Spring 2017

Survey and data analysis of weak gel treatments in injection wells

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Recommended Citation

Chen, Zhuxing, "Survey and data analysis of weak gel treatments in injection wells" (2017). *Masters Theses*. 7635.
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SURVEY AND DATA ANALYSIS
OF WEAK GEL TREATMENTS
IN INJECTION WELLS

by

ZHUXING CHEN

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN PETROLEUM ENGINEERING

2017

Approved by

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Dr. Peyman Heidari

ABSTRACT

Excessive water production is a major concern in mature reservoirs. Weak gels have been applied in injection wells for in-depth profile modification. However, the data range and distribution of each parameter that affects performance of weak gels have not been studied thoroughly.

China has the largest amount of chemical-based conformance control treatments. This paper presents a summary of comprehensive data ranges and distributions for weak gel treatments based on the laboratory experiments and field applications in China from 2001 to 2010. The data set includes 76 cases compiled from China Academic Journals papers. In this study, reservoir properties, gel properties and production data are specifically studied with statistical analysis methods. Box plots and histograms are used to display the range and distribution of each parameter and bar charts and cross plots are used to show comparisons among different categories, such as polymer type and crosslinker type.

Based on statistical analysis, HPAM is more widely used over broad ranges of temperatures and brine salinities in China, although other polymers, such as AP and KYPAM, have better stabilities in severe conditions (high temperature or high salinity). For crosslinkers, chromium(III) crosslinkers and phenol-formaldehyde crosslinkers are more widely used in China, and phenol-formaldehyde crosslinkers are more widely used over a broad range of temperatures, from low to high temperatures, although they are normally designed for high temperature applications.

ACKNOWLEDGMENTS

Thanks to my advisor, Dr. Baojun Bai, for giving me the opportunity of working in the EOR research group and giving me guidance and encouragement of my graduate study.

Thanks to my committee members, Dr. Mingzhen Wei and Dr. Peyman Heidari, for their kind support.

Thanks to Munqith Aldhaheri, Na Zhang, Yandong Zhang and Yifu Long for giving me suggestions of my research.

Last but not least, thank my parents for their support and love.

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NOMENCLATURE

Symbol	Description
BG	Bulk Gel
CDG	Colloidal Dispersion Gel
WG	Weak Gel
HPAM	Partially Hydrolyzed Polyacrylamide
AP	Hydrophobically Associating Polymer
AMPS	2-Acrylamide-2Methyl Propane-Sulfonate
PV	Pore Volume
PF	Phenol-Formaldehyde
PPG	Preformed Particle Gel

1. INTRODUCTION

Excessive unwanted water production is a common problem encountered in most mature reservoirs as a result of long-term water flooding (Bai et al. 2013). Due to conformance problems, excessive water production becomes an issue when it competes directly with oil production. The water tends to flow from an injection well to the production well through highly conductive natural fractures that run directly from the injection well to the production well. Excessive water production during oil recovery operations adds unnecessary operating costs, including water lifting, treating, handling and disposal costs, to the recovery of oil (Seright et al., 2003). A report from the U.S. national laboratory indicates that the oil industry was, on the average, producing worldwide 3 bbl of water for every 1 bbl of oil. Same report also shows the oil industry in the United States was producing 7 bbl of water for every 1 bbl of oil (Veil et al., 2004).

Conformance problems can be classified into two main categories, including near-wellbore problems and reservoir-related problems (Chou et al., 1994). General means to improve conformance include increasing the viscosity of the flooding fluid, reducing the permeability of high-permeability flow channels, increasing the permeability of low-permeability flow, and improving conformance through the wellbore. Spatial variation in the fluid-flow capacity because of reservoir permeability heterogeneity is the root cause of reservoir conformance problems.

Gels have proven to be one of the most popular materials for use in permeability-reducing conformance-improvement treatments (Seright et al., 2003; Sydansk, 2007). Weak gel, that has a relatively low gel strength but can still be crosslinked in reservoir condition, serves as a cost-effective and function-effective agent for permeability-reducing and fluid-flow-blocking in conformance-improvement treatments. Due to its low gel strength, low surface viscosity and long delayed gelation time, it can penetrate into deep-reservoir compared to classic bulk gel.

Screening criteria serves as the first step for evaluating potential gel formulations for candidate reservoirs. Screening criteria are critical at the start of a gel project because gel projects capital sensitive and involve high degree of risk and can yield significant undesirable consequences if they fail (Munqith et al. 2016).

The objectives of this study are to study the distributions of each parameter that affects performance of weak gel treatments, to study the special cases that are helpful to understand the weak gel formulations for different reservoirs and to establish the comprehensive data ranges for applying weak gel treatments in injection wells. Such comprehensive data ranges are established based on statistical analyses of a large set of experimental and field data.

