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Quantitative Analytical Model of the Formation Damage by Gel Particles

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Abstract

Formation damage by gel particles has become one of the most important problems in mature reservoirs. The objective of the quantitative analytical model is to identify an analytical model to the best fit of the preformed particle gels ($PPGs$) filtration test results. This work will analyze the experiments results of low permeability core samples to evaluate the effect of various brine concentrations and particle sizes. This study used a linear analytical model relationship between cumulative volumes versus filtration time with a good fits result. A linear curve equation for the best fitting equation was obtained. According to quantitative analytical model for all of our filtration tests, the cumulative filtration test volume is explained by the following equation: ($Vcf = mt + b$). Where, Vcf is the cumulative filtration volume, m is the slop of the linear curve, t is the filtration time, and b is the intercept of the linear curve. Quantitative analytical model results showed the value of the slop m increases as the injection pressure increases. Compared with the experiments, the results show that, if the value of the intercept ($b > 2$) the damage occurred because the gel particles invasion started into the core surface. Results from the quantitative analytical model were indicated to have a good fitting with almost all of the experimental results. It is the first time to use quantitative analytical model to analysis the formation damage by the $PPGs$. The results can be used to select the best gel treatment design.

Keywords: Quantitative analytical model; formation damage; preformed particle gels; conformance control treatment design; mature reservoirs.

1. Introduction

A filtration test is a simple means of evaluating formation damage (Vetter et al., 1987., Ershagi et al., 1986). The oil industry currently uses two standard filtration tests both static and dynamic, to assess damage to core samples. The former is suitable when testing for injection into the matrix rock; the latter assesses injection into a fracture (Eylander et al., 1988). Filtration test experiments have been used in the past to study the damage of cores fully saturated with brine, oil, or residual oil while injecting suspended particles, oily water, or a combination of both in these cores (Al-Abduwani et al., 2005b; Hsi et al., 1994; Coleman & Mclelland 1994; Ali et al., 2009). Elsharafi and Bai 2012 2013, 2015, and 2016 studied the effect of deformable swollen gel particles on low-permeability zones. This research used static filtration tests experiments results to determine whether or not swollen $PPGs$ affected unswept oil zones/areas. In addition, a filtration test was used to find methods for minimizing PPG damage. This research determined the better fits to the previous lab results (Elsharafi and Bai 2012, 2013, 2015, and 2016).

2. Literature Review

The primary objective of the quantitative analytical model is to identify an analytical model to the best fit of the *PPG* filtration test results obtained and analyze when the *PPGs* damage the cores. The volume versus square-root-of-time data for filtration tests is effectively described by Equation 2.1, first developed by Outmans (1963) for drilling muds'.

$$Vfl = Vsp + m\sqrt{t} \tag{2.1}$$

Where, Vfl is the cumulative fluid-loss volume,Vsp is the spurt volume, and m is the slope of the linear part of the curve. Barkman and Davidson (1972) included the effect of solid particle invasion for static filtration tests. They noted that, if $b < 0$, no damage has occurred. If $b > 0$, the cores have been damaged. Variable b is the intercept of the straight line which was used to determine whether or not damage has occurred. Barkman and Davidson (1972) suggested that the invasion of the solid particles takes place during the early part of the filtration test. They derived a simple equation during a linear filtration test. Their study included the cumulative volume (VB) at the bridging time ($\sqrt{t_B}$). They also indicated that a plot of cumulative volume versus square root of time should produce a straight line when $t \gg t_B$.

$$VB = b + m\sqrt{t_B} \tag{2.2}$$

Where, b is the intercept of the straight line and m is the slop of the straight line. Gulbis (1983) proposed using time rather than the square root of time. He displayed his result in Equation 2.3. His model provides a good fit with dynamic data taken from dynamic fluid-loss tests. Gulbis (1983) used a hollow-core device.

$$Vfl = Vsp + mt \tag{2.3}$$

Roodhart (1985) proposed the use of both time and square-root-of-time for dynamic fluid loss. Roodhart (1985) used poloymetric Equation 2.4. This Equation includes both kick-building phase with a short time and an equilibrium flow region with a longer time.

$$Vfl = Vsp + m\sqrt{t} + Bt \tag{2.4}$$

The constant (B) is, essentially, a fitting parameter that relates to the equilibrium flow region. Penny et al. (1985) introduced the power law model. They added the exponential tn rather than t. Thus, equation 2.5 fits well with curves that have a longer time.

$$Vfl = Vsp + m\,tn \tag{2.5}$$

Bourgoyne et al. (1986) indicated that the preferred filtration test plot of a cumulative filtration loss versus the square root of time should be a straight line passing through the origin point when no spurt loss occurred. Some spurt loss, however, will always occur. This occurrence shifts the curve vertically, indicating that the intercept is not equal to zero. Chin (1995) determined that, for small wellbores diameter the square-root-of-time relationship cannot be used because of the effect of radial flow. The linear flow theory essential in the conventional analysis cannot be used. Logeron et al. (1995) used both the relationship between the cumulative filtration volume versus time and the cumulative filtration volume versus square root of time to determine particle invasion. Logeron et al. (1995) used long cores for static filtration test. The relationship between the cumulative filtration volume versus the square root of time for static filtration tests indicates that, after a few minutes, the filtration tests curves almost a liner. Equation 2.6 describes the filtrate volume.

