Impact of Fiber on the Gelation Time and Strength of Re-Crosslinkable Particle Gels

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Abstract

In the Petroleum industry, water is inadvertently produced during the production of hydrocarbons due to the heterogeneity of reservoirs. Fluid flow in such reservoirs favors high permeable zones resulting in un-swept areas. As production continues, these high permeable zones become depleted of hydrocarbons and transition to a highway for waterflow. This results in a significant increase in the water-to-oil ratio, leading to the abandonment of the well, leaving approximately 2/3 of oil unrecovered. Re-crosslinkable preformed particle gel (RPPG) has been developed and implemented to restrict fluid flow in high permeable zones, redirecting fluid flow to un-swept areas of the reservoir. In this research, fiber was incorporated into the gel to increase its' plugging performance. Our lab results show that the addition of fiber increased the gel strength across the whole spectrum of conditions. For this reason, fiber can be used as an effective additive to enhance the RPPG plugging performance.

Introduction

Water flooding as a secondary oil recovery method has been widely implemented in oilfields to displace oil to increase oil recovery. However, the injected water prefers to flow through the high permeable zones, fractures and or fracture like channels due to the heterogeneous nature of reservoirs. Over time these injection pathways breakthrough to production wells, once communication is established, the effectiveness of secondary oil recovery is limited. Currently more than eight barrels of water are produced for each barrel of oil in the U.S. Excess water production results in an increased load on fluid handling facilities, increased levels of corrosion and scale, and increased environmental concerns, all of which can eventually shut down the wells (Pu et al. 2019). In effort to reduce the water produced and further increase the sweep efficiency a gel treatment can be implemented. A gel treatment disrupts the natural pathway of injected water in high permeable zone to production wells. The aim of the treatment is to redisperse the fluid flow from high permeable zones into less permeable regions.

In order for a gel treatment to be effective, the gel must be able to plug swept zones and have minimal damage to unswept areas of the reservoir. There are two main gel treatments; In-situ-crosslinking polymer gel and performed particle gels. For in-situ cross-linked polymer systems, a polymer solution and a crosslinking agent are injected together into the reservoir forming an in-situ hydrogel within the high-permeability zones in the reservoir (Tessarolli et al. 2018). Performed particle gels (PPGs) are synthesized, dried, and granulated at a surface facility then transported for use in the field. During the gel treatment, PPG is hydrated, then injected into the formation.

In-situ polymer gel treatments have their own draw backs. With two separate components this process is more susceptible to unfavorable side reactions and diffusion into the reservoir. Unfavorable side reactions will decrease the plugging performance and reduce penetration into high permeable zones. Diffusion can result in the reactants to over penetrate or create a nonuniform distribution in the reservoir causing damage to unswept areas. In-situ crosslinking polymer gel treatments leave more to desire out of a gel treatment. With the inability to dial in the gelation time and gel strength other options are considered.

It is necessary to develop a novel gel system that has better performance to block such abnormal features in mature oil fields (Pu et al. 2019). The use of PPG can avoid many restrictions that may exist with the in-situ polymer gel systems, such as controllable gelation time and the negative effect of shearing on the gelation performance (Zhu et al. 2017). Resulting in PPG being more predictable, with more than 2000 mature water-flooded reservoirs treated in China (Wang 2019). Once breakthrough occurs in a PPG pack, the gel will be washed out from the abnormal feature. In efforts to increase PPGs' mechanical capabilities a "self-healing" attribute was introduced into PPG. This attribute allowed the gel to re-crosslink with itself, consequently being named Re-crosslinkable Preformed Particle Gel (RPPG). In addition, the mechanical properties of these PPGs can be enhanced by adding nano clay, reported by (Zhu et al. 2017).

RPPG can withstand higher pressure than the conventional PPG pack, which can avoid the problems of composition variation or nonuniform distribution (Pu et al. 2018). Comparatively once breakthrough occurs in a PPG pack the gel will be washed out, whereas re-crosslinked RPPG is less susceptible to wash out. RPPG can be enhanced with additives to take advantage of the network of crosslinks being formed. In addition, it is expected that compositions having re-crosslinked polymers and embedded fiber have a higher elastic modulus and an improved plugging performance than compositions without fiber (Bai et al. 2022). However, in order to verify this hypothesis solid lab data needs to be obtained.

