GEL PACK—A NOVEL CONCEPT TO OPTIMIZE PREFORMED PARTICLE GELS (PPGs) CONFORMANCE CONTROL TREATMENT DESIGN

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ABSTRACT

Preformed particle gels (PPGs) have been widely applied to reduce the permeability of super-high permeability streaks/fractures. Appling PPGs both decreases water production and increases sweep efficiency in mature oilfields. Either the success or failure of a PPG treatment depends largely on whether or not PPGs can effectively reduce the permeability of channels to an anticipated level. This work sought to investigate the influence of several factors on PPG blocking efficiency. A filtration model was designed to determine the permeability of PPGs packed in channels/fractures. Two types of PPGs were used for these filtration experiments: Daqing (DQ) and LiquiBlock^{TM} 40K. Particle sizes fell between 30 and 120 meshes. Results indicate PPG permeability decreased as load pressure increased. Additionally, PPGs with a larger particle size exhibited higher PPG pack permeability than PPGs with a smaller particle size. The PPG permeability with a low brine concentration was more than the PPG pack permeability with a high brine concentration when the PPG pack was not compressed by a piston. However, PPG pack permeability was less when using a low brine concentration whether the PPG pack was compressed. Thus gel pack with a desired permeability can be designed by selecting both proper gel strength and appropriate particle size at reservoir pressure.

INTRODUCTION

Water is the most abundant fluid in an oil field (Kuchuk et al., 1999). Oil field operators have conducted numerous studies to evaluate the drawbacks of water production. These researchers found that unwanted water production damages surface equipment and causes casings leak. Excess water increases costs related to disposal, scale, corrosion, water/oil separation, and more (Dalrymple, 1997). Additionally, excess water reduces hydrocarbon production, even in formation zones, that still carry a considerable volume of hydrocarbons (Sydank et al., 2000).

Currently, an average of three barrels of water are produced for each barrel of oil produced globally (Bailey, 2000). The situation is even worse in the US, where more than ten barrels of water are produced for each barrel of oil (EPA, 2014; Seright, 2004). The annual cost of both treating and removing water is estimated to be 40 billion USD (Bailey, 2000).

Reservoir heterogeneity severely affects the flow of gas, oil, and water in a reservoir. It can also affect the choice of production strategies, reservoir management, and ultimate oil recovery. Many reservoirs have been hydraulically-fractured (either intentionally or unintentionally), or developed large channels due to both mineral dissolution and production during water flooding.

Conformance control treatments are typically more economical than other EOR (enhanced oil recovery) techniques. They can both increase oil production and decrease water production by treating only small swept zones/areas (Borling et al., 1994). Gel treatment is the most efficient, cost-effective means for both decreasing water production and improving reservoir homogeneity in mature oil fields (Stright & Liang, 1994).

Traditionally, in-situ gels have been widely used to control conformance. A mixture of polymer and crosslinker, called gelant, is injected into a target formation. It reacts to form a gel that either fully or partially seals the formation at reservoir temperature. As a result, the gelation occurs under reservoir conditions. A new gel treatment method uses preformed particle gels (PPGs) to overcome the limitations of in-stiu gels (Bai et al., 2008). PPGs are formed at surface facilities before injection. As a result, no gelation is present in the reservoirs. PPGs require less equipment for surface preparation. Gel particles vary in diameter from nanometers to a few millimeters (Bai et al., 2007).

Additional techniques were established during research laboratory investigations, including: using microgels for both relative permeability modification and in-depth division (Chauveteau et al., 2001; Feng et al., 2003; Frampton

et al., 2004; Pritchett et al., 2003); applying a pH sensitive polymer for novel conformance control (Al-Anazi et al., 2001; Beson et al., 2007; Choi & Shrman, 2009); employing colloidal dispersion gels for both conformance and mobility control (Al-Assi et al. 2009; Bjorsvik et al., 2001; Chang et al., 2004; Peng et al., 1998; Li et al., 2004; Wang et al., 2006).

Many researchers have been focused on both the transport and the plugging efficiency of PPGs in both fractures and super-high permeable formations (Zhang et al., 2010 & 2011; Bai et al., 2007). Zhang and Bai (2011) found a millimeter-sized PPG forms a gel pack in open fractures. Gel pack permeability thus depends on both particle size and brine concentration (Zhang & Bai, 2011). No quantitative analysis was provided. Elsharafi and Bai (2012 and 2013) have been studied the effect of both week and strong preformed particle gels on the formation damage of low-permeable layers.

This work used two PPG pack permeability models to determine both which parameters affect PPG blocking efficiency and to what extent each parameter impacts the permeability of a gel pack. Factors considered included particle size, strength, brine concentration, and loading pressure.

EXPERIMENTAL DESCRIPTION

Materials

Preformed Particle Gels (PPGs). Two types of PPGs were used for these experiments: both a weak gel (LiquiBlock™ 40K) and a strong gel (Daqing (DQ)).The particle sizes for both the LiquiBlock™ 40K gel and the DQ gel were between 30 and 120 meshes. Both PPGs can swell more than 15 times their original volume. Table 1 and 2 list the typical characteristics of LiquiBlock™ 40K gel and DQ gel, respectively. Table 3 list the swelling ration and the gel strength both before compression (G'_b) and after compressed (G'_a) for both gels.