$$Vf = b + m\sqrt{t} \tag{2.6}$$

Where, both b and m are constants which are affected by mud, core properties, and filtration test parameters. Many researchers have used the square root of time, typically with dynamic filtration tests, and long cylindrical core samples. Long cores have been used to have a sufficient time to flow the mud filtrate invasion before filtrate break through. This study could not obtain a linear function for the square root of time when cumulative volume versus square root time was plotted for experiments results. These experiments were dealing with a short samples, small diameters, and single linear flow systems. When the square root of time was used to analyze the experiments results, neither a good fitting nor an analysis explanation for all of the curves because the shapes were smaller with a downward trend. This study attempted to use semi-log plots. Semi-log plots couldn't explain the core damage since the curves trend was upward with same shapes. This study also attempted to use poloymeteric equations. Analysis of these equations was not explaining the experiments results. This study used a linear analytical model relationship between cumulative volumes versus filtration time with a good fits result.

This work will analyze the experiments results of low permeability sandstone core samples to evaluate the effectiveness of various preformed particle gels ($PPGs$) with different brine concentrations and particle sizes.

3. Results and Analysis

Linear curve equations for the best fitting equation as you can see in the Figures 3.13.23.33.43.53.6, the fitting equation for the all curves show in the tables 3.13.23.33.43.53.6. When core damage occurred, the filtration volume curves for static filtration tests required a few minutes to become a linear function of the time. According to quantitative analytical model for all of our filtration tests, the cumulative filtration test volume is explained by the following equation.

$$Vcf = mt + b \tag{3.1}$$

Where, Vcf is the cumulative filtration volume, m is the slop of the linear curve, t is the filtration time, and b is the intercept of the linear curve. Quantitative analytical model results showed the value of the slop m increases as the injection pressure increases. Compared with the experiments results, Tables 1 through 6 illustrate that, if the value of the intercept $b > 2$ the damage occurred because the gel particles invasion started into the core surface. Results from the quantitative analytical model were indicated to have a good fitting with almost all of the experimental results. According to our analytical results, the $PPGs$ lost some water (volume lost). The value of water loss could explain the core damage. These water losses typically occurred at first injection pressures. The shift of the volume vertically in the y-intercept was occurred even no core damage because the $PPGs$ lose some water.

Figure 3.1: Typical Filtration Curves for LiquiblockTM40K Gel with $5 - 25mD$: a)1% Brine with 30 mesh b) 10% Brine with 30 mesh c) 1% Brine with 80 mesh d) 1% Brine with 100-120 meshes