This study will focus on how the addition of fiber impacts the gelation time and gel strength of RPPG, along with the intrinsic properties of the gel. The bottle test method from (Sydansk 1988) and a Thermo Scientific™ HAAKE™ MARS™ III Rheometer were used in conjunction to determine the impact.

Experimental Materials, Instruments and Procedures

Material Introduction and Preparation

Re-crosslinkable performed particle gel, RPPG, consisting of two components, crosslinked polyacrylamide with embedded crosslinker, was used for the experiments. The RPPG is white, translucent granular shaped particles with angular edges. RPPG has the apparent bulk density of 1.33to 1.45 g/cm^3 at 5% total water content (Pu et al. 2018).

Gelation Time

Bottle testing was used in this work to study and to establish trends of gel parameters and variables (Sydansk 1988). The gel-strength code A-J defined in Figure 1 was used from (Sydansk 1988) and (Lashari et al. 2019). Gelation time is measured in this process, which refers to the time the gel takes to reach the maximum gel-strength code. The start of the gelation time occurs when the particles are saturated with weak cohesion/linking of particles. Gelation time determines the length of time and depth that the system will reach when forming the impermeable barrier in the rock-reservoir (Kelly et al. 2020). At the end of gelation time the boundaries between particles have dissolved and the gel is interconnected.

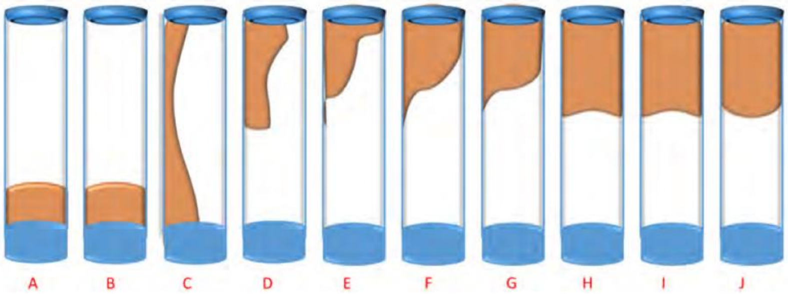


Figure 1 Gel Strength Code (Lashari et al. 2019)

Rheological Studies

A Thermo Scientific™ HAAKE™ MARS™ III Rheometer was utilized to determine the elastic modulus (G'). In this study P35 Ti L rotor was used with parallel plate geometry. The gap between the rotor and plate was set to 1mm. G' of the gel was measured with an oscillation sweep amplitude of .1 to 1000 Pa with a frequency of 1 Hz, independent of time to determine where each modulus remained constant. Measurements of G' as a function of time was taken during an oscillation time curve for a duration of 120 s at a frequency of 1Hz with 40 data points.

