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Correlating the Performance of Friction Reducers with Source Water Chemistry

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Abstract

This paper provides a detailed evaluation of the impact that field source water chemistry has on the performance of friction reducers being used for hydraulic fracturing. In this research, correlations are established between friction reducer performance and source water chemical composition, allowing operators to shorten the learning curve within their fracturing operations, use the most appropriate fluid systems, and potentially mitigate job failures.

Extensive testing has been conducted to evaluate friction reducer performance in the presence of different ionic components such as calcium, magnesium, iron and chloride. Performance testing was determined by varying individual ions, as well as using source waters from multiple field locations having total dissolved solid (TDS) levels of well over 100,000 ppm. Testing parameters included friction reduction, hydration rate via viscosity, and rheological characterization for viscosifying-type friction reducers. Principal component analysis was used as statistical tool to characterize the variation in water chemistry and to establish its relationship with friction reducer performance.

Introduction

Hydraulic fracturing in the oil and gas industry is essential to the production of hydrocarbons from tight rock formations. To create fractures, large volumes of fracturing fluid are pumped at high rates into the formation. Fracturing fluids are predominantly a water and sand mixture with a small percentage of chemical additives. Among the latter, polymers are a key component required to have properties such as friction reduction, viscosity development, clean breaks and high retained conductivity. Recently, due to cost savings and operational efficiencies (fewer chemicals and less fracturing equipment on location) the use of polyacrylamides as friction reducers has expanded. Among the many polyacrylamides used in oil and gas operations, Viscosity-building Friction Reducers (VFR), also referred to as High-Viscosity Friction Reducers (HVFR), are increasingly being used today ([Van Domelen et al., 2017](#); [Dahlgren et al., 2018](#); [Motiee et al., 2016](#); [Sanders et al., 2016](#)). HVFR fluid systems have proven successful since in addition to reducing pipe friction during hydraulic fracturing operations, they develop higher viscosities than traditional

slickwater systems, reducing water and chemical requirements, enabling on-the-fly design change flexibility and achieving higher regain conductivities than linear and cross-linked gels.

Most of the water used in hydraulic fracturing comes from surface water sources such as lakes, rivers and municipal supplies. However, new technology advancements have allowed for the use of produced water as well, facilitating its recycling by re-injection into underground formations (Lu et al., 2016). Produced water is found in the same formations as oil and gas. It may originate as natural water in the formations holding oil and gas or can be water that was previously injected into those formations. Typically, produced water contains some of the chemical characteristics of the formation from which it was produced and from the associated hydrocarbons. The inorganic chemical characteristics of produced water vary considerably depending on the geographic location and the geologic formation from which the petroleum and water were produced. The organic content of produced water depends heavily on the type of hydrocarbon produced (Stephensen, 1992).

To optimize fracturing operations, laboratory testing is critical to evaluate compatibility and performance among the chemicals selected to be pumped with source water. Test results allow for adjustments to be made to the fracturing chemicals based on water chemistry and performance. An important variable that highly affects the performance of polyacrylamide-based friction reducers is ion content. Performance, therefore, becomes dependent on both the ion type (cationic, anionic, monovalent or divalent) and the concentration present in the source water (Xu et al., 2016).

The research hereby presented is based on over two hundred source water samples, ranging from freshwater to produced water sources from different operators in several key basins. Testing included water chemistry analysis as well as friction flow loop and rheology profiles as a function of temperature. These results aid in pinpointing specific problematic ions and their impact on HVFR performance and has helped field logistics in troubleshooting and preventing screenouts.

Testing Methods and Data Analysis

Source Water Used for Study

To characterize and correlate the ions influencing friction reducer performance, two different approaches were utilized; the first was to incorporate the use of synthetic waters in order to control the specific ions desired for evaluation, the second was to use actual field source waters collected from various areas of operation.

Table 1 shows the compositions of the synthetic waters used, where selected ions were added. Each synthetic water was prepared by using distilled water along with one of the selected ions at different concentrations. Friction reducer performance was evaluated for each of the various ion's effect individually via friction loop and viscosity versus shear rate at 25°C.

Table 1—Composition of Synthetic Waters used in Study

Ions	Compound	Concentration of ion (mg/L)
Ca ²⁺	CaCl ₂	25, 100 & 3100
Mg ²⁺	MgCl ₂	500 & 3000
HCO ₃ ⁻	NaHCO ₃	100 & 200
SO ₄ ⁼	Na ₂ SO ₄	200 & 2000
Cl ⁻	KCl	25, 200 & 2000
Fe ²⁺ & Fe ³⁺	FeSO ₄ .7H ₂ O & FeCl ₃	25 & 50
Ba ²⁺	BaCl ₂ .2H ₂ O	25, 200 & 2000

To better understand friction reducer performance with actual field source waters, over 200 water samples were analyzed from the Bakken, Niobrara, Anadarko, Permian and Eagle Ford basins (Figure 1) for water chemistry and subsequently tested for friction and rheology studies. Due to their repeatability in water chemistries and to prevent over-crowding of data, this paper will present the results for the most representative samples: 36 freshwater and 12 produced water samples.

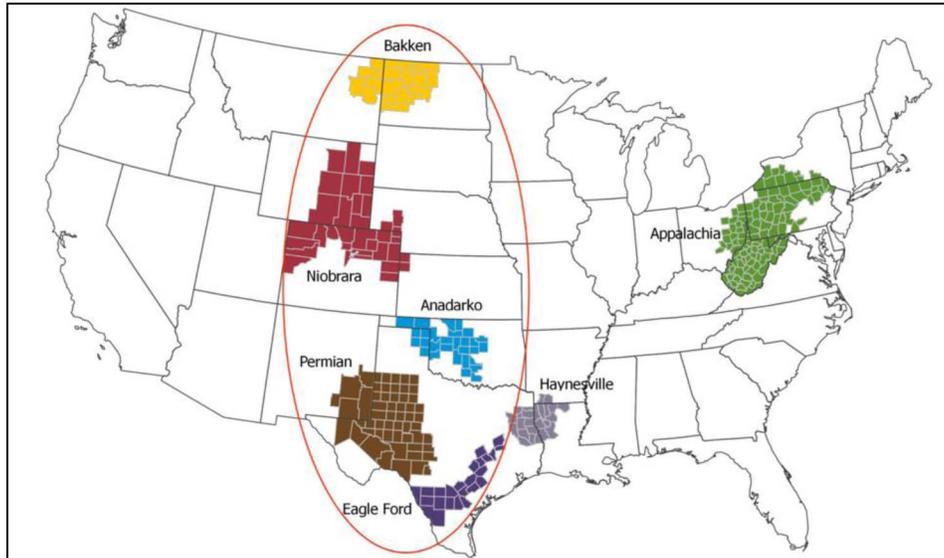


Figure 1—Study Areas for Source Waters

Water analyses were carried out by either colorimetry, titration or using probes. Parameters and ions analyzed included: fluid description (appearance, odor and color), pH, specific gravity, total chlorides and TDS (as conductivity at 25°C) with probe, alkalinity, total hardness, calcium and magnesium by titration, manganese, total iron, barium and sulfate with a Hach DR890 colorimeter, and hydrogen sulfide with Hach HS-C kit. Table 2 shows an example output of the water analysis described above.

