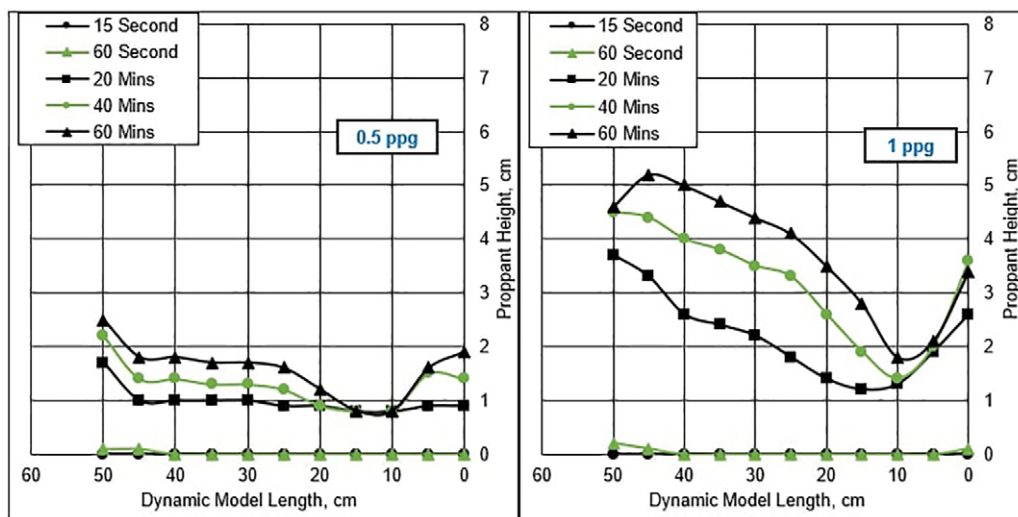


Fig. 22—Proppant dune height over time using different sand sizes at 25°C.

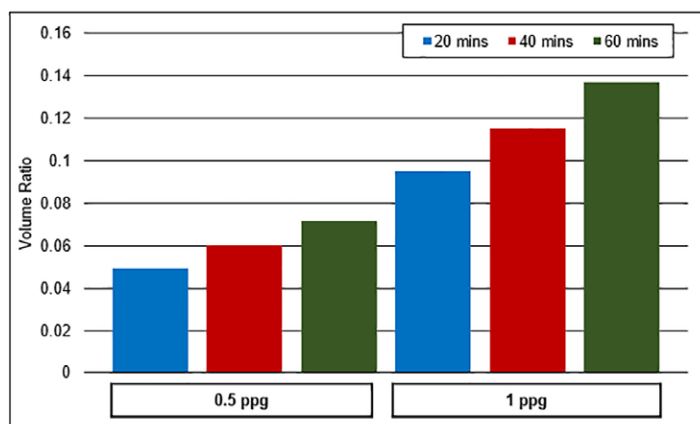


Fig. 23—Volume ratio over time using different sand concentrations at 25°C.

Conclusion

It is important to understand the impact of increasing the temperature on HVFR, which might help to determine the fluid capability to suspend and transport proppant in the fracture as the temperature is improved. This research provides a comprehensive understanding of the effect of temperature on proppant transport through fracture networks. Valuable information was found related to the impact of the temperature on the rheological parameters, static settling, and proppant distribution across the dynamic slot. Rheological measurements of two fracture fluids (i.e., HVFR and guar) were used to investigate the effect of temperature on the viscosity, elasticity, time-dependent effect, and loss factor. In the static system, various particle sizes were used to study the impact of temperature on the solid settling velocities, whereas proppant transport through a dynamic system was conducted using various proppant sizes and concentrations. The following points summarize the main results of this study:

- HVFRs provide a better viscosity at a lower shear rate compared to guar linear fluids, but at shear rates of 100 s^{-1} or higher, both of these fracture fluids show comparably low viscosities. This suggests that relying on the fluid's viscosity may not be sufficient to transport the proppant into network fractures.
- In comparison to guar, the viscosity of the HVFR exhibited a better resistance to temperature over time, especially at 50°C . However, at 75°C , the friction reducer's viscosity decreased significantly after a short time (approximately 450 seconds).
- The elasticity of guar was very low, even at the low temperature of 25°C . However, the HVFR showed a higher elastic parameter, even when the temperature was increased to 75°C , which exceeded that of the guar. This might be the key reason to recommend the friction reducer over guar.
- In the static fracture model, the HVFR demonstrated an outstanding ability to suspend the spherical particles for a significant time, even with increasing temperatures, which was superior to guar. However, at 75°C , the HVFR exhibited a large reduction in its capability to suspend solid particles for a significant amount of time.
- There was a noticeable decrease in the particle settling velocities as the ratio of the solid particle size to the fracture width was increased. Also, the wall effect increased as the fluid temperature increased, which might have occurred because rising temperatures often reduce beneficial fluid properties, such as viscosity.
- The proppant transport in the dynamic fracture model indicated that the HVFR could carry and hold the sand farther inside the network fractures. Furthermore, at temperatures below 75°C , a small dune was formed after a period of time, whereas guar produced a large amount of sand after a short period, even at the low temperature of 25°C .

Nomenclature

- D_p = spherical particle diameter, m
 G' = storage modulus, Pa
 G'' = loss modulus, Pa
 HVFR = high-viscosity friction reducer, gpt
 k = flow consistency index, $\text{Pa}\cdot\text{s}^n$
 n = flow behavior index
 V = settling proppant velocity, m/s
 λ = relaxation time of the friction reducer
 ω = angular frequency, rad/s

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Appendix A

Table A-1 presents the volume of the distributed proppant shown in Fig. 15 for the HVFR and guar.

Time (minutes)	25°C		50°C		75°C	
	Proppant Volume (cm ³)	Volume Ratio	Proppant Volume (cm ³)	Volume Ratio	Proppant Volume (cm ³)	Volume Ratio
4 gpt HVFR						
20	30.5372	0.0490	48.1203	0.0689	98.6028	0.2278
40	41.4782	0.0602	70.612	0.1277	196.069	0.5376
60	50.4762	0.0718	87.0585	0.1671	205.0098	0.5462
25 ppt guar						
20	90.2208	0.1586	164.4269	0.4401	188.8173	0.5221
40	128.905	0.2357	225.5711	0.5820	227.6285	0.6180
60	165.9827	0.3046	240.0364	0.6200	249.0661	0.6725

Table A-1—Volume of the proppant inside the dynamic model using both fracture fluids at various temperatures and volume ratios.

Appendix B

Table B-1 presents the volume of the distributed proppant shown in Fig. 18 for the HVFR at 25°C.

Time (minutes)	4 gpt HVFR at 25°C			
	Mesh Size 30/50		Mesh Size 40/70	
	Proppant Volume (cm ³)	Volume Ratio	Proppant Volume (cm ³)	Volume Ratio
20	30.5372	0.0490	9.2456	0.0127
40	41.4782	0.0602	17.7102	0.0246
60	50.4762	0.0718	25.7429	0.0361

Table B-1—Volume of the proppant inside the dynamic model and the volume ratio using different proppant sizes at 25°C.

Appendix C

Table C-1 presents the volume of the distributed proppant shown in Fig. 21 for the HVFR at 25°C.

Time (minutes)	4 gpt HVFR at 25°C			
	0.5 ppg		1 ppg	
	Proppant Volume (cm ³)	Volume Ratio	Proppant Volume (cm ³)	Volume Ratio
20	30.5372	0.0490	72.1932	0.0948
40	41.4782	0.0602	99.2442	0.1151
60	50.4762	0.0718	125.6157	0.1369

Table C-1—Volume of the proppant inside the dynamic model and the volume ratio using different proppant concentrations at 25°C.