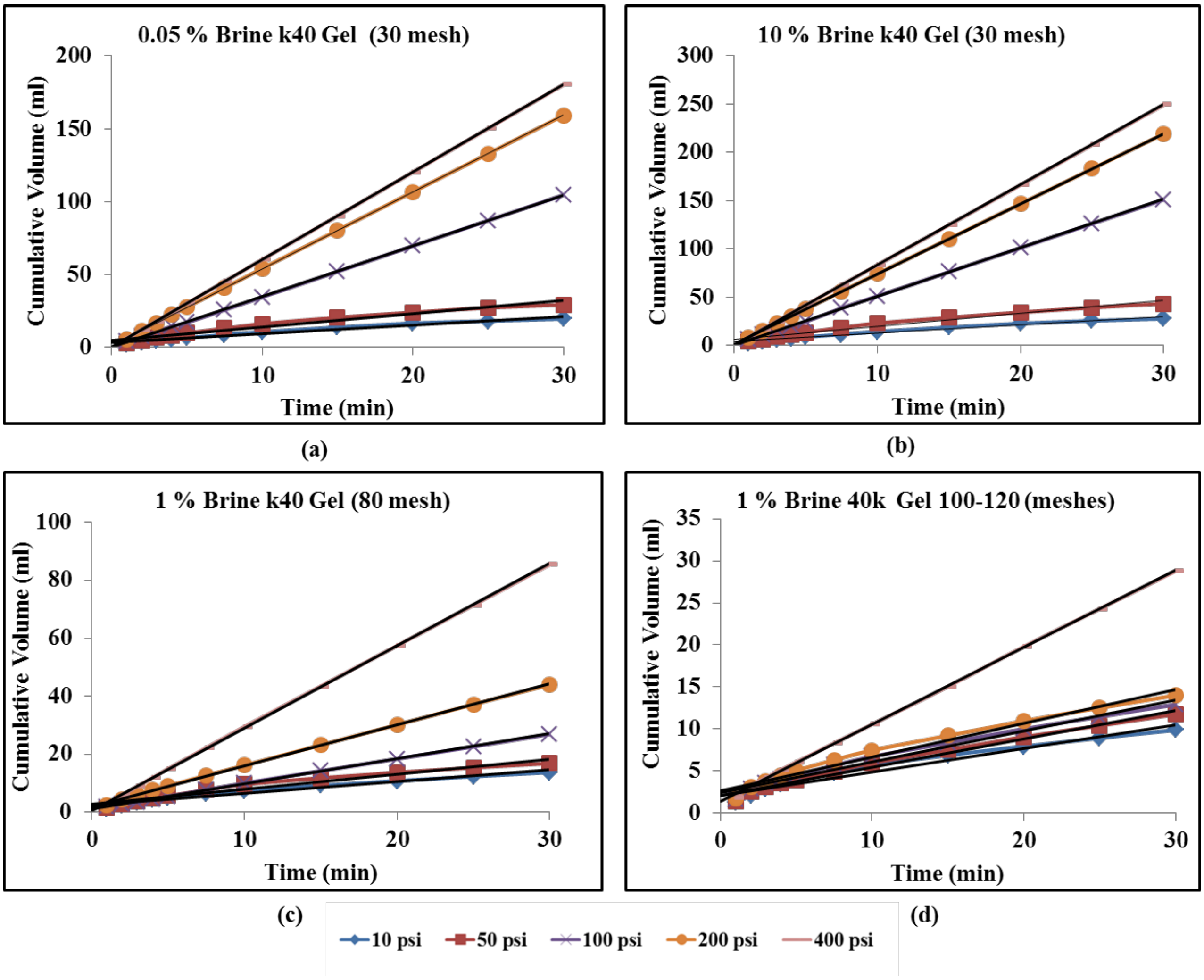

Table 3.1: Shows the Quantitative Analytical Model Equations for Liquiblock TM 40K Gel with Core Permeability of $5 - 25\,mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	NaCl %	Pressure (psi)	Fitting Equation	R^2
		10	V = 0.6053t + 3.3299	0.9638
		50	V = 0.9129t + 4.672	0.9627
30	0.05	100	V= 3.4697t + 0.2552	0.9999
		200	V = 5.2797t + 1.062	1
		400	V = 6t + 0.25	1
		10	V = 0.8675t + 4.2124	0.9741
		50	V = 1.3495t + 6.2147	0.9709
30	10	100	V = 5.0218t + 0.7348	0.9999
		200	V = 7.2757t + 1.2437	1
		400	V = 8.302t + 0.3097	1
		10	V = 0.4054t + 2.4853	0.9615
		50	V = 0.5212t + 2.7319	0.9559
80	1	100	V = 0.8689t + 1.037	0.9996
		200	V = 1.4184t + 1.7904	0.9994
		400	V = 2.8396t + 0.6267	0.9999
		10	V = 0.2804t + 2.1115	0.9552
		50	V = 0.3396t + 2.0403	0.9842
100-120	1	100	V = 0.369t + 2.3905	0.9804
		200	V = 0.401t + 2.6657	0.9752
		400	V = 0.9184t + 1.341	0.9997

Table 3.2: Shows the Quantitative Analytical Model Results Liner Equations Liquiblock TM 40K gel with Core Permeability of $100 - 120\,mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	Brine Concentration (%	Pressure (psi)	Fitting Equation	R^2
		10	V = 0.9518t + 3.9823	0.9849
		50	V = 6.2262t + 17.708	0.9914
30	1	100	V = 14.039t + 0.1579	1
		200	V = 18.552t - 1.8127	1
		400	V = 26.379t - 1.1825	1
		10	V = 1.1206t + 4.8726	0.9884
		50	V = 8.1346t + 14.637	0.9967
30	10	100	V = 15.039t + 0.1579	1
		200	V = 20.082t - 0.8346	0.9999
		400	V = 30.138t - 1.703	1
		10	V = 1.3416t + 2.0352	0.9963
		50	V = 1.7164t + 2.4766	0.9957
50-60	1	100	V = 1.9533t + 2.3838	0.9995
		200	V = 2.6199t + 2.1604	0.9988
		400	V = 3.3885t + 3.4377	0.9986
		10	V = 0.3139t + 2.1768	0.9656
		50	V = 0.3546t + 2.1567	0.9826
100-120	1	100	V = 0.3842t + 2.3801	0.9877
		200	V = 0.4529t + 2.3416	0.9791
		400	V = 0.8185t + 1.8896	0.9975

Figure 3.2: Typical Liner Curves Analytical Model for Liquiblock TM 40K Cel with $100 - 120\,mD$: (a) 1% Brine with 30 mesh (b) 10 % Brine with 30 mesh (c) 1% Brine with 50-60 meshes (d) 1% Brine with 100-120 meshes