Brine Concentration. Brine concentration significantly affects the PPG swelling ratio. A high salinity brine results in both a lower swelling ratio and a higher swollen particle strength. Sodium chloride (NaCl) was used to prepare all brines. Four brine concentrations, 0.05, 0.25, 1, and 10 wt % NaCl, prepared at room temperature, were selected to prepare the swollen PPGs.

Preparing the Sandstone Core Samples. Several sandstone cores were cut for the PPG pack experiments. The purpose of the core was to prevent gel flush out. The dimensions of all short cores were 1.5 inch (3.7 cm) in length and 1.5 inch (3.7 cm) in diameter. The sandstone cores were put in an oven at 120° C for 24 hours. They were first vacuumed and then saturated to 100% with the desired brine.

EXPERIMENTAL SETUP

Model I. Figure 1a represents the first gel pack model. This model was a long, acrylic, round tube to which end plates were attached by caps. The inside diameter of the round tube measured 3.8 cm. The top cap had one hole connected to the pump through both the tubing and the fitting. This hole served as an inlet for the injection brine. The bottom cap had one hole as well through which brine was discharged. Core samples were placed on the bottom of the round tube, fitted using two O-rings. PPG samples were poured into the round tube above the core. A piston was inserted into the tube to both compress the PPGs and prevent direct contact between the injected brine and the PPGs.

The piston had a hole on the top plugged with a threaded plug nut. The plug nut was open while measuring PPG pack permeability. The space above the piston was filled with brine solution. Two pressure gauges were connected to the round tube both above the core sample and below the piston to record both pressures, respectively. The pressure transducer was necessary to accurately record the differential pressure using a data acquisition system. The model was static so that both PPG and water flooding could clearly be seen.

Model II: Figure 1b represents a similar equipment design without a piston. This model was used to measure the effect of brine concentration change on the PPG pack permeability.

Experimental Procedures. Procedures for these experiments were as follow: (1) core samples were first vacuumed and then saturated with brine , after that porosity (Φ) was obtained; (2) the core sample was fitted onto the bottom of the gel pack permeability model; (3) a completely swollen PPG was poured into the round tube, sitting on top of the core; (4) both PPG height and volume were measured; (5) PPG pack permeability was measured before being compressed; (6) the piston was inserted on the top of the particle gels inside the round tube; (7) the particle gel was compressed by the piston, which was pressed by pump pressures (load pressure) of 50-, 75-, 100-, 125-, 150-, 200-, 225-, 250-, 275-, and 300 psi; (8) the height, water loss, and pressure drop for compressed PPGs were all measured

for 30 minutes for each pressure used; (9) both PPG pack permeability and PPG compressibility were calculated for each load pressure.

Calculation of PPG Pack Permeability. Both the flow rate and the differential pressure were measured. PPG pack permeability was measured according to results obtained during lab work. The liner Darcy equation was used to calculate PPG pack permeability. PPG pack permeability (K_{gel}) was calculated using

$$K_{gel} = \frac{Q\mu h}{0.78\, d^2\, \Delta P_{gel}} \quad ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Calculation of PPG Pack Compressibility. Both PPG stabilized pressure around the compressed gel and PPG height were recorded. The compressibility of the gel (C_{gel}) was calculated for both gel types with different particle sizes and different brine concentrations using

$$C_{gel} = \frac{-1}{V} * \frac{\Delta V}{\Delta P_{gel}} \ ,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

RESULTS AND ANALYSIS

PPG Pack Permeability.

Effect of Particle Size. Various particle sizes were used to determine the effect of particle size on PPG pack permeability. Figure 2 illustrates the effect of different particle sizes (30, 50-60, 80, and 100-120 meshes) for both gels on the PPG pack permeability both with and without compression. Experimental results indicate less PPG pack permeability occurred with small particle sizes. Results also indicate that a weak gel (Liquiblock^{TM} 40K gel) has a lower PPG pack permeability than a strong gel (DQ gel). Both weak and small particle gels have the lowest PPG pack permeability; weak PPGs with small particles compressed further.

Different flow rates (1, 2, 3 ml/min) were used to measure PPG pack permeability before using piston (KG_{BP}). Lower flow rates (0.5, 0.75, 1 ml/min) were used to measure the PPG pack permeability after using piston (KG_{AP}). Lower flow rates were preferred to protect the PPG pack permeability model because increasing the pressure meant potentially breaking the round tube.

Effect of Brine Concentration. The effect of the brine concentration on PPG pack permeability was studied to better understand which brine caused more PPG pack permeability decline both before and after the gel was compressed by a piston. A PPG was prepared using a particle size of 30 mesh with various brine concentrations to verify this brine concentration effect.

Figure 3 presents the results of various brine concentrations. Brine concentration exhibited a significant influence on PPG pack permeability. These results indicate that the PPG with a lower brine concentration has a higher PPG pack permeability before being compressed by a piston. However, PPG with a higher brine concentration had a higher permeability after being compressed by a piston because PPGs with a high brine concentration compressed less.

Reduction of the PPG pack permeability (K_R) after being compressed by a piston increased by up to 97.86 % for Liquiblock^{TM} 40K and up to 98.59 % for DQ gel. A weak PPG with a lower brine concentration would thus be the preferred product to decrease high permeability zones/areas. The weak gels with low brine concentration were both softer and more deformable than those with a high brine concentration. As a result, more compression and less PPG pack permeability was occurred.