2. LITERATURE REVIEW

Conformance control is any action taken to improve the injection or production profile of a well. It encompasses procedures that enhance recovery efficiency, improve wellbore/casing integrity, and satisfy environmental regulations (Azari and Soliman, 1996).

2.1. GEL TREATMENT

Gel treatment is a cost-effective method to improve sweep efficiency in reservoirs and to reduce excessive water production during oil and gas production (Bai et al., 2008). Polymer gels have been applied in injection wells for near-wellbore conformance control and reservoir scale in-depth fluid diversion and have been applied in production wells for shutoff. Polymer gels can be divided into in-situ gels and preformed particle gels. Traditionally in-situ gels were used for controlling water production where a mixture of polymer and crosslinker is injected into the formation to form gels at reservoir conditions (Sydansk and Moore, 1992; Jain et al., 2005; Delshad et al., 2013). The basic premise of any gel technology is that the gelant will preferentially enter high permeability anomalies responsible for low volumetric sweep efficiency. Once the gels reduce the flow capacity in the "thief zones", both vertical and areal sweep efficiency will be improved (Muruaga et al., 2008). PPGs are formed at the surface, then dried and crushed into small particles to be injected into the reservoir (Bai et al., 2007). PPGs overcome drawbacks of in-situ gels, such as lack of control on gelation time, uncertain gelling due to shear degradation, chromatographic fractionation and dilution by brine water (Delshad et al., 2013).

2.2. TYPES OF IN-SITU GELS

When metal ions are added to a polymer solution, a reaction occurs between the metal ion and the carboxyl group. When the polymer concentration is less than the critical overlap concentration (C^*), conventional bulk gels cannot form and predominantly intramolecular and minimal intermolecular crosslinks can occur. However, when the polymer concentration exceeds the critical overlap concentration, intermolecular crosslinks can occur between two or more polymer molecules and continued intermolecular crosslinking may led to the formation of a continuous network of polymer molecules (Al-Assi, et al.2006). In-situ gels can be divided into bulk gels, CDGs and weak gels. The difference between a CDG and a bulk gel is shown in Figure 2.1.

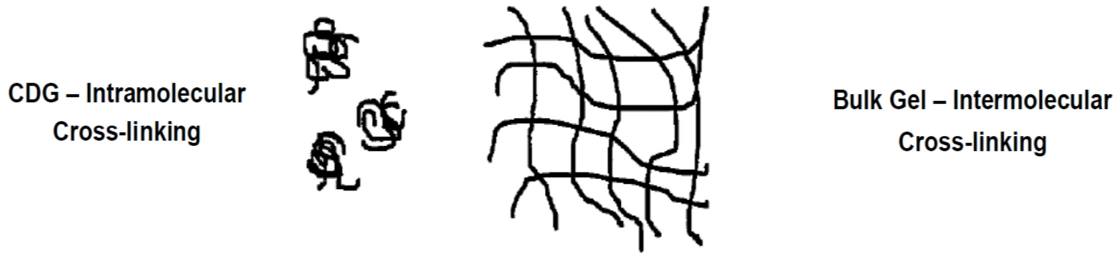


Figure 2.1. Comparison of CDG and bulk gel (Mack and Smith 1994; Ming 2014).

2.2.1. Bulk Gels. Bulk gels are high polymer concentration gels designed for applications in reducing water channeling in naturally fractured formations or in reservoirs with multi-darcy permeability anomalies (Wang et al. 2003; Diaz et al. 2008; Muruaga et al. 2008). The high polymer concentration result in a continuous semi-solid 3D network structure (Munqith et al. 2016). Conventionally, bulk gels utilize high polymer and crosslinker concentrations to form strong gels in near-wellbore area. For conventional bulk gel technology, the high polymer and crosslinker concentrations commonly employed make it uneconomical to inject large volumes of gels to correct in-depth problems (Mack et al. 1994). Typical injected volumes range from a few hundred to tens of thousands of barrels (Munqith et al. 2016).

Near-wellbore treatments of matrix formations with bulk gels has been shown to be an effective means for achieving the total shutoff of selected formation intervals, and has been used to reduce both water and gas production. Near-wellbore treatments with bulk gels can also be used to modify the conformance of injected fluids where crossflow is not a consideration (Albonico et al. 1995).