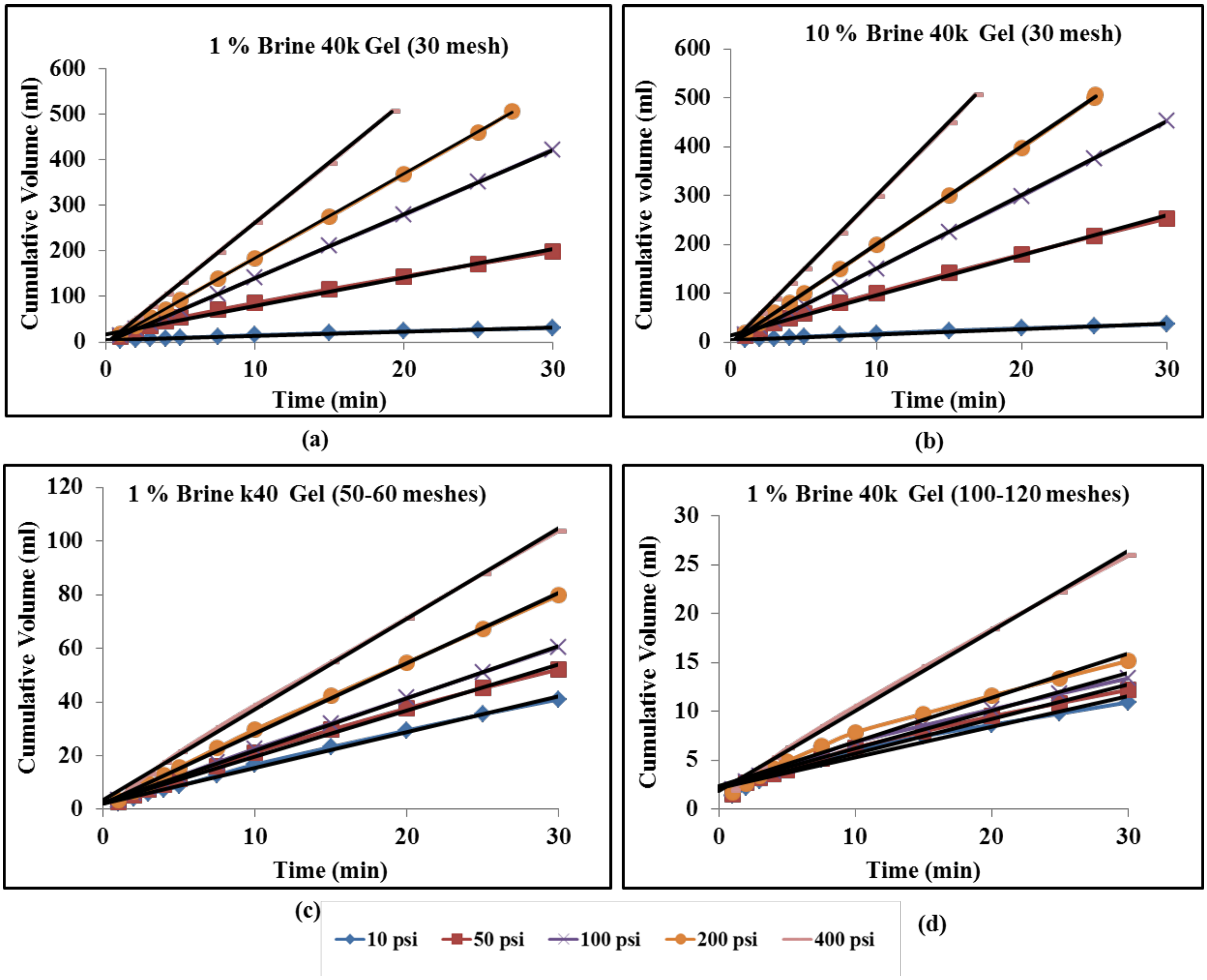

Figure 3.3: Typical Liner Curves Analytical Model for Liquiblock TM 40K Gel with $290 - 320\,mD$: (a) 0.05% Brine with 30 mesh (b) 1 % Brine with 30 mesh (c) 1% Brine with 50-60 meshes (d) 1% Brine with 100-120 meshes