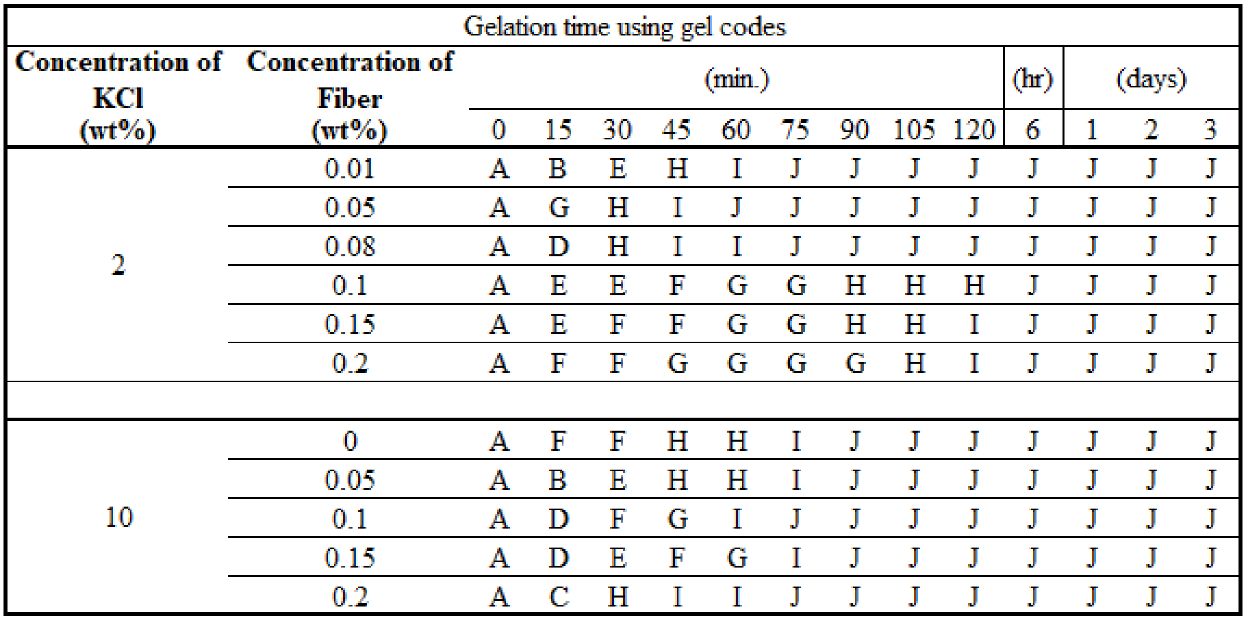
Results and Discussion

Effect of Fiber Concentration on Gelation Time and Gel Strength

Bottle testing (Sydansk 1988) was used in determining gelation time in this study. Bottling testing was chosen due to its' ability to rapidly test gelation rate and gel strength of an assortment of gels. Once RPPG swells and starts crosslinking, gel strength increases until a gel strength code of J. This process is important to understand because it allows for a window when the gel is injectable. The window closing is the result of the elastic modulus increase to a point where τ applied cannot deform the gel enough to push it through. As a result, the placement of gel has a direct impact on the effectiveness of a gel treatment.

Table 1 shows the fiber concentration effect on gelation time. Results indicate that fiber has no impact on the gelation time. In Table 1 there was difficulty in measuring gelation time for gels consisting of 2% KCl concentration,1/10 RPPG ratio and 7% bentonite concentration because of a clumping effect that was occurring shown in Figure 2. The clumping effect created a "ball" of bulk gel that had weak adhesion initially but became more adhesive over time. This clump effect was prevalent in all tests containing bentonite, but with varying magnitude.

Figure 2 Clumping Effect recorded at 1/10 RPPG ratio, 7% Bentonite, 2% KCl, and 0.2% Fiber concentration



Concentration of KCl (wt%)	Concentration of Fiber (wt%)	Gelation time using gel codes												
		(min.)									(hr)	(days)		
		0	15	30	45	60	75	90	105	120	6	1	2	3
2	0.01	A	B	E	H	I	J	J	J	J	J	J	J	J
	0.05	A	G	H	I	J	J	J	J	J	J	J	J	J
	0.08	A	D	H	I	I	J	J	J	J	J	J	J	J
	0.1	A	E	E	F	G	G	H	H	H	J	J	J	J
	0.15	A	E	F	F	G	G	H	H	I	J	J	J	J
	0.2	A	F	F	G	G	G	G	H	I	J	J	J	J
10	0	A	F	F	H	H	I	J	J	J	J	J	J	J
	0.05	A	B	E	H	H	I	J	J	J	J	J	J	J
	0.1	A	D	F	G	I	J	J	J	J	J	J	J	J
	0.15	A	D	E	F	G	I	J	J	J	J	J	J	J
	0.2	A	C	H	I	I	J	J	J	J	J	J	J	J

Table 1 Gel strength measurements of gel with various concentrations of fiber at 2.0% and 15.0% KCl concentrations

The mechanical property studied to determine strength of the gel was the elastic modulus (G'), which is the measurement of how rigid a solid is. Gel strength indicates the performance of the hydrogel as a blocking agent (Kelly et al. 2020). As shown in Figure 3, Fiber did impact the mechanical property of the gel. An increase from 0% to 0.2% fiber concentration results in an average increase of 27.8% its' original elastic modulus. Both gels consisted of 1/10 RPPG, 7% Bentonite, with varying fiber concentration, but G' of the gel in low salinity was typically 30% greater than that of a gel in high salinity. The difference can be attributed to the cation balancing with the negative charge on the clay, increasing flocculation of the clay platelets (Sutherland, B. R. et al. 2014). As a result, it reduced the bonds formed between the clay and polymer.