2.2.2. Colloidal Dispersion Gels (CDGs). Colloidal dispersion gels are typically large volume, low polymer and crosslinker concentration gels designed to improve sweep efficiency in unfractured matrix reservoirs that exhibit poor water flooding performance. The gels involve low polymer and crosslinker concentration that make injection of large volumes of gels economical and allow in-depth placement and provide a solution to in-depth channeling and crossflow problems inherent with waterline, which cannot be solved by near-wellbore gels (Mack et al. 1994). The CDG injection solution properties are similar to a mobility polymer, imparting viscosity to the injection water and adsorbing to the reservoir rock (Norman et al. 1999).

2.2.3. Weak Gels. Munqith et al. (2016) indicated that weak gels are a subdivision of the bulk gel systems. Weak gels have low surface viscosities and long delayed gelation time and can penetrate deep into reservoir to form weak gels to plug high permeability zones under reservoir conditions and in the subsequent water flooding or chemical flooding, weak gels can be gradually pushed even deeper into the formation (Wang et al. 2003; Suleimanov and Veliyev 2016). Weak gels overcome the disadvantages of bulk gels, such as worse penetration and narrower plugging radius, and the disadvantages of CDGs, such as stronger flowing property and poor plugging and diverting properties (Wang et al. 2001). Weak gels are used in high-permeability or fractured reservoirs (Sheng, 2011). Weak gels function both as an IFD agent and an oil displacement agent simultaneously, and can effectively resolve the inter-layer conflicts caused by permeability contrast and improve mobility ratio (Wang et al., 2003).

2.3. MECHANISMS OF PROFILE CONTROL USING WEAK GELS

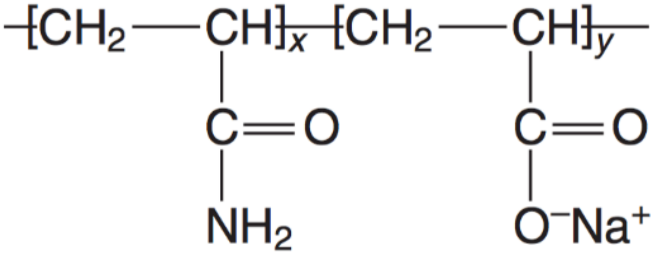
2.3.1. Profile Modification. The produced water from production wells is hardly avoidable in the development of water flooding. Profile control has been a very effective method in water flooding development to increase water injection efficiency and decrease produced water (Wang et al., 1995).

2.3.2. In-Depth Fluid Diversion. In heterogeneous reservoir, the permeability variation normally extends throughout the expanse of the reservoir, so large volumes of gels must be placed deep into the formation to correct in-depth permeability variation. If gels are placed near-well to correct in-depth permeability variation, subsequent injection fluid can bypass the gels via vertical crossflow (Mack et al., 1994).

2.4. GEL FORMULATIONS

2.4.1. Types of Polymers. In chemical EOR, various polymers have been studied such as partially hydrolyzed polyacrylamide (HPAM), hydrophobically associating polymer (AP), salinity tolerant KYPAM and 2-acrlamide-2-methyl propane-sulfonate co-polymer(AMPS) (Kumar et al. 2015).

2.4.1.1 HPAM. Partially hydrolyzed polyacrylamide (HPAM) is the most widely employed water-soluble polymer for use in both polymer water flooding and oilfield conformance polymer-gel treatments (Sydansk et al., 2011). Polyacrylamide absorbs strongly on mineral surface. Thus, the polymer is partially hydrolyzed to reduce adsorption by reacting polyacrylamide with a base, such as sodium or potassium hydroxide or sodium carbonate (Sheng, 2011). HPAM polymer is favored due to its low cost, its commercial availability, its viscosity-enhancing power in low-salinity brines, its normally good injectivity and its resistance to microbial degradation and is disfavored because its sensitivity to water salinity and hardness and its sensitivity to mechanical or shear degradation (Sydansk and Romero-Zeron, 2011). When HPAM is applied in reservoirs with high temperature and high salinity, its molecular structure is curly shaped, which results in a sudden drop in viscosity of the polymer solution (Zhao et al., 2004).The structure of HPAM is shown in Figure 2.2.



$$-\left[CH_2-\underset{\substack{|\\ C=O\\ |\\ NH_2}}{CH}\right]_x\left[CH_2-\underset{\substack{|\\ C=O\\ |\\ O^-Na^+}}{CH}\right]_y-$$

Figure 2.2. Structure of HPAM (Sheng 2011).