Effect of Load Pressure. PPG pack permeability for both gel types with various load pressures was measured. Figure 4 illustrates the effect of load pressure on PPG pack permeability using different particle sizes (30, 50-60, and 100-120 meshes) mixed with 1% brine concentration for both gels. Both gels compressed more while using a higher load pressure; PPG pack permeability decreased further. Increasing the load pressure caused more PPG pack permeability reduction for both gels.

The PPGs selected were permeable. In addition, their PPG pack permeability changed as the load pressure increased. Load pressures significantly reduced the PPG pack permeability of both gels in the fluid channels or/and fractures. This reduction was affected by particle size, brine concentration, gel strength, and load pressure.

Effects of Brine Concentration Change on Gel Pack Permeability**.** The effect of brine concentration changes was examined using models both with and without a piston**.** PPGs with various brine concentrations were used. Different constant flow rates (0.5, 0.75, and 1 ml/min) were used to calculate PPG pack permeability. Figures 5 presents pressure curves with both different brine concentrations and different constant flow rates for both LiquiBlock™ 40K gel and DQ gel (with a piston). Results indicate that the stabilized pressure affected by both the brine concentration and the flow rate; both the lowest brine concentration and the highest flow rate had a high stabilized pressure. Switching of brine first from 10 % to 1 % and then to 0.05 % caused an increase in PPG pack permeability. Therefore, PPG particle sizes increased and the stabilized pressure decreased. Tables 4 and 5 present the measurement results of PPG pack permeability for both LiquiBlock™ 40K gel and DQ gel.

Figure 6 displays the results of the brine concentration change effect on PPG pack permeability (without a piston). A 10 % brine concentration was injected into the gel pack using flow rates up to 30 ml/min. The brine concentration was first changed from 10 % to 1 % and then to 0.05%. A flow rate of 1 ml/min was used as a constant injection flow rate to measure the PPG packs permeability for different brine concentrations. Both a stabilized pressure and height curves vs. injection times were obtained for each brine.

Figure 6a displays the stabilized pressure of Liquiblock™ 40K gel with various brine concentrations. The pressure required more time to stabilize when the brine concentration decreased.

Figure 6b displays the height of the PPG for various brine concentrations. The PPG height increased as the brine concentration decreased. Table 6 displays the effect of brine concentration change for different experiments without a piston. Table 6 also includes measurements of the various PPG pack permeabilities for different brine concentrations. PPG pack permeability was measured according to experimental results for each brine concentration.

DISCUSSION

PPG Water Loss Measurements. Figure 7 presents the results of water loss, for different particle sizes, for both gels. This figure illustrates the effect of load pressure on water loss for different particle sizes with the same brine concentration. These results also indicate that Liquiblock™40K gel (weak gel) lost more water than the DQ gel (strong gel). The cumulative water loss of various particle sizes (30, 50-60, and 100-120 meshes) was 39.05, 17.69, 13.38 mL for Liquiblock™40K and 34.79, 14.21, 9.70 mL for DQ gel, respectively. The weak PPG lost more water, indicating weak PPGs compressed more than strong PPGs. As a result, the PPG pack permeability for weak gels was less than the strong gels, which lost less water. The PPG with both a large particle size and a low brine concentration lost significantly more water than both the small particle size and high brine concentration.

PPG Pack Compressibility Measurement. Results indicate that gel compressibility was affected by both gel types and particle sizes. The compressibility measurement determined that the compressibility of the large particle size was more than while when using a small particle size. The strong gel (DQ) compressed less than the weak gel (LiquiBlock™ 40K). Figure 8 presents the results on a semi-log plot of various particle sizes using various load pressure. Figure 8 fit well with exponential model. Table 7 lists the fitting equations.

CONCLUSIONS

1. A permeable gel pack was formed in the fluid channels by gel particles. Permeability depended upon particle strength, particle size, brine concentration, and load pressure.
2. The gel pack was compressed, reducing permeability as the load pressure increased.
3. Permeability of the gel pack increased as the particle size increased. Thus, the blocking efficiency of particle gels on the channels or/and fractures was reduced when large sized or/and strong particles were selected.
4. This work is the first to report that gel particles will typically form a permeable gel pack in fluid channels rather than fully block these fluid channels.
5. In field applications, operators often increase either gel particle size or gel strength if they intend to increase blocking efficiency. Contrary to the conventional concepts in PPG treatment practices, gel particles can better block fluid channels if weak and/or small particles are used for conformance control treatments.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge financial support for this project, which is provided by the Research Partnership to Secure Energy for America (RPSEA) through the Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources program, authorized by the U.S. Energy Policy Act of 2005. RPSEA is a nonprofit corporation whose mission is to provide a stewardship role in ensuring the focused research, development, and deployment of safe and environmentally responsible technology that can effectively deliver hydrocarbons from

domestic resources to the citizens of the United States. RPSEA, operating as a consortium of premier U.S. energy research universities, industry, and independent research organizations, manages the program under a contract with the U.S. Department of Energy's National Energy Technology Laboratory (NETL). The authors want also to thank the Petroleum Engineering Department at Sirte University, Libya, Petroleum Engineering Department at Missouri University of Science and Technology, Rolla, Missouri, USA, McCoy School of Engineering at Midwestern State University, Wichita Falls, Texas, USA, and Baker-Hughes for their support.