Table 2—Example Analysis of a Field Source Water

Water Analysis Report		
Chemist Name : T. Luzan/ S. Hazra Date Received : 09.26.2018 Date Analyzed : 09.27.2018		
		
General Information	Water 1	Water 2
Water	Encana Powell 33C Fresh Water	Encana Powell 33C Produced Water
Fluid appearance	Clear	Turbid
Precipitate at bottom	White fluffy	Brown
Fluid color	Colorless	Brwonish yellow
Fluid Odor	None	Organic smell
pH	7.92	7.01
Oxidation Reduction Potential	178 mV	221 mV
specific gravity	1.001	1.050
Parameters	Concentration (mg/L)	Concentration (mg/L)
Alkalinity (1) (as CaCO ₃ mg/L)	130	260
Total Hardness (1) (as CaCO ₃ mg/L)	1,310	6,840
Calcium (1) (as CaCO ₃ mg/L)	690	6,080
Magnesium (1) (as CaCO ₃ mg/L)	620	760
Manganese (2) (Mn)	0.02	1.75
Iron (2) (Fe)	0.21	8.1
Phosphate (3) (PO ₄)	0 - 5	0 - 5
Sulfate (2) (SO ₄)	630	230
Barium (2) (Ba)	5	10
Hydrogen Sulfide (4) (H ₂ S)	0	0
Chloride (3) (Cl)	705	41,780
TDS (5) (as conductivity at 25°C)	2,139	76,100

Methods of Analyses - (1) Titration, (2) Colorimetry,
 (3) Paper Strip, (4) HACH Hydrogen Sulfide HS-C, (5) Probe

Friction Flow Loop

To evaluate turbulent drag reduction, a flow loop apparatus was custom-built in house. Dimension of the pipe is 0.25-inch stainless steel high-flow, low-shear flow loop pumping at ranges between one and eight gallons per minute. The friction loop uses a Coriolis flow meter, two absolute pressure transducers, and one differential pressure transducer to accurately determine the friction reducer additive performance in any given fluid by measuring pressure drop across a section of developed flow. Three factors were considered; maximum friction reduction achieved, inversion time (or hydration time) and stability.

Rheology Measurements

Rheology studies were carried out with a Brookfield LVDV-Pro II viscometer equipped with a UL adapter to measure low viscosities when needed. Viscosity measurements were also determined with an Anton Paar MCR102 rheometer equipped with a double gap cup and bob geometry for low viscosities (DG27). These rheometer devices have proven to be useful in evaluating HVFR fluid systems due to their ability to accurately measure very low viscosities (i.e., below 20 cp) which are normal for the HVFR systems. The devices can also measure viscosity at a wide range of shear rates which helps to evaluate shear-thickening, another important attribute of HVFR fluids due to their characteristic of developing significantly increased viscosity as the shear rate is decreased.

Principal Component Analysis (PCA)

Principal component analysis (PCA) is a statistical procedure designed to minimize the dimensionality of multivariate data while considering as much of the variation in the original data set as possible. If the variables within the original dataset are largely correlated and the ratio of explanatory variables to the number of observations is higher than normal, then this procedure is very useful. Principal components aim at transforming the original variable into a new data set that have linear combinations of the variables that are not correlated to each other and ordered based on the magnitude of variation of the original variables that they describe (Everitt and Hothorn, 2011).

In this paper, PCA was performed to cluster water samples into different clusters based on measurements of alkalinity, TDS, calcium (Ca^{2+}), magnesium (Mg^{2+}), iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$), sulfate (SO_4^{2-}), barium (Ba^{2+}) and chloride ions (Cl^-). This classification helped in identifying and correlating the water chemistry and the performance of HVFR in a particular water sample. The approach used in this study ensured that the percentage variability of dimension 1 and dimension 2 together were 70% or higher in order to maintain the reliability of the analysis. To perform PCA on the produced water sources, 12 samples were used. Because of such a small samples size, several analyses were performed with the use of a larger amount of samples; each time the same outcome was achieved which helped to confirm the reliability of the method.

Experimental Studies – Viscosity Measurements (Synthetic Water)

The first part of this study began with evaluating the viscosity performance of the HVFR fluid in distilled water containing ion concentrations ranging from 25 – 3100 mg/L of calcium, magnesium, bicarbonate, sulfate, chloride, iron and barium. The HVFR polymer loading was kept at three gallons per thousand gallons. With each ion tested separately, viscosity was measured at various shear rates ranging from 5 sec^{-1} to 150 sec^{-1} at room temperature. Results were compared to a baseline performance of HVFR fluid in distilled water. Figures 2 thru 8 help to demonstrate the impact of the various ions on the viscosity development of the HVFR system. One can observe from these tests that Ca^{2+} , Mg^{2+} and Fe^{2+} have the strongest effect on viscosity even at lower concentrations (500 mg/L or below). The Fe^{2+} caused a decline in viscosity at a concentration as low as 25 mg/L. The HCO_3^- , SO_4^{2-} , Cl^- and Ba^{2+} ions did not show as much of a significant effect on viscosity as Ca^{2+} , Mg^{2+} or Fe^{2+} .

This testing also included the use of a performance booster which is designed to help mitigate the negative performance effects on the HVFR system. The performance booster was successful in enhancing the viscosity for all of the ions, increasing viscosity to nearly one-half of the baseline performance. However when the ion concentration was too high the booster failed to make a significant impact. This result can be observed in Figures 2 and 3 at calcium and magnesium concentrations of 3100 and 3000 mg/L, respectively.