2.4.1.2 AP. Hydrophobically associating polymers have been developed for oil field applications (SNF, 2007). The term hydrophobically associating polymer is a broad classification (Glass, 2000) and it refers to water soluble polymers that have undergone some hydrophobic modification and special hydrophobic molecular groups are added into polymer chains so that a hydrophobically associating polymer contains one or more water-soluble monomers (acrylamides) and a small fraction (0.5-4%) of water-insoluble (hydrophobic) monomers (Sheng, 2011). Hydrophobically associating polymers possess a unique thickening mechanism and most are environmentally benign and polymer networks form in solution and consist of intra- and inter-molecular hydrophobic junctions (Tripathi et al., 2006). Thus, greater aqueous-phase viscosities result at the same concentrations as conventional polymers (Akatas et al. 2008). Therefore, associative polymers have the potential to reduce costs for enhanced oil recovery applications. These polymers, however, have not been tested widely in porous media. The structure of a typical hydrophobically associating polymer is shown in Figure 2.3.

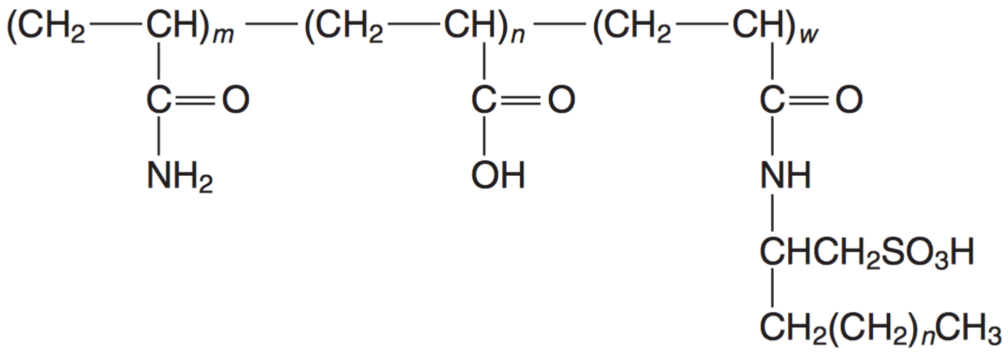


Figure 2.3. Structure of a typical hydrophobically associating polymer (Sheng 2011).

2.4.1.3 KYPAM. KYPAM is salinity-tolerant polyacrylamide and it can also be called comb-shape polyacrylamide. In KYPAM, as the new functional monomer aromatic hydrocarbon with ethylene is introduced, the side chains have both hydrophilic and hydrophobic groups. Because of the repulsion between the hydrophilic group, the hydrophobic group, and the repulsion among the hydrophilic groups, the side chains are arranged in a comb shape, stretching the flexible chains (Sheng, 2011). Sulphonate makes

AMPS capable good resistance of divalent and salinity in general and acrylamide gives AMPS thermal stability and resistance to hydrolysis, acid and alkaline (Sheng, 2015). Weak gels formed by KYPAM have better salt tolerance than weak gels formed by other polymers (Tang et al. 2005). Wang et al. (2006) indicates KYPAM provides high viscosity in brine water than that provided by conventional HPAM polymer. The structure of KYPAM is shown in Figure 2.4, where R_1, R_2, and R_3 could be either H or C_1-C_{12} alkyl, which mainly affect the elasticity of the polymer and A represents an ionic functional group that is tolerant to Ca^{2+} or Mg^{2+} (Sheng 2011).

2.4.1.4 AMPS copolymer. Polyacrylamide themselves are subject to thermal decomposition. However, AMPS unit can be added to the polymer to enhance thermal integrity (Holtsclaw and Funkhouser, 2010). Furthermore, calcium tolerance can be improved by using copolymers of AMPS. AMPS, 2-Acrylamide-2Methyl Propane-Sulfonate, has water-soluble anionic sulfonate, shielding acrylamide, and unsaturated double bond (Sheng 2011). The structure of the AMPS copolymer is shown in Figure 2.5.

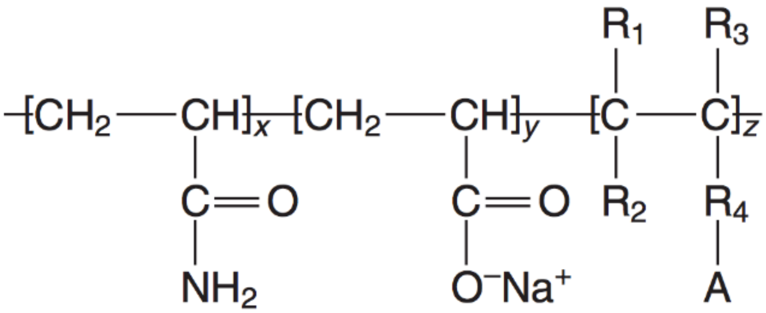


Figure 2.4. Structure of KYPAM (Sheng 2011).

2.4.2. Types of Crosslinkers