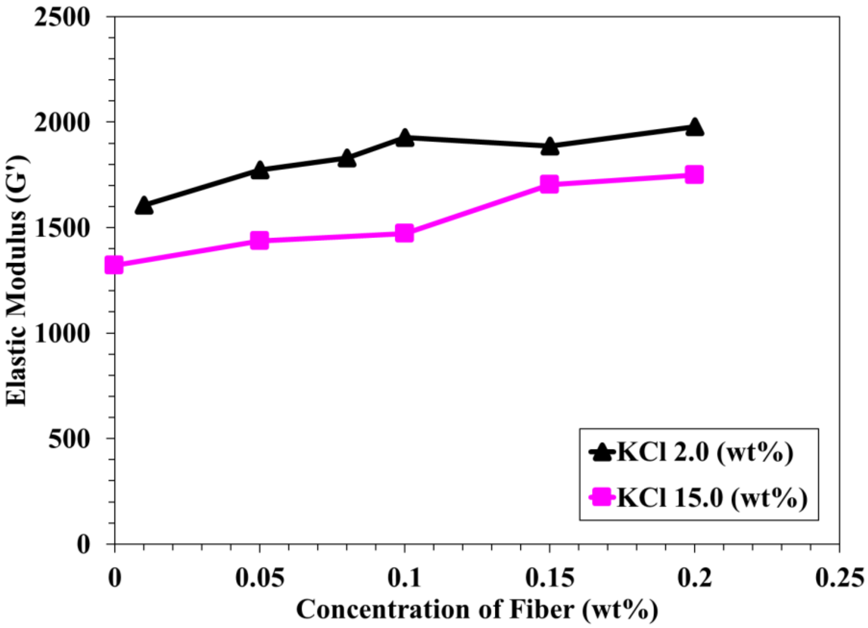


Figure 3 Effect of Fiber on gel with various concentrations of fiber at 2.0% and 15.0% KCl concentration

Effect of Bentonite on Gelation Time and Gel Strength

Bentonite clay can be used to enhance the mechanical properties of the gel. Bentonite clay forms a suspension of particles due to the negatively charged platelets (Sutherland, B. R. et al. 2014). As the gel is re-hydrolyzing, the hydrolyzed polyacrylamide allows a surface for the negative surface of bentonite clay to bond. This bond is the result of coulombic attraction. As a result, this bond creates a hybrid polymer/clay composite gel, greatly decreasing the swelling ratio of the gel (Bai, B. et al. 2007). However, bentonite clay enhancements can be effected by the salinity.

As seen in Table 2 the addition of clay results in a decrease in gelation time. The decrease occurs because gelation time is a function of gel strength. An increase from 0.0% to 7.0% bentonite concentration results in the ability of the polymer to form a composite gel. This was made evident across the various RPPG ratios tested at a concentration of 2.0% KCl and 0.05% fiber. With a more rigid gel being formed in comparison to a gel without bentonite, it will inherently achieve the maximum gel strength code of J sooner.

Gelation time using gel codes														
RPPG ratio	**Concentration of Bentonite**	(min.)									(hr)	(days)		
(wt%)	**(wt%)**	0	15	30	45	60	75	90	105	120	6	1	2	3
1/5	0	A	B	D	E	H	J	J	J	J	J	J	J	J
	7	A	B	F	G	H	J	J	J	J	J	J	J	J
1/10	0	A	B	D	E	H	J	J	J	J	J	J	J	J
	7	A	G	I	J	J	J	J	J	J	J	J	J	J
1/16	0	A	B	B	B	B	D	E	E	E	H	H	H	J
	7	A	C	D	D	D	D	D	E	E	J	J	J	J

Table 2 Gel strength measurements of gel with various concentrations of bentonite at 1/5, 1/10, and 1/16 RPPG ratio

Figure 4 shows an increase from 0% to 7% bentonite increased the elastic modulus over 2.5 times its initial value regardless of swelling ratio, both gels consisted of 1/10 RPPG, 2% KCl. Bentonite clay results in the formation of a composite polymer/clay gel. As a result, a denser and more rigid gel is produced. It is suggested that the reinforcement properties of polymer clay composite gel are attributed mainly to hybrid effect of interfacial properties and restricted mobility of the polymer chains (Bai et el. 2007).