Nomenclature

A	Cross section area inside the round tube in (cm^2).
C_{gel}	Compressibility of the gel in (psi^{-1}).
d	Inside diameter of the round tube in (cm).
h	Height of the PPG sample in (cm).
K_{gel}	PPG pack permeability in (md).
KG_{BP}	PPG pack permeability before using a piston in (md).
KG_{AB}	PPG pack permeability after using a piston in (md).
K_R	Reduction of the PPG pack permeability after compressed using a piston in (%).
V	Volume of the fully swollen gel before compression in (cm^3).
μ	Viscosity of the brine in (cp).
Q	Flow rate in (cm^3/s).
ΔP_{gel}	Drop pressure across the gel in (psi).
ΔV	Difference between volume of compressed gel and non-compressed gel in (cm^3).

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Table 1 - Typical Characteristics of LiquiBlock™ 40K Gel

Properties	**Value**
Absorption Deionized Water (g/g)	>200
Apparent Bulk Density (g/l)	540
Moisture Content (%)	5
pH Value	5.5-6.0 (+/- 0.5; 1% gel in 0.9% NaCl)

Table 2 - Typical Characteristics of DQ Gels

Properties	Value
Absorption deionized Water (g/g)	> 15
Apparent Bulk Density (g/l)	850
Moisture Content (%)	0.96
pH Value	6.5-7.0 (+/- 0.5; 1% gel in 0.9% NaCl)

Table 3 - Swelling Ratio and Gel strength both Before and After Gel Was Compressed by Piston for Both Gels (LiquiBlock™ 40K Gel and DQ Gel)

No.	Type of Gel	Particle Size (mesh)	NaCl (%)	Swelling Ratio ml/ml	G'_b (pa)	G'_a (pa)
1	40K	30	0.05	155.00	402.50	1380.00
2	40K	30	0.25	85.00	837.00	1978.00
3	40K	30	1.00	49.00	1141.00	2419.00
4	40K	30	10.0	27.00	1920.00	2729.00
5	DQ	30	0.05	17.50	4089.30	5994.00
6	DQ	30	0.25	16.80	4328.20	6358.00
7	DQ	30	1.00	16.25	4486.50	6583.00
8	DQ	30	10.0	15.50	4603.40	7368.00

Table 4 - Effect of Brine Concentration Change on Liquiblock™ 40k Gel Pack Permeability (With Piston)

No.	Gel Type	NaCl %	Q (cm^3/min)	Δ_p (psi)	A (cm^2)	μ (cp)	H (cm)	K_{gel} (mD)	Average K_{gel} (mD)
1	40k	10	0.50	2.50	11.33	1	15.56	67.26	68.49
2	40k	10	0.75	3.70	11.33	1	15.56	68.17	
3	40k	10	1.00	4.80	11.33	1	15.56	70.06	
4	40k	1.0	0.50	2.30	11.33	1	15.56	72.64	74.09
5	40k	1.0	0.75	3.40	11.33	1	15.56	73.70	
6	40k	1.0	1.00	4.40	11.33	1	15.56	75.94	
7	40k	0.05	0.50	2.10	11.33	1	15.56	79.55	82.92
8	40k	0.05	0.75	3.00	11.33	1	15.56	83.53	
9	40k	0.05	1.00	3.90	11.33	1	15.56	85.67	

Table 5 - Effect of Brine Concentration Change on DQ Gel Pack Permeability (With Piston)

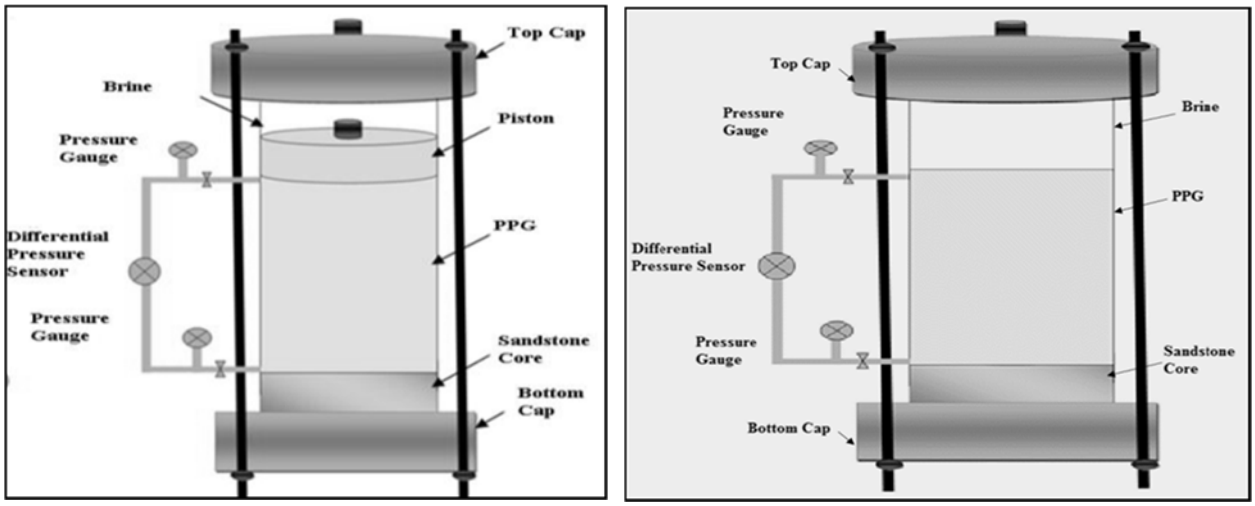
No	Gel Type	NaCl %	Q (cm^3/min)	Δ_p (psi)	A (cm^2)	μ (cp)	H (cm)	K_{gel} (mD)	Average K_{gel} (mD)
1	DQ	10	0.50	2.2	11.33	1.00	17.48	85.58	88.85
2	DQ	10	0.75	3.2	11.33	1.00	17.48	88.56	
3	DQ	10	1.00	4.1	11.33	1.00	17.48	92.14	
4	DQ	1.0	0.50	2.0	11.33	1.00	17.48	94.45	97.19
5	DQ	1.0	0.75	2.9	11.33	1.00	17.48	97.70	
6	DQ	1.0	1.00	3.8	11.33	1.00	17.48	99.42	
7	DQ	0.05	0.50	1.8	11.33	1.00	17.48	104.94	108.35
8	DQ	0.05	0.75	2.6	11.33	1.00	17.48	108.98	
9	DQ	0.05	1.00	3.4	11.33	1.00	17.48	111.12	