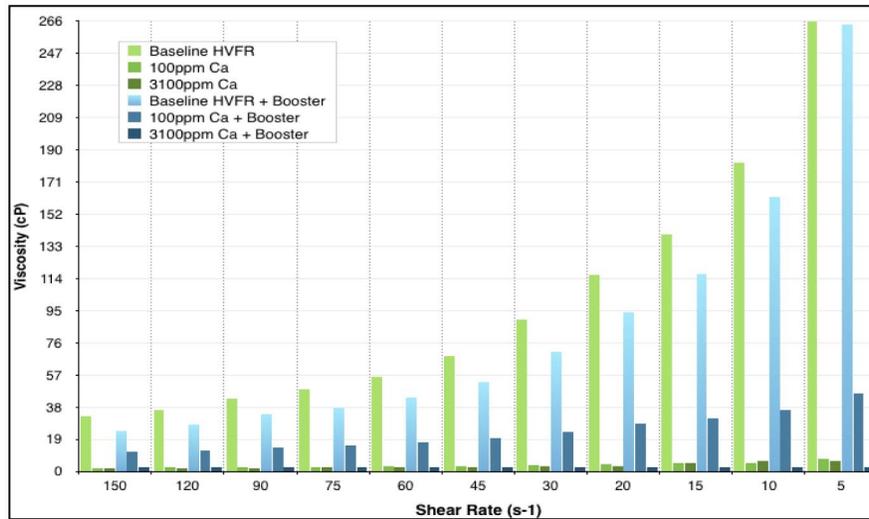


Figure 2—Effect of calcium on HVFR with and without performance booster

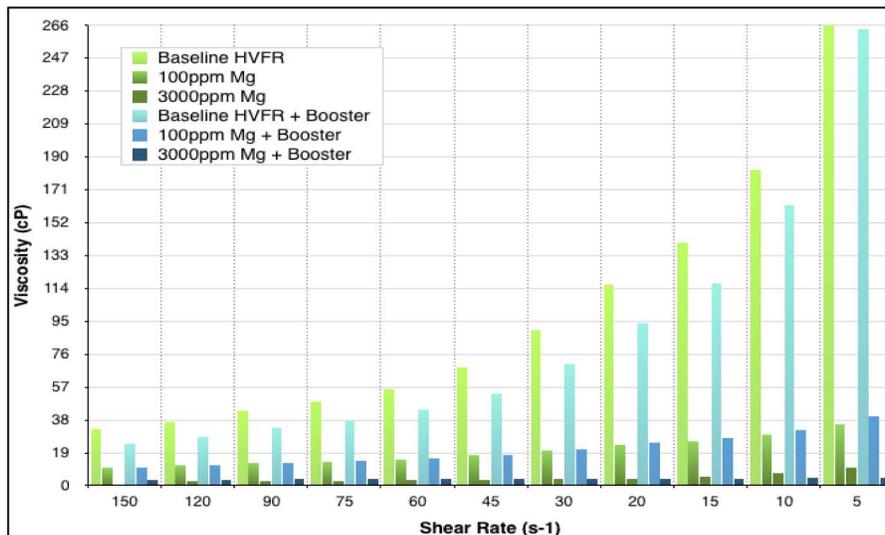


Figure 3—Effect of magnesium on HVFR with and without performance booster

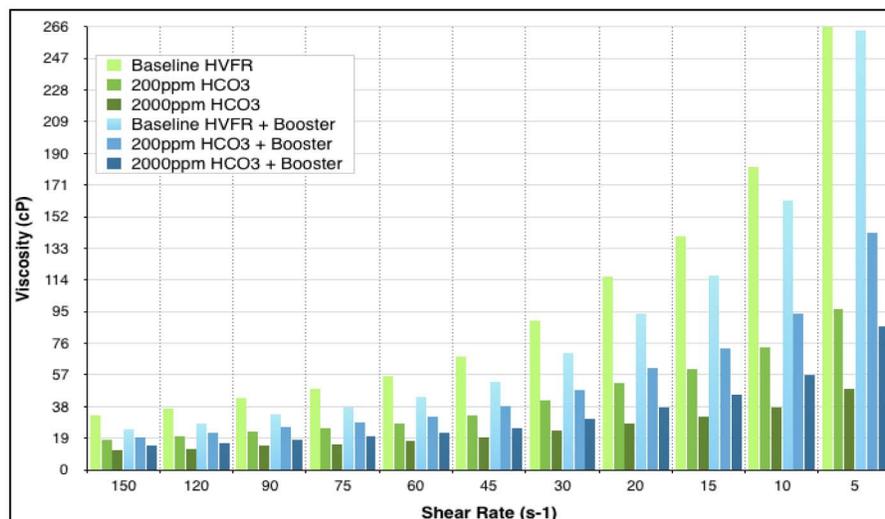


Figure 4—Effect of alkalinity (bicarbonate) on HVFR performance booster

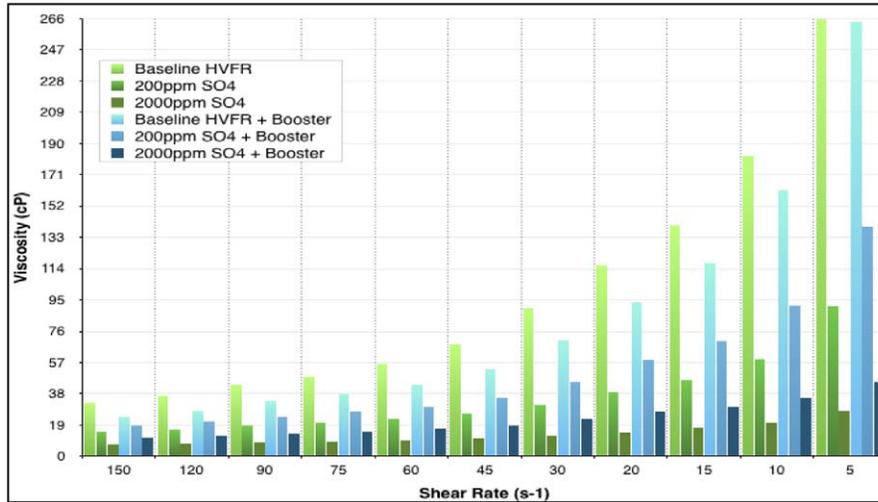


Figure 5—Effect of sulfate on HVFR with and without with and without performance booster

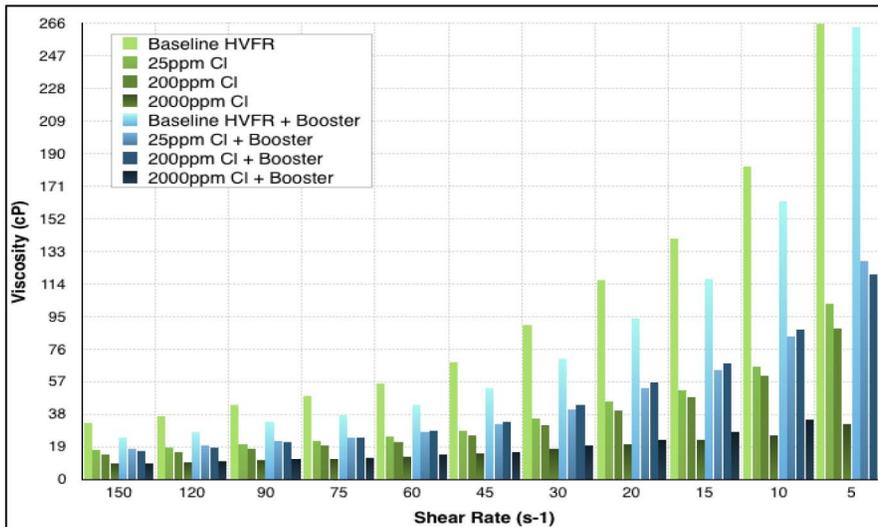


Figure 6—Effect of chloride on HVFR with and without performance booster

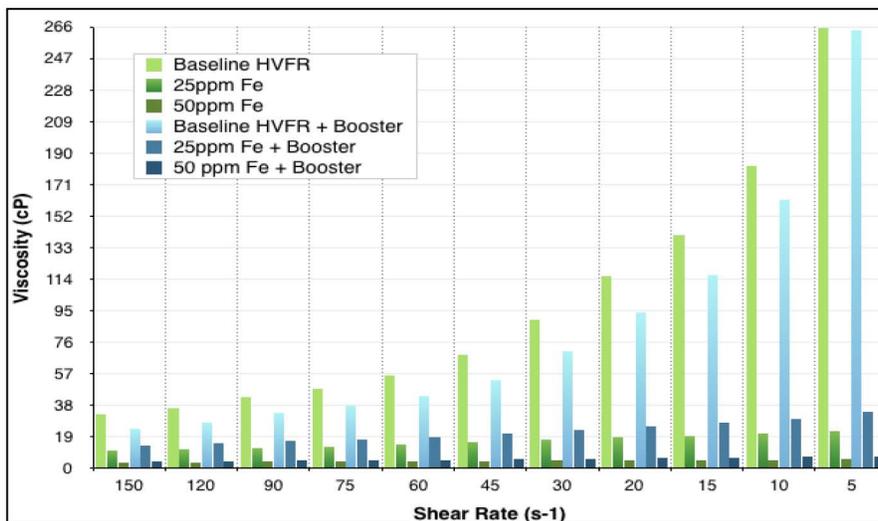


Figure 7—Effect of iron on HVFR with and without performance booster

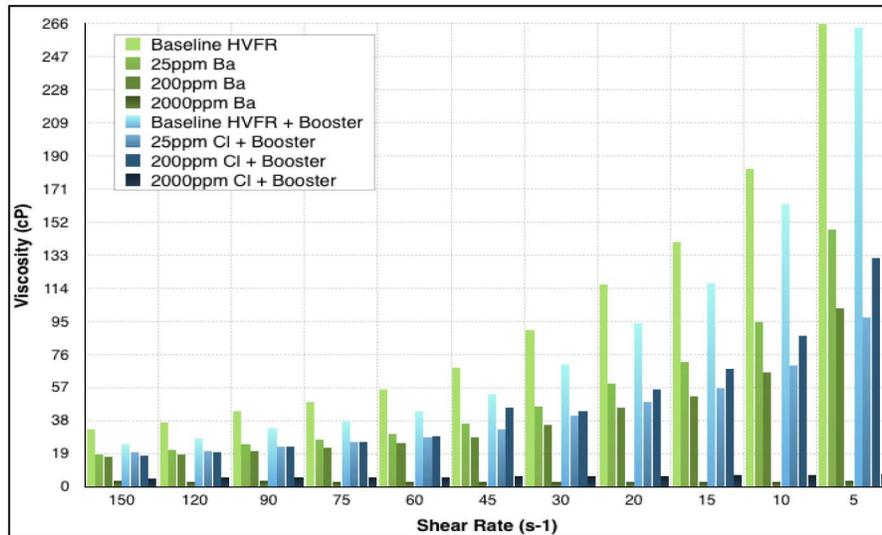


Figure 8—Effect of barium on HVFR with and without performance booster

Experimental Studies – Friction Reduction Measurements (Synthetic Water)

The next step in the testing process was to evaluate friction reduction in the flow loop at room temperature at five gpm flow rate. Again, each fluid tested was prepared in distilled water using a single ion type for evaluation. Figures 9 and 10 show charts of friction reduction as a function of time for the various ions tested with the synthetic waters. Most of the ions had a detrimental effect on friction reduction, albeit at higher concentrations compared to that of viscosity. One can observe that friction pressures started increasing as the concentration of ions reached 100 mg/L or higher. The ions Ca^{2+} and Mg^{2+} showed negative effects on friction reduction, however it was the Fe^{2+} and Fe^{3+} ions that had the strongest effect. These ions also had the strongest negative effect observed in the viscosity measurements. Finally, HCO_3^- and SO_4^{2-} did not have a significant effect while Cl^- shows only a small effect on friction reduction at a concentration of 2000 mg/L or higher.