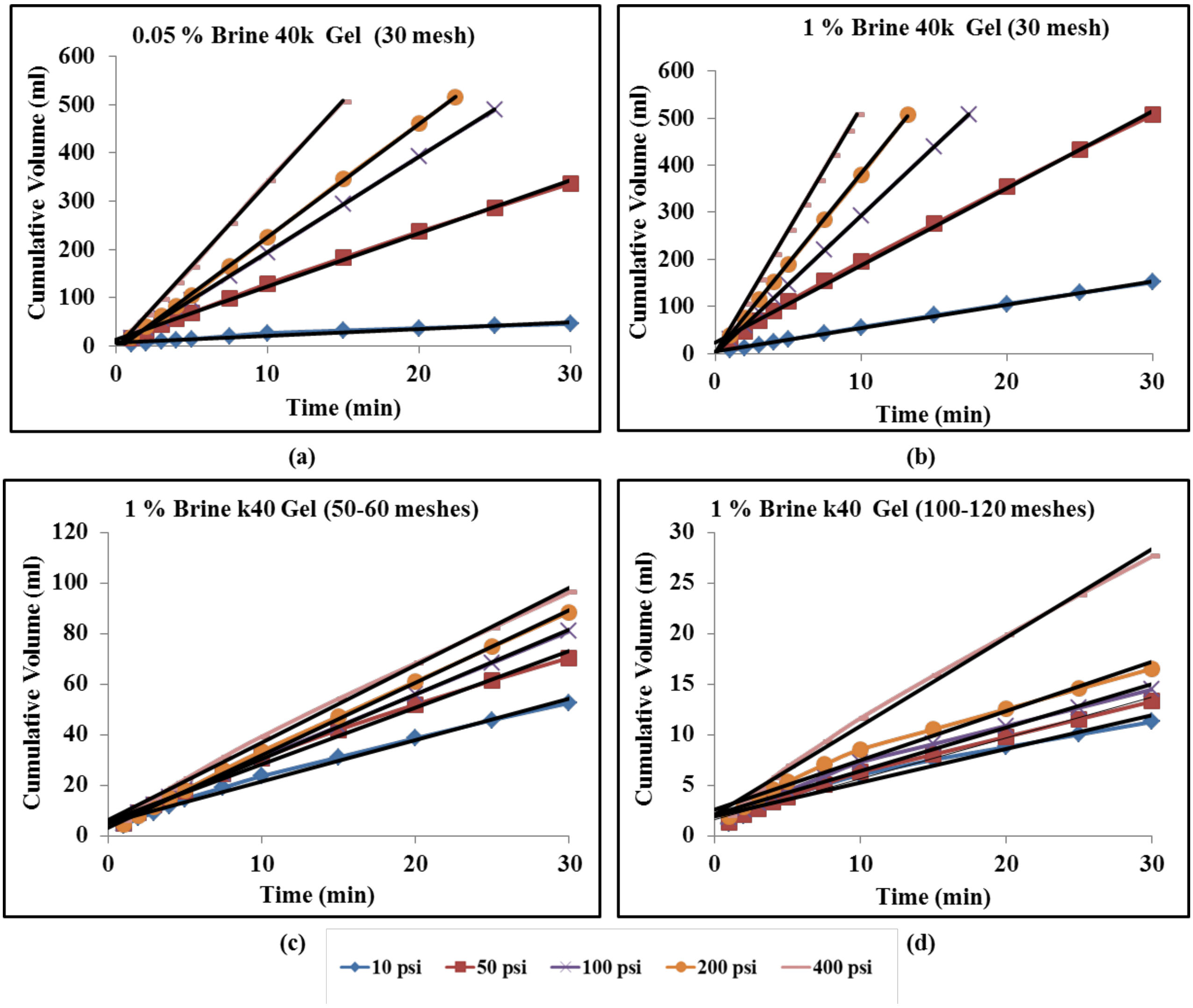

Figure 3.4: Typical Liner Curves Analytical Model for DQ Gel with $5 - 25\,mD$: (a) 0.05% Brine with 30 mesh (b) 10 % Brine with 30 mesh (c) 1% Brine with 50-60 meshes (d) 1% Brine with 100-120 meshes