Table 6 - The Effect of Brine Concentrations Change on PPG Pack Permeability (Without a Piston) .

No	NaCl %	Q(cm^3/min)	Δ_p (psi)	H (cm)	μ	A (cm^2)	K_{gel} (md)
1	10.00	1.00	0.105	7.00	1.00	11.33	1441.60
2	1.00	1.00	0.135	12.5	1.00	11.33	2002.22
3	0.05	1.00	0.150	17.7	1.00	11.33	2551.63

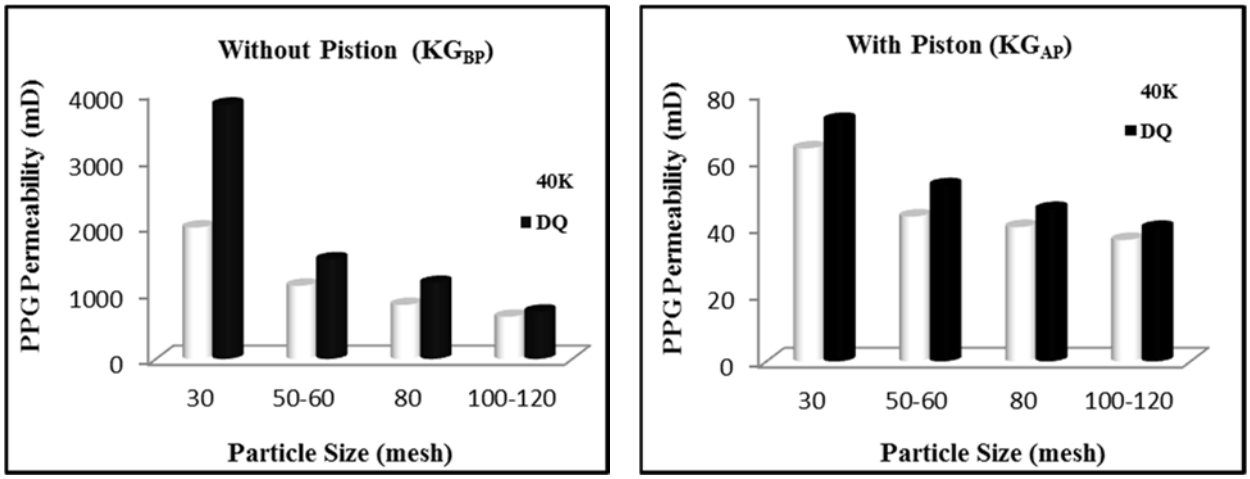
Table 7 - Fitting Equations for Compressibility vs. Load Pressure for Various Particle Sizes.

Gel Type	Particle Size (mesh)	Brine Concentration	Fitting Equation	R^2
40K	30	1	$y = 0.0023e^{-0.005x}$	0.9788
40K	50-60	1	$y = 0.0008e^{-0.004x}$	0.9985
40K	100-120	1	$y = 0.0007e^{-0.004x}$	0.9936
DQ	30	1	$y = 0.0019e^{-0.004x}$	0.9925
DQ	50-60	1	$y = 0.0008e^{-0.005x}$	0.9831
DQ	80	1	$y = 0.0005e^{-0.004x}$	0.9914
DQ	100-120	1	$y = 0.0004e^{-0.004x}$	0.9914