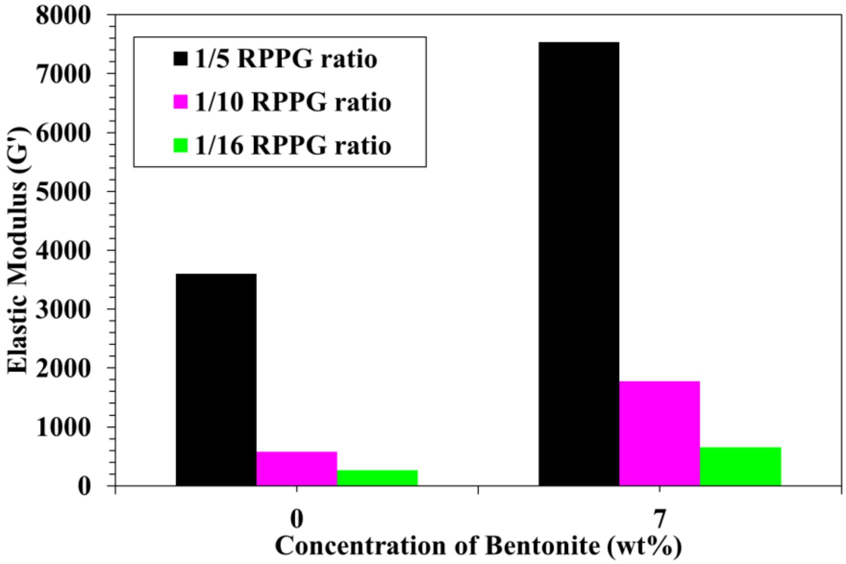


Figure 4 Impact of bentonite on gel strength at various RPPG ratios

Effect of Brine Concentration on Gelation Time and Gel Strength

Salinity has an impact on the properties of preformed particle gels. At low salt concentrations, electric repulsive forces will separate the molecules in the gel and create more space for water coming in; but when in high salinity water, the negatively charged group will be balanced by the cations and will restrict further water absorption (Bai et al. 2007). This results in the swelling ratio to decrease with the increase in salinity. Additionally, when the salt concentration increases the cations present in solution balance the negatively charged clay platelets resulting in flocculation.

In Table 3 it can been seen that as brine concentration increases the gelation time increases in trials consisting of 7% bentonite concentration, 1/10 RPPG ratio, and 0.05% fiber concentration. An increase in brine concentration increases the flocculation of bentonite clay due to cations in solution balancing the charges. As a result, an increase in salinity decreases bentonites' ability to bond from columbic forces due to balanced forces. This attributes to a weaker bulk gel forming. This same effect is also prominent in Figure 5, as salinity increases a less rigid bulk gel is formed, which attributes to the decrease in elastic modulus of 7% bentonite. However, in the absence of bentonite an increase in brine concentration increases the elastic modulus. This is the result of the swelling ratio decreasing as salinity increases.

Gelation time using gel codes														
Concentration of Bentonite (wt%)	**Concentration of Brine (wt%)**	(min.)									(hr)	(days)		
		0	15	30	45	60	75	90	105	120	6	1	2	3
0	2	A	B	D	E	H	J	J	J	J	J	J	J	J
	10	A	B	C	G	H	J	J	J	J	J	J	J	J
	15	A	B	F	G	H	J	J	J	J	J	J	J	J
7	2	A	G	H	I	J	J	J	J	J	J	J	J	J
	10	A	C	H	I	J	J	J	J	J	J	J	J	J
	15	A	B	E	H	H	I	J	J	J	J	J	J	J

Table 3 Gel strength measurements of gel with various concentrations of KCl with 0.0% and 7.0% bentonite concentration

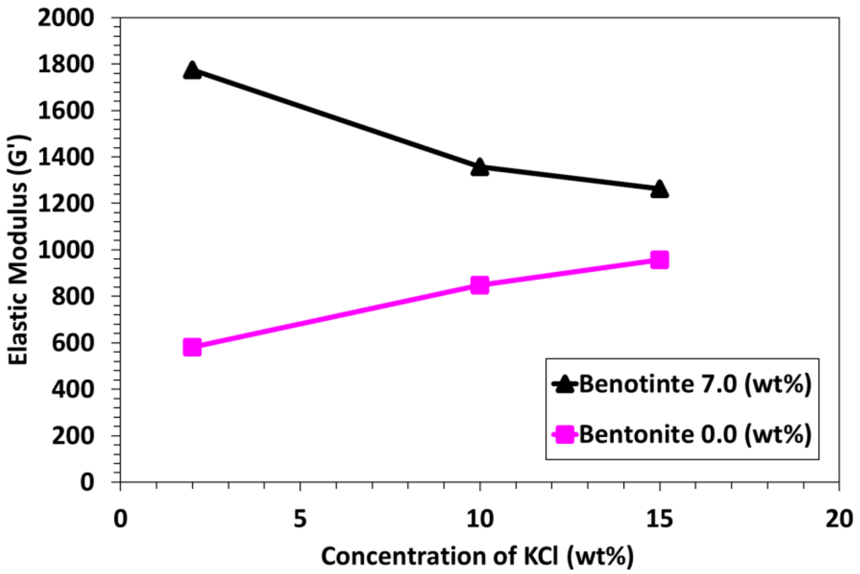


Figure 5 Effect of KCl concentration on gel with various concentrations of KCl with 0.0% and 7.0% bentonite concentrations