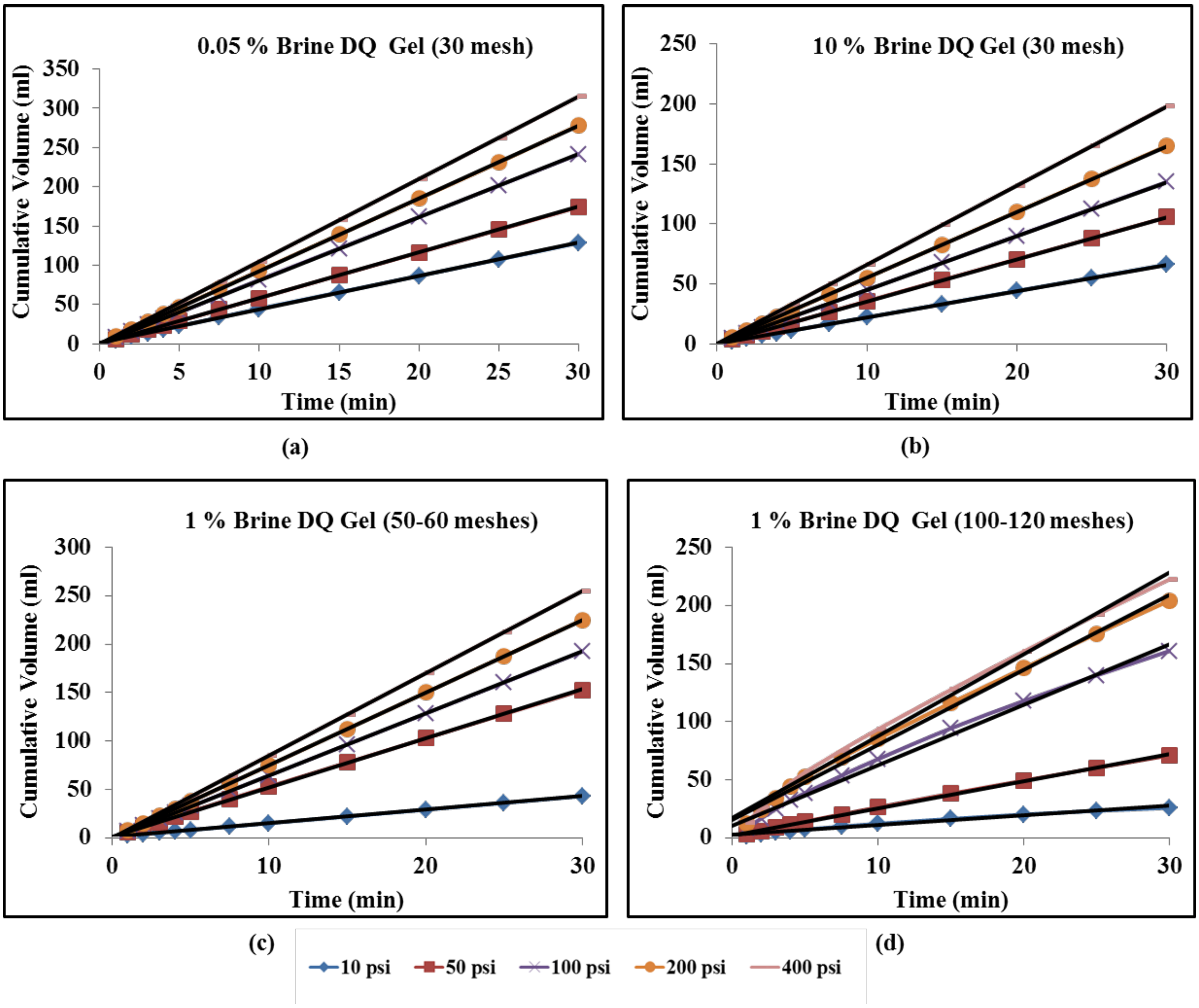

Table 3.3: Shows the Quantitative Analytical Model Results Liner Equations Liquiblock TM 40K Gel with Core Permeability of $290 - 320\,mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	Brine Concentration	Pressure (psi)	Fitting Equation	R^2
30	0.05	10	V = 1.4523t + 5.9433	0.9506
		50	V = 11.049t + 11.578	0.9982
		100	V = 19.745t - 3.5441	1
		200	V = 23.503t - 9.8703	0.9999
		400	V = 34.267t - 5.3881	0.9998
30	1	10	V = 4.9922t + 4.2492	0.9988
		50	V = 16.435t + 22.47	0.9979
		100	V = 29.139t + 1.1352	1
		200	V = 38.187t - 0.4057	0.9999
		400	V = 52.417t + 0.1568	1
50-60	1	10	V = 1.6433t + 5.0904	0.9911
		50	V = 2.2391t + 5.935	0.9928
		100	V = 2.5645t + 4.5541	0.9988
		200	V = 2.877t + 3.211	0.9988
		400	V = 3.0678t + 6.2657	0.9966
100-120	1	10	V = 0.3337t + 1.9061	0.9701
		50	V = 0.4034t + 1.6256	0.9895
		100	V = 0.4288t + 2.1567	0.9869
		200	V = 0.4896t + 2.5707	0.9805
		400	V = 0.8746t + 2.1282	0.9956

Figure 3.5: Typical Liner Curves Analytical Model for DQ Gel with $100 - 120\,mD$: (a) 10% Brine with 30 mesh (b) 1 % Brine with 100-120 meshes