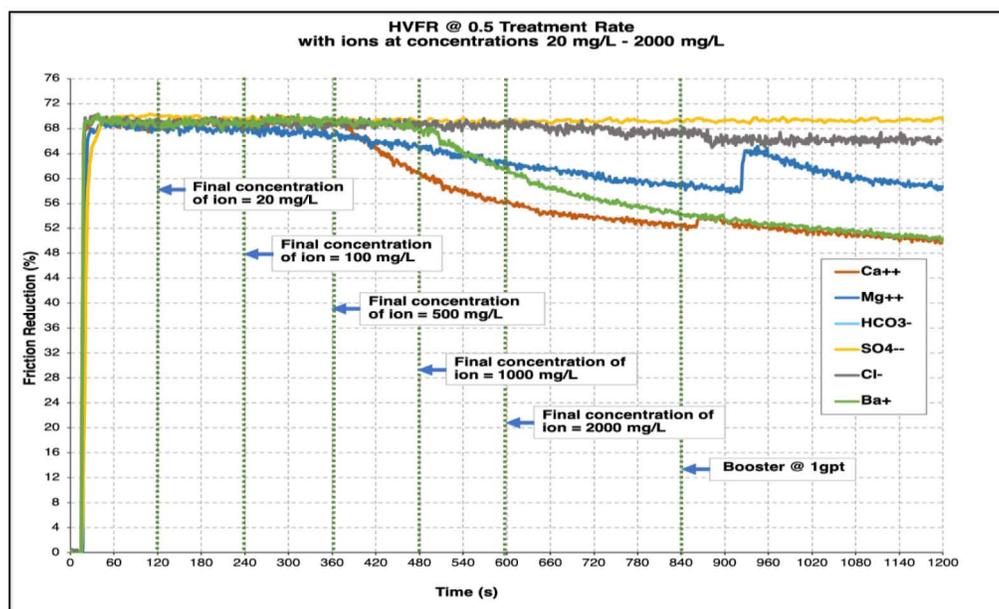


Figure 9—Effect of ions on friction reduction properties of HVFR with and without performance booster

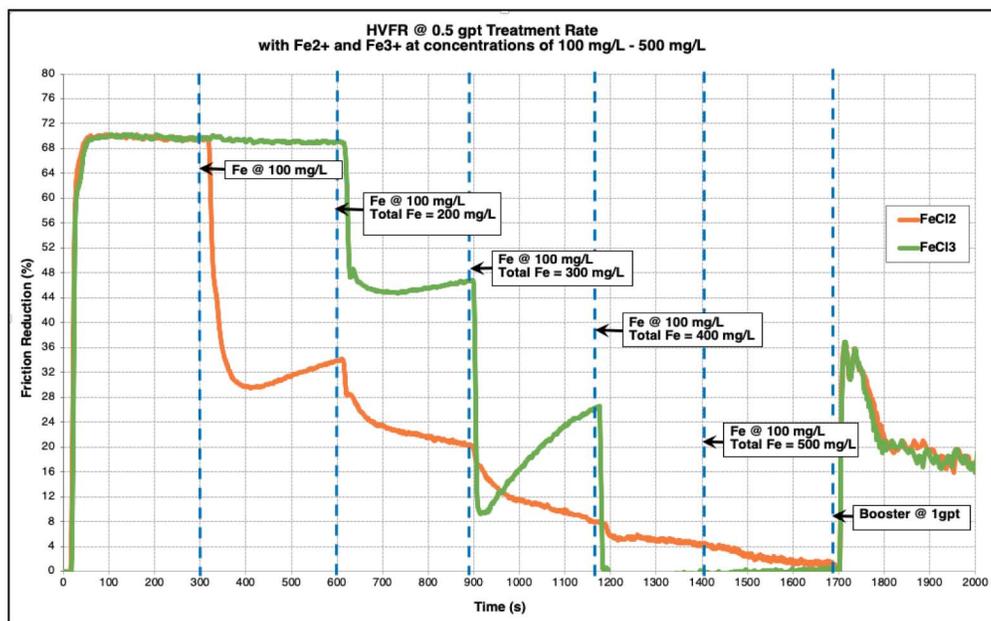


Figure 10—Effect of Fe²⁺ and Fe³⁺ on friction reduction properties of HVFR with and without performance booster

Experimental Studies - Viscosity Measurements (Field Source Water)

At this point in the study, the testing began incorporating the use of actual field source waters. The samples were divided into two groups based on the source of waters and their total dissolved solids (TDS) levels. Water from ponds, rivers or any other fresh water sources with TDS less than 5000 mg/L were grouped under "fresh water" samples. Flowback and produced water with TDS levels greater than 5000 mg/L were grouped under "produced water" samples. A total of 36 fresh water samples and 12 produced water samples were used in this study for their uniqueness and variability. (Refer to Table 3 in the Appendix for the complete set of water chemistries used in the study.)

Figures 11 and 12 show the viscosity profiles of the HVFR fluid system, prepared in the low TDS fresh field water, as a function of time at 150°F. These viscosity profiles are consistent with the HVFR fluid in these types of relatively clean waters and generally show good viscosity development, a key characteristic desired for these types of fluid systems in order to transport proppant efficiently out into the created hydraulic fracture network. A few of the fresh water samples, however, exhibited lower viscosity due to the presence a single ion. In Figure 13 for example, the sample named CO₂ (identified on the chart) had a very high concentration of SO₄²⁻ which resulted in a negative effect on viscosity. Similarly, sample NFE1 had a high iron concentration compared to other samples which caused lower viscosity development.

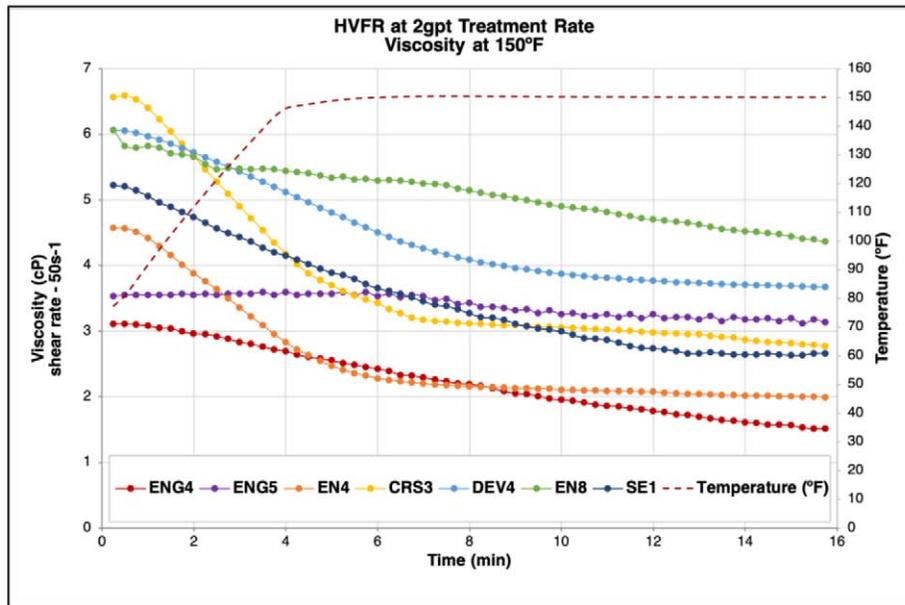


Figure 11—Viscosity of HVFR in low TDS (fresh) field water at 2gpt treatment rate at 50s-1