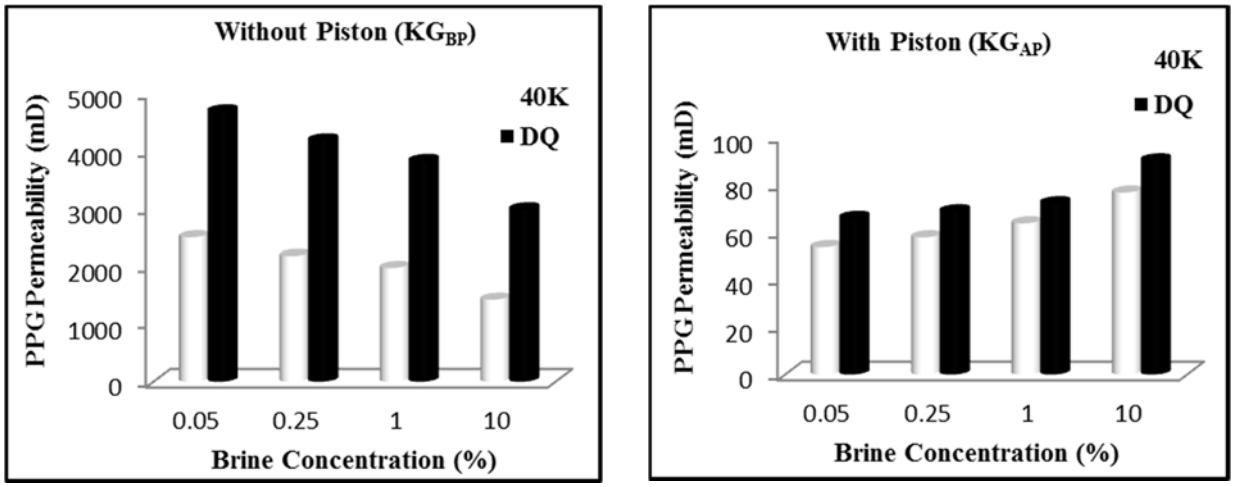
(a) (b)

Figure 1 - Gel Pack Schematic a) Model I b) Model II



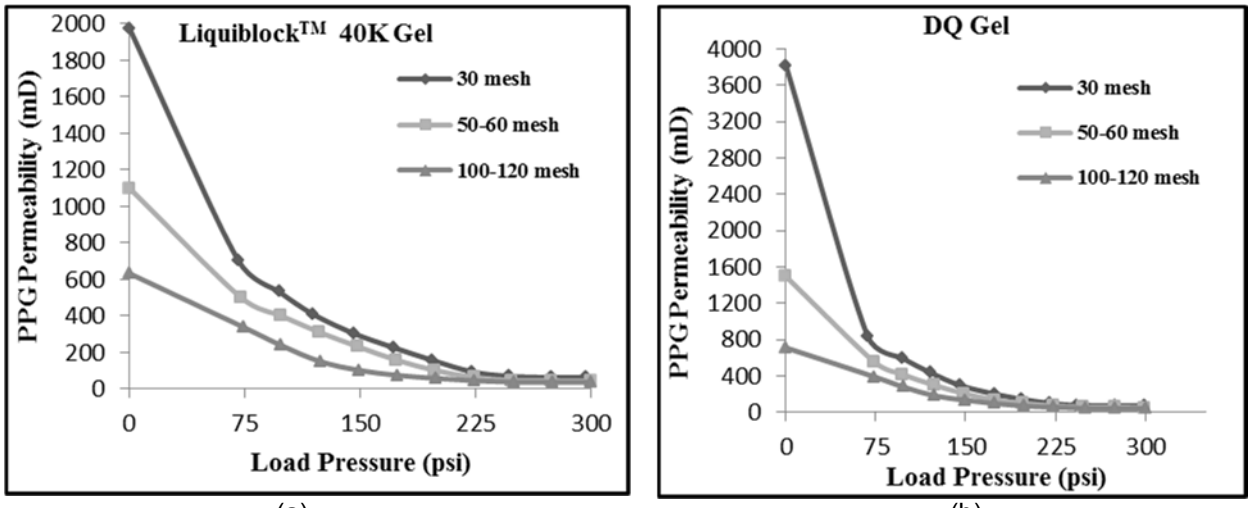
(a) (b)

Figure 2 - PPG pack permeability for various particle sizes of LiquiblockTM40K gel and DQ gel a) without piston and b) with piston.



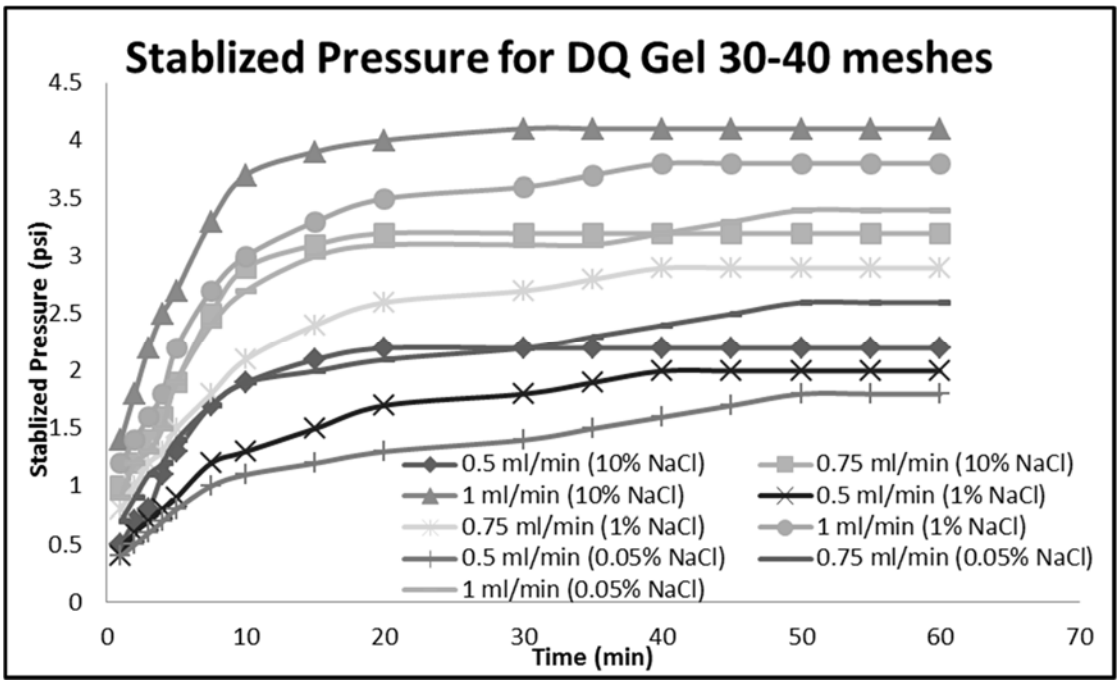
(a) (b)