Effect of RPPG ratio on Gelation Time and Gel Strength

Table 4 shows the impact RPPG concentration has on the rate of gelation. As RPPG ratio increases the density of gel matrix increases resulting in a drastic decrease in gelation time. Additionally, an increase bentonite concentration from 0% to 7% at 2.0% KCl and 0.05% fiber concentration decreased the gelation time at both 0.0% and 0.7% bentonite concentration. This is the result of a more rigid bulk gel being formed, effectively achieving maximum gel strength sooner. Figure 6 demonstrates that an increase from 1/16 to 1/5 RPPG ratio the gel strength to nearly tripled its initial value, regardless of bentonite concentration. As the matrix density of the gel increases the elastic modulus increases.

		Gelation time using gel codes												
Concentration of Bentonite (wt%)	**RPPG ratio (wt%)**	(min.)									(hr)	(days)		
		0	15	30	45	60	75	90	105	120	6	1	2	3
0	1/16	A	B	B	B	B	D	E	E	E	H	H	H	J
	1/10	A	B	D	E	H	H	H	I	I	J	J	J	J
	1/5	A	H	H	J	J	J	J	J	J	J	J	J	J
7	1/16	A	C	D	D	D	D	D	E	E	J	J	J	J
	1/10	A	G	H	I	J	J	J	J	J	J	J	J	J
	1/5	A	I	J	J	J	J	J	J	J	J	J	J	J

Table 4 Gel strength measurements of gel with various RPPG ratios with 0.0% and 7.0% bentonite concentration

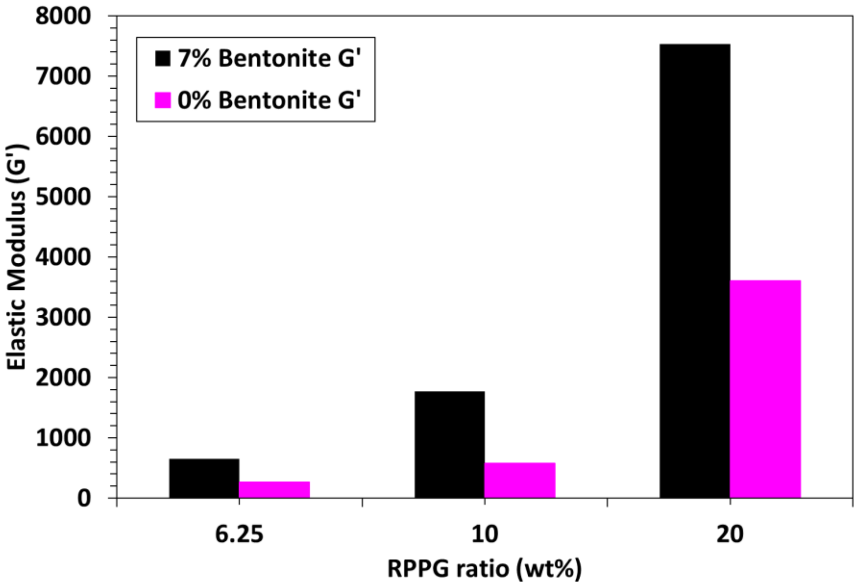


Figure 6 Impact of RPPG ratio on gel strength at various concentrations of bentonite

Conclusion

In this study the impact of fiber on gel performance was systematically tested across various constituents. It was found that the addition of fiber attributed to an increase in gel strength. The increase is the result of the fiber reinforcing the gel matrix. Additionally, an increase in RPPG ratio will further increase the density of the gel matrix aiding to the rigidity and reinforcement of the gel. The results show that the presence of fiber does not effect gelation time. Furthermore, fiber does not alter the effectiveness of bentonite as an additive, but only enhances it. However, an increase in salinity will result in a decrease in bentonites effectiveness. It should be noted that a gel not containing bentonite will experience an increase in gel strength due to a decrease in the swelling ratio. Inconclusion fiber can be used an additive to enhance the mechanical properties of the gel while maintaining intrinsic characteristics of the gel.

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