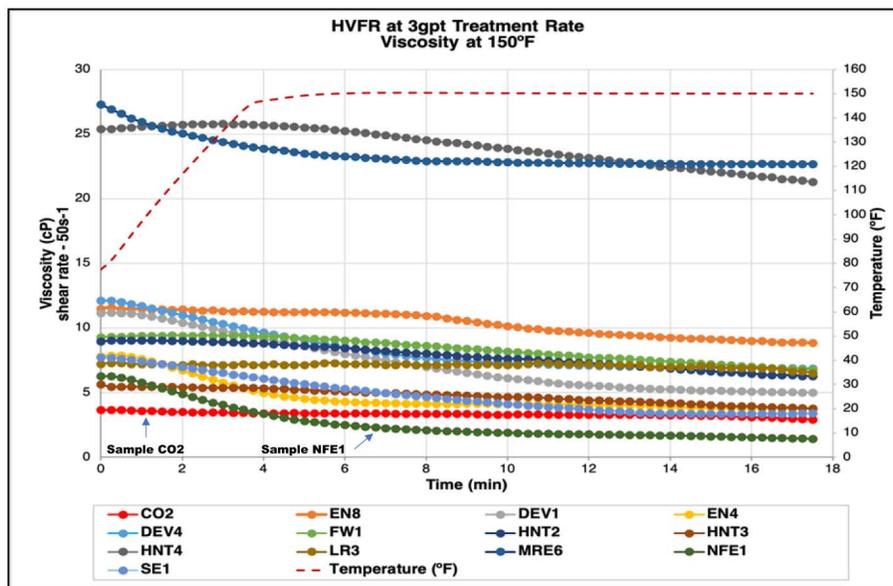


Figure 12—Viscosity of HVFR in low TDS (fresh) field water at 3 gpt at 50 sec⁻¹

Figures 13 and 14 show the viscosity profiles of the HVFR fluid system, prepared in the high TDS produced field water, as a function of time at 150°F. These viscosity profiles are consistent with the HVFR fluid in produced waters in which lower overall viscosity development is observed due to the interaction of the various ions on the HVFR polymer. These produced water sources generally contain many different types of ions, often at elevated concentrations.

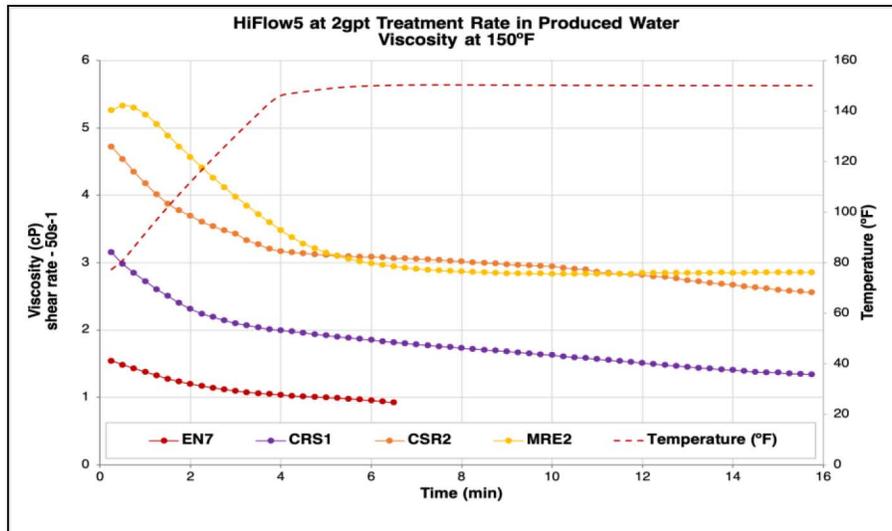


Figure 13—Viscosity of HVFR in high TDS (produced) field water at 2gpt at 50 sec⁻¹

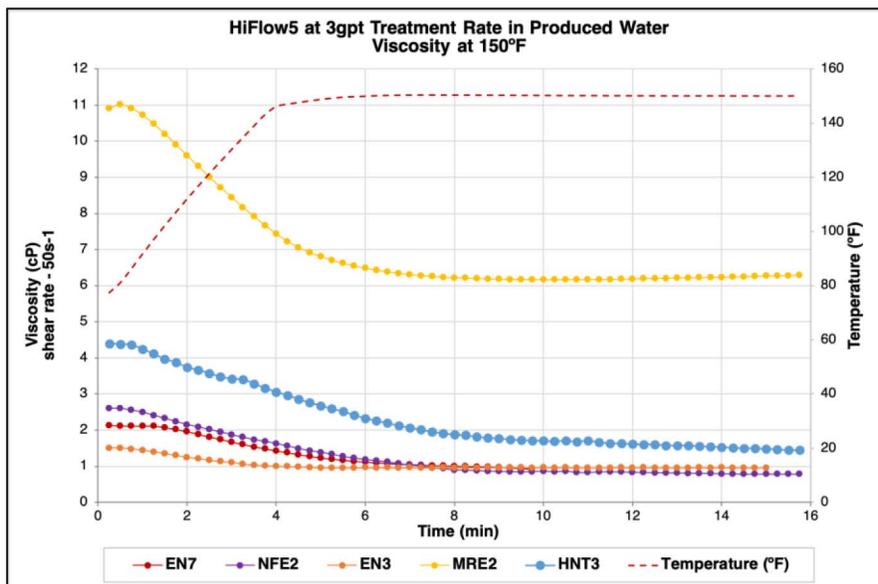


Figure 14—Viscosity of HVFR in high TDS (produced) field water at 3gpt at 50s⁻¹

To counteract the negative effects of the various ions in high TDS produced waters, the performance booster chemical often provides good results which can be observed in Figure 15. In this testing, viscosity measurements at 4 gpt concentration of the HVFR were made with one of the high TDS produced waters (LEN3). Figure 15 shows much better viscosity development with the use of the booster in the high TDS water.

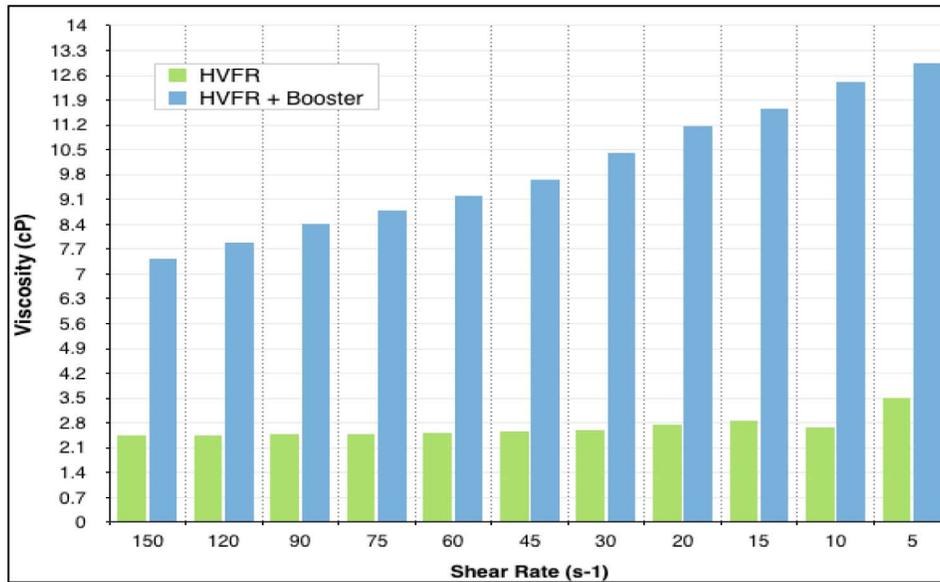


Figure 15—Viscosity of HVFR in LEN3 produced water at 4gpt with and without performance booster at 1 gpt

Experimental Studies – Friction Reduction Measurements (Field Fresh Water)

Continuing the testing with the field source waters, friction reduction properties, hydration rate and stability were tested using the water samples in the flow loop at room temperature. Figures 16-18 show the results of friction reduction in several field fresh water samples. In all of the samples, irrespective of their chemistries, excellent friction reduction was observed at a HVFR loading of 0.5 gpt.