Figure 3 - PPG pack permeability for various brine concentrations of LiquiblockTM 40K gel and DQ gel a) without piston and b) with piston.

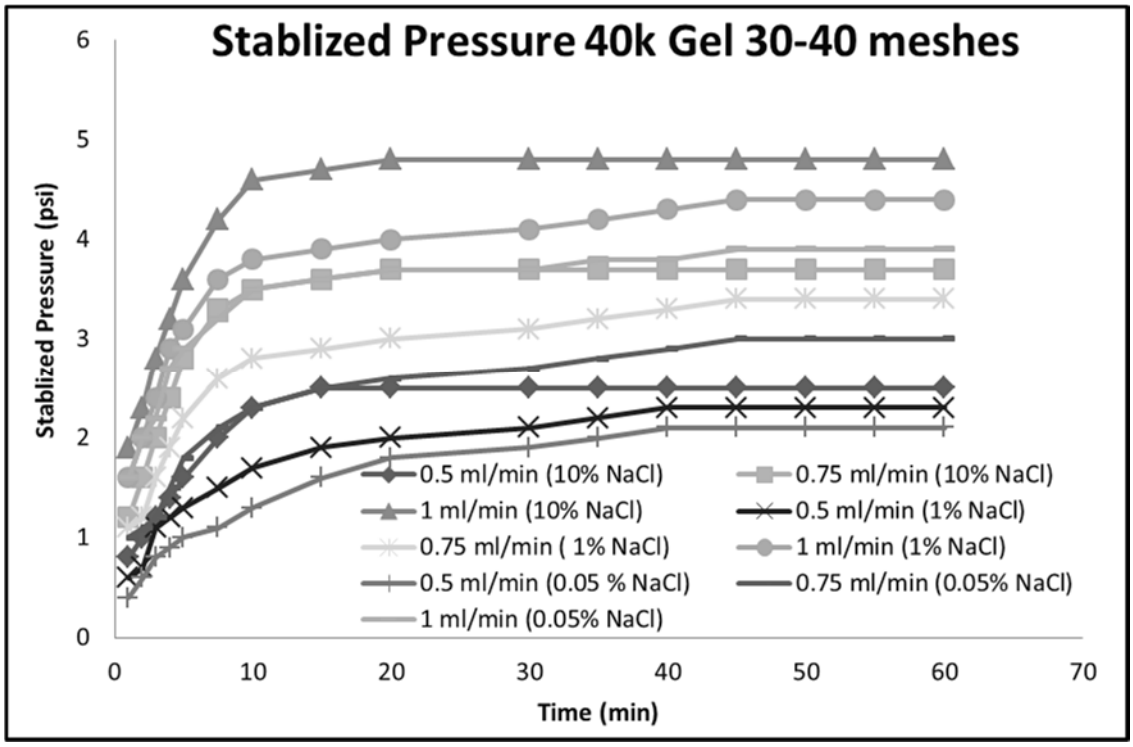


(a) (b)

Figure 4 - The effect of load pressure on PPG pack permeability for various particle sizes of a) LiquiblockTM40K gel, and b) DQ gel.

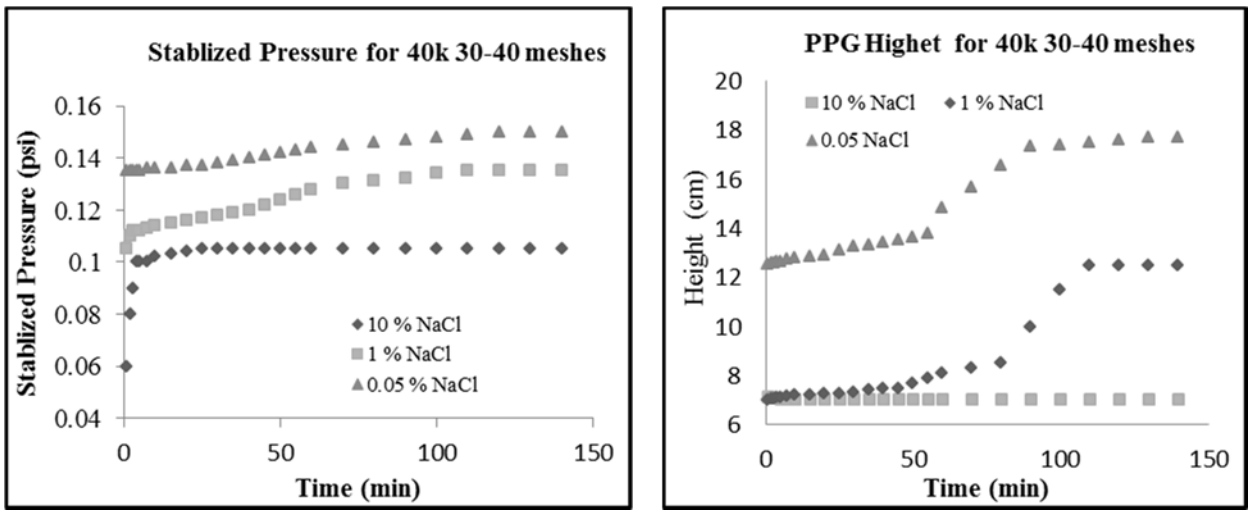


(a)