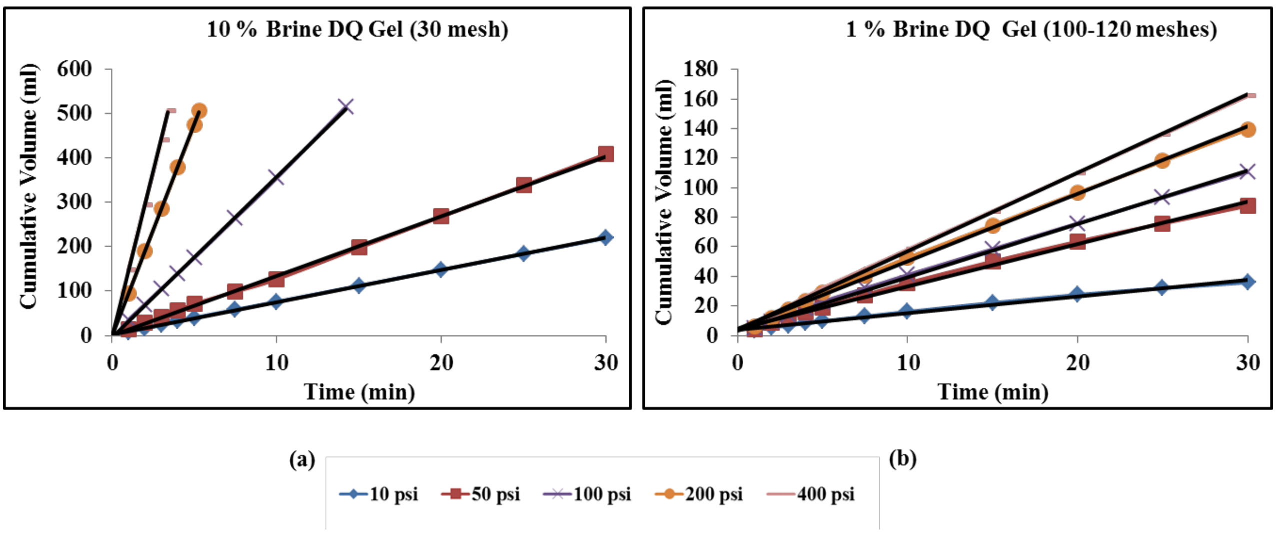

Table 3.4: Shows the Quantitative Analytical Model Results Liner Equations DQ Gel with Core Permeability of $5-25\,mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	Brine Concentration	Pressure (psi)	Fitting Equation	R^2
30	0.05	10	V = 4.2701t + 0.9464	0.9999
		50	V = 5.8084t + 0.0429	1
		100	V = 8.0679t - 0.1105	1
		200	V = 9.2589t + 0.14	1
		400	V = 10.5t	1
30	1	10	V= 3.1817t - 0.6141	1
		50	V = 4.6267t + 0.557	1
		100	V = 5.8436t + 0.4783	1
		200	V = 6.9t	1
		400	V = 7.8t	1
30	10	10	V = 2.2t	1
		50	V = 3.5213t + 0.0127	1
		100	V = 4.5t - 0.1	1
		200	V = 5.5t	1
		400	V = 6.6t	1
50-60	1	10	V = 1.4043t + 1.2609	1
		50	V = 5.0672t + 1.5313	0.9999
		100	V = 6.4105t + 0.4281	1
		200	V = 7.501t + 0.1796	1
		400	V = 8.501t + 0.2796	1
80	1	10	V = 1.222t + 1.473	0.9997
		50	V = 4.0672t + 1.7313	0.9998
		100	V = 5.1324t + 1.7069	0.9997
		200	V = 6.501t + 0.1796	1
		400	V = 7.5t	1
100-120	1	10	V = 0.8293t + 2.8354	0.9842
		50	V = 2.3431t + 2.0654	0.9987
		100	V = 5.2105t + 10.772	0.9928
		200	V = 6.4458t + 15.864	0.9944
		400	V = 7.0541t + 17.127	0.9941

Table 3.5: Shows the Quantitative Analytical Model Results Liner Equations DQ Gel with Core Permeability of $100-120\,mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	Brine Concentration	Pressure (psi)	Fitting Equation	R^2
30	10	10	V = 7.2733t + 2.4563	0.9998
		50	V = 13.502t - 0.3676	0.9993
		100	V = 36.251t - 4.1154	0.9997
		200	V = 95.353t - 0.7789	0.9999
		400	V = 148.88t - 1.8588	0.9998
100-120	1	10	V = 1.1287t + 3.7965	0.9929
		50	V = 2.8852t + 4.165	0.9955
		100	V= 3.6056t + 3.4918	0.9988
		200	V= 4.5652t + 4.5052	0.9984
		400	V= 5.2969t + 4.0754	0.9994

Figure 3.6: Typical Liner Curves Analytical Model for DQ Gel with $290 - 320\,mD$: (a) 1% Brine with 30 mesh (b) 10 % Brine with 30 mesh (c) 1% Brine with 50-60 meshes (d) 1% Brine with 290-320 meshes