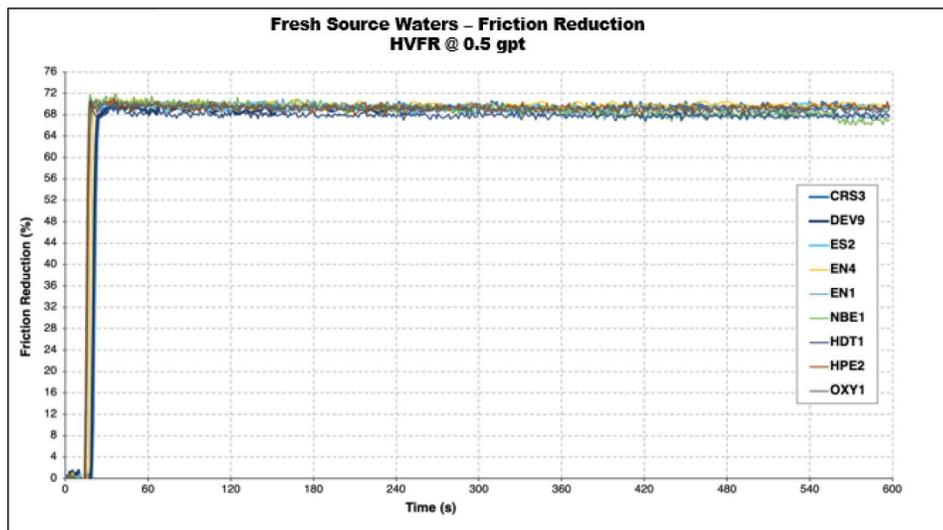


Figure 16—Friction reduction with HVFR at 0.5 gpt treatment rate

Figures 17 and 18 show the friction reduction profiles starting at a HVFR concentration of 0.5, but then stepping up the concentration in increments of 0.5 gpt to a maximum value of 3 gpt. As the concentration of the HVFR increased, the level of friction reduction decreased as expected, but not significantly.

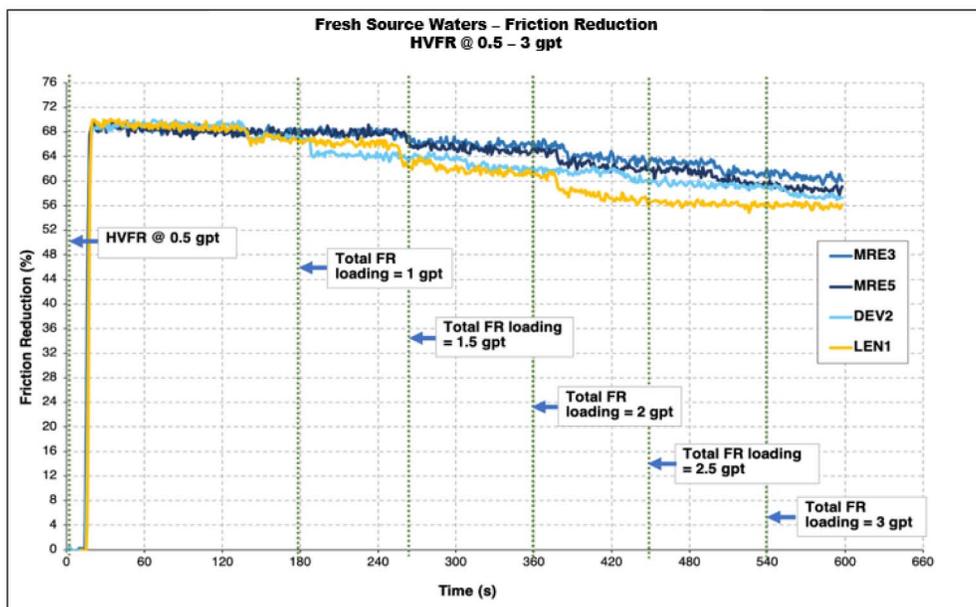


Figure 17—Friction reduction with HVFR at 0.5 – 3 gpt treatment rate

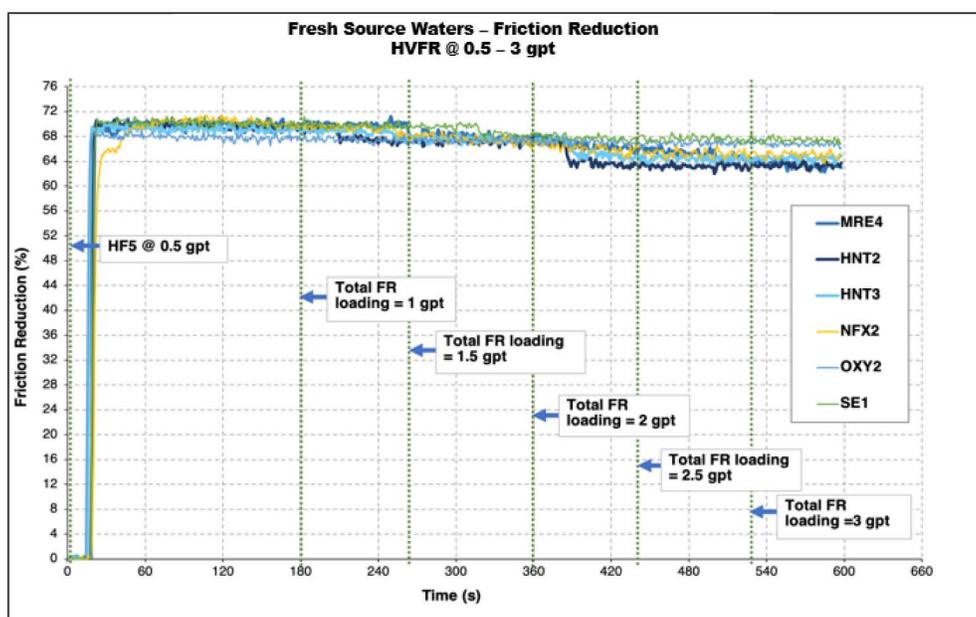


Figure 18—Friction reduction with HVFR at 0.5 – 3 gpt treatment rate

Experimental Studies – Friction Reduction Measurements (Field Produced Water)

In the produced water samples, differences in performance of the HVFR was far more evident since single ions have stronger influence than a synergistic influence of all ions together. Figure 19 shows that the effect of the ions on hydration and stability were much more prominent in these samples. These results could be correlated to the effects of ions in the water samples. Produced water samples containing higher Fe^{3+} exhibited inferior frictional performance compared to other samples. The sample labeled HPE3 in Figure 19 is shown as one of the lowest performing fluids due to higher levels of Fe^{3+} . Similarly, magnesium and sulfate affected the hydration rate in sample DEV7. Significant improvement in performance was attained with the use of the booster. Samples CRS1 and CRS2 showed very good friction reduction properties as the

booster was used throughout the test on those two samples. For sample HPE3, the booster was added at a time corresponding to about 570 seconds and an immediate increase in the friction reduction was observed.