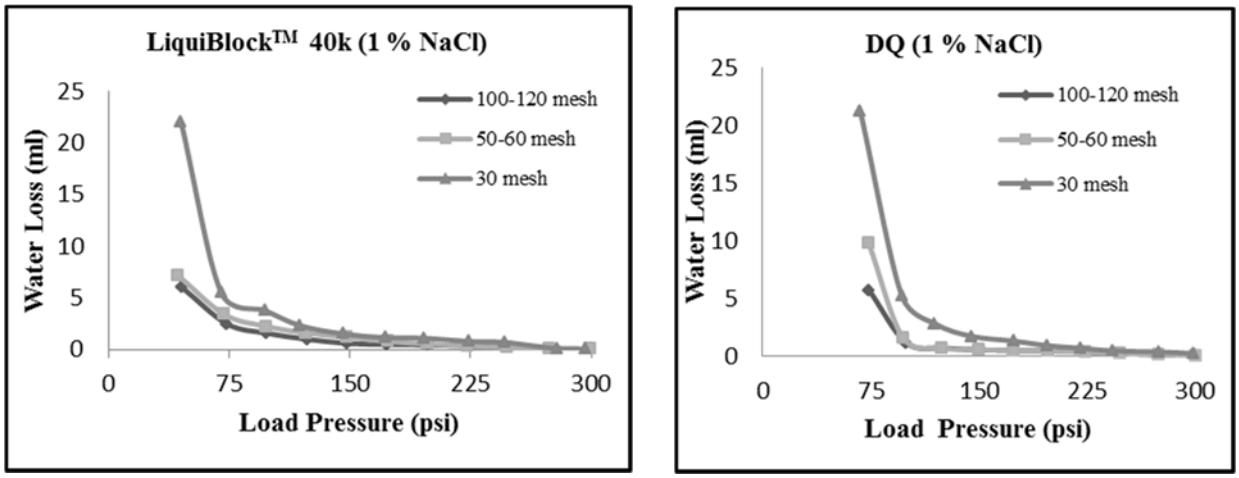
(b)

Figure 5 - The stabilized pressure vs. time 30-40 meshes with a different brine concentrations
a) LiquiblockTM40K gel and b) DQ gel



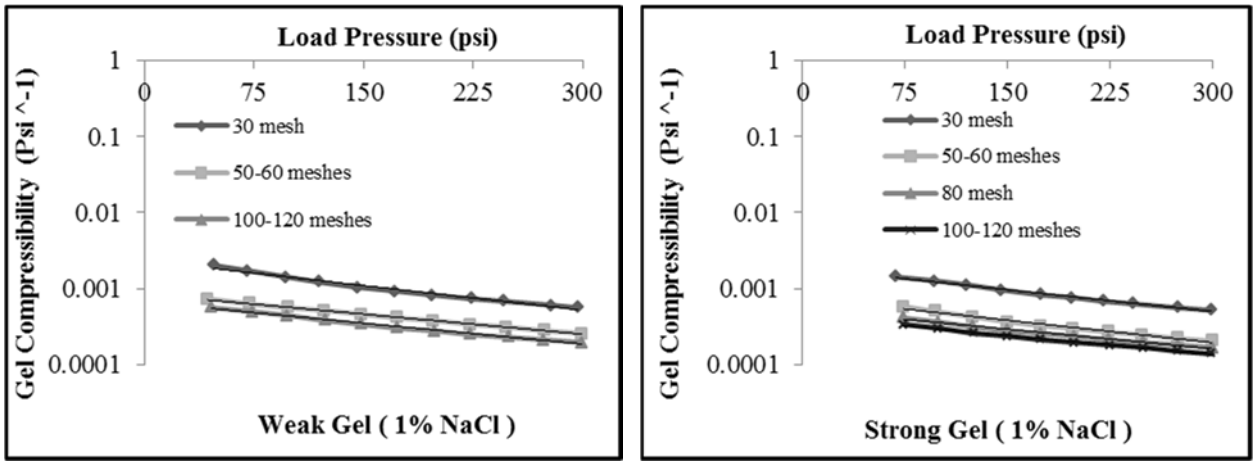
(a) (b)

Figure 6 - The effect of brine concentration change for LiquiblockTM 40k gel without a piston
a) Stabilized pressure b) PPG height



(a) (b)

Figure 7 - Water loss measurements for both gels a) LiquiBlockTM 40K gel and b) DQ gel



(a) (b)

Figure 8 - Shows the measurements of gel compressibility used different load pressure
a) Weak Gel (LiquiBlockTM 40K gel) b) Strong Gel (DQ gel)