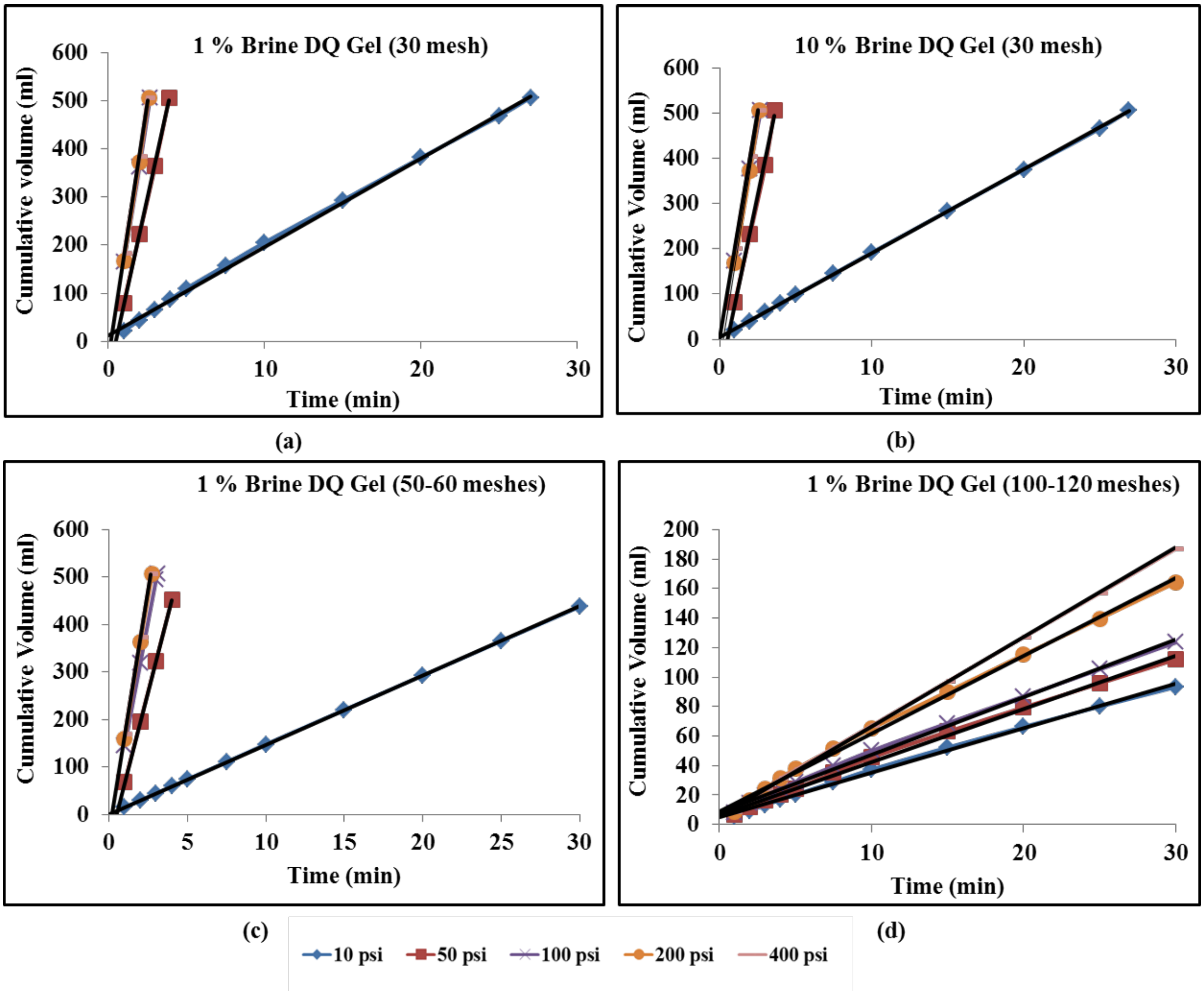

Table 3.6: Shows the Quantitative Analytical Model Results Liner Equations DQ Gel with Core Permeability $290 - 320\, mD$ for Various Particle Sizes and Brine Concentrations

Particle Size (mesh)	Brine Concentration	Pressure (psi)	Fitting Equation	R^2
30	0.05	10	V = 20.155t + 8.5524	0.9993
		50	V = 161.62t - 20.959	0.9999
		100	V = 199.78t - 20.591	0.9997
		200	V = 204.43t - 16.544	1
		400	V = 202.29t + 2.1429	0.9999
30	1	10	V = 18.403t + 13.165	0.9989
		50	V = 146.3t - 69.089	0.9994
		100	V= 203.08t - 39.833	0.9995
		200	V= 211.84t - 46.429	0.9995
		400	V= 213.18t - 33.382	0.9982
30	10	10	V = 18.641t + 3.8415	0.9990
		50	V = 161.17t - 85.316	0.9962
		100	V = 196.44t - 20.233	0.9992
		200	V = 211.07t - 45	0.9993
		400	V = 199.37t + 1.8362	0.9996
50-60	1	10	V = 14.567t + 1.4621	1
		50	V = 128t - 60	1
		100	V = 173.44t - 27.825	0.9998
		200	V = 198.59t - 36.973	0.9996
		400	V = 203.67t - 33.073	1
100-120	1	10	V = 3.0261t + 4.7957	0.9972
		50	V = 3.6166t + 6.1198	0.9968
		100	V = 3.9188t + 8.0818	0.9972
		200	V = 5.2669t + 9.0281	0.9969
		400	V = 6.0806t + 5.439	0.9995

4. Conclusions

- It is the first time to use quantitative analytical model to analysis the formation damage by the $PPGs$.
- The relationship curves between the cumulative volume versus filtration time show that if the value of the curve intercept $b > 2$ the gel will damage the formation.
- Water loss value from the particle gel can give an indication about the formation damage. Weak gels loss more water than strong gel. Therefor the particle sizes will be smaller and penetrate further through the reservoir rocks.
- Preformed particle gels loss water at first injection pressures. The shift of the volume vertically in the y-intercept because the Preformed particle gels lose some water.
- This research results can be used to properly select the gel particles that will not damage the formation for the best a particle gel treatment.

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