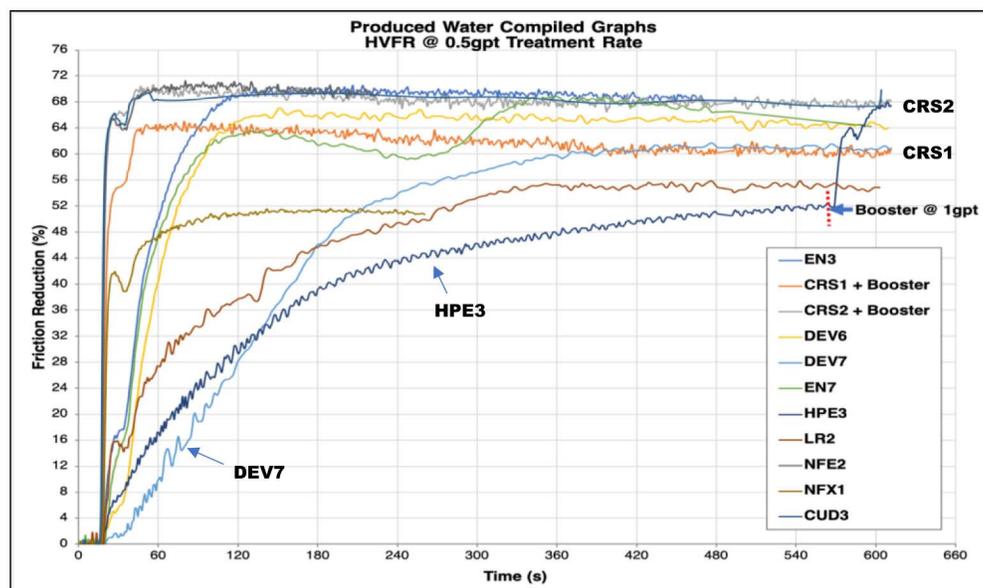


Figure 19—Friction reduction with HVFR at 0.5 gpt with some samples treated with performance booster at 1 gpt

The testing data shown in this paper demonstrates that various types of ions in field waters have different levels of interaction with the HVFR fluid system. One of the objectives of this paper was to try to further understand, and possibly predict, the performance of friction reducers based on the chemistry of the source water to be used for fracturing operations. To further these relationships, the authors incorporated the use of statistical technique called PCA, described earlier in the Experimental Methods section of this paper.

PCA analyses, shown in Figures 20 and 21, highlight the effect of single ions and the interaction between other ions. Based on the position of the water sample on the plot, its chemistry can be correlated to the performance of HVFR. In case of fresh field water samples shown in Figure 20, there are generally low ion levels in these water samples, which can be seen from the positive performance of the HVFR fluid system in these waters. As an example of how the PCA analysis can be used to identify a potentially poor water source, the field water sample labeled CO2 shows up on the PCA chart as an outlier from the rest of the samples. As indicated in the viscosity profiles for these waters earlier in this paper, sample CO2 exhibited one of the lowest viscosities of this group of waters.

Another example of the PCA approach can be used by observing the positions of produced water samples MRE2 and CRS2 shown in Figure 21. Although these samples have very large differences in TDS levels, their performance in terms of viscosity is very similar. Both these samples have a synergistic effect of ions together and not one single ion acts as an influencing factor in determining its performance.

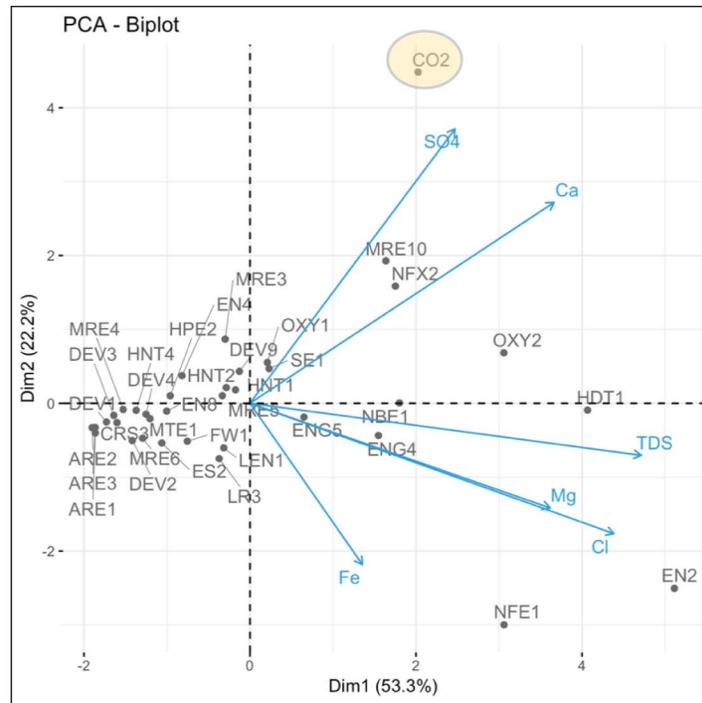


Figure 20—PCA-biplot of fresh field water samples

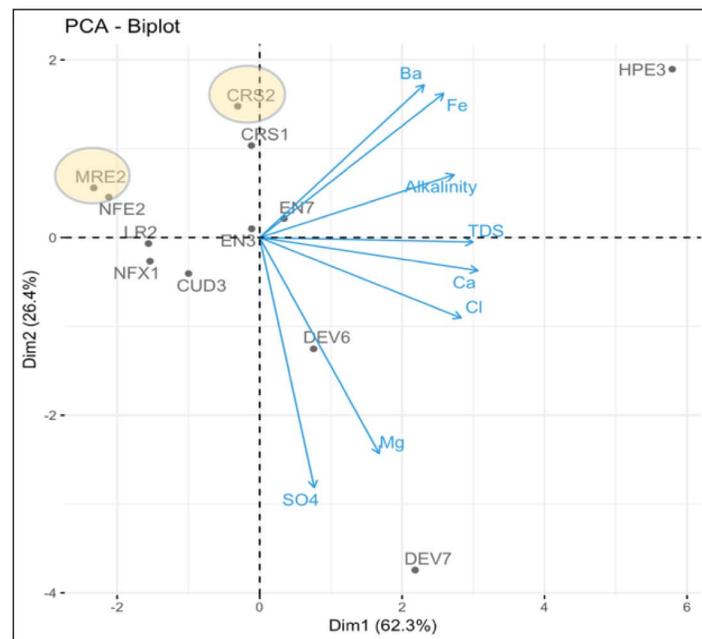


Figure 21—PCA-biplot of produced water samples

Conclusions

This paper provides information on how specific ions affect the performance of HVFR fracturing fluids. Although a HVFR type fluid system was used for this testing, similar performance results are observed with anionic friction reducers in general, whether they are the viscosifying type or not. The following important conclusions can be made:

- In low TDS waters, ions generally have more of a synergistic effect when they are present in low concentrations and therefore do not impact the performance of friction reducers negatively.
- Calcium, magnesium and iron were found to have the largest detrimental effect on viscosity of the HVFR system, while iron has the strongest detrimental effect on friction reduction. Overall, iron was found to have the most detrimental effect on the overall HVFR performance.
- Magnesium and sulfate delay the hydration rate of the HVFR, but do not affect the level of friction reduction achieved.
- Barium and sulfate have a strong negative correlation which means they cannot co-exist in high concentrations.
- Total dissolved solids (TDS) values by themselves are not a complete indicator of fluid performance. The overall composition of ions in the source water, along with the concentration of those ions, is critical in understanding the impact that source water will have on the fracturing fluid system.
- Performance enhancing chemicals show positive results on the friction reduction and viscosity development of the HVFR fluid in different source waters.

This study incorporated the use of Principal Component Analysis to identify ions which exist in excess in the waters that were evaluated. This approach can be used as a predictive tool to help identify potential performance issues of various water sources on the hydraulic fracturing operations. With this method, optimized fracturing fluid chemistries can potentially be identified through simple water analyses. As the industry continues to incorporate different water sources, including higher amounts of produced water, it is important to understand how the various water types will affect the key performance parameters of fracturing fluids, and to quickly identify the most cost-effective and highest performing fluid systems.

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Appendix

Table 3—Water Chemistry Data

ID	pH	SG	Alkalinity	Hardness	Ca	Mg	Fe	SO4	Ba	Cl	TDS
AMP1	7.95	1	65	55	42	13	1.21	19	16	21	97.1
CPS1	7.13	1.008	690	1500	820	680	1.27	900	3	6047	10400
CPE1	8.01	1	185	640	445	195	0.03	430	2	68	729
CLR1	7.16	1.012	1210	1470	490	980	2.42	12	460	8820	16930
CLR2	7.8	1.01	500	1350	980	370	1	120	2	8498	14949
CLR3	7.93	1.015	86	3360	2800	560	0.76	11	100	2680	16250
CRS1	6.91	1.078	860	12000	7100	4900	16.4	24	49	42000	112000
CRS2	7.2	1.082	440	8100	5400	2700	6.8	2	180	40900	101200
CRS3	8.52	1	106	249	174	75	0.09	67	10	60	340
CUD1	7.78	1	250	476	460	16	0.003	11	7	388	1163
CUD2	7.5	1.001	364	1500	1420	80	0.004	1600	1	791	2580
CUD3	6.9	1.044	108	11610	8650	2960	3.16	760	22	41350	64400
ENE1	7.13	1.002	600	1250	680	570	0.18	205	4	3456	5660
ENE2	7.88	1	310	1320	980	340	0.03	660	4	346	1282
ENE3	7.57	1.002	300	2530	1570	960	0.04	1420	2	1160	2870
FW1	8.36	1	425	575	295	280	0.07	64	3	372	859
FW2	8.38	1.012	390	3430	2120	1310	0.41	500	5	12963	22540
HNT1	8.38	1	480	870	580	290	0.03	650	0	352	1221
HNT2	7.51	1	390	980	720	260	0.18	400	1	224	1271
HNT3	7.87	1.008	410	3600	2260	1340	0.25	2600	3	4747	9180
HNT4	8.33	1	280	650	420	230	0.04	18	1	46	292
HPE1	8.39	1.006	720	570	480	290	0.05	7000	2	3136	7160
HPE2	8.19	1	430	890	680	210	0.01	50	0.01	126	497
HPE3	5.57	1.138	6900	52200	34800	7400	39	400	300	122400	209300
LEN1	8.17	1	168	740	170	570	0.01	330	1	401	1406
LEN2	6.54	1.05	269	13850	10260	3590	27	340	80	42425	62800
LR1	6.84	1.018	396	5006	2892	2114	2.6	64	26.4	15670	25769
LR2	7.35	1.03	460	11400	3900	7500	0.1	200	1	27300	46200
LR3	7.93	1	260	1680	220	1460	0.1	200	1	220	728
MRE1	9.74	1	480	430	220	210	0.11	88	10.5	68	571
MRE2	8.98	1.003	1145	870	560	310	0.09	400	14	704	6160
MRE3	8.04	1.002	780	1145	810	335	0.1	950	0	29	1135
MRE4	7.9	1.001	440	321	235	86	0.09	200	2	29	365
MRE5	8.49	1.002	490	1120	890	230	0.03	1	3	224	1198
MRE6	9.3	1	400	520	90	430	0.04	115	2	90	614
MRE7	9.14	1	880	330	220	110	0.04	1	1	82	922

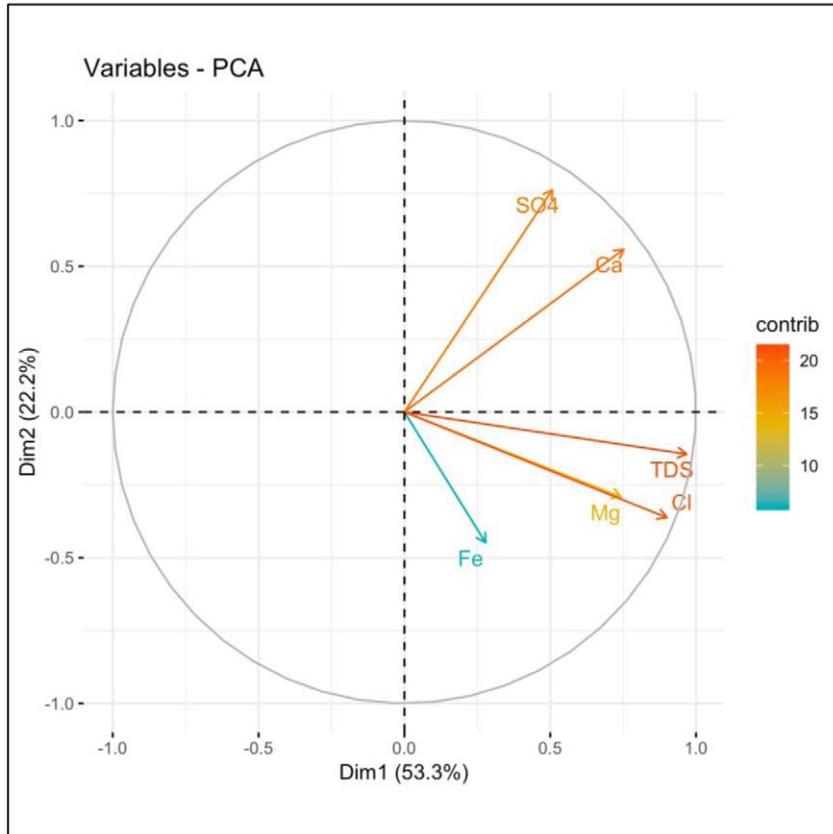


Figure 22—PCA analysis of fresh water samples

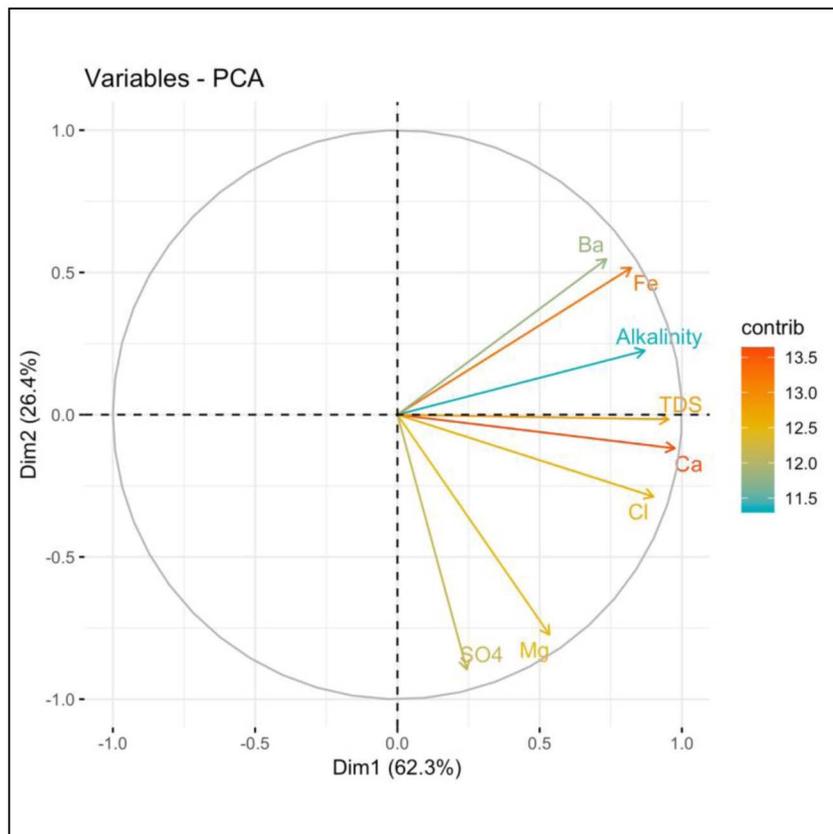


Figure 23—PCA analysis of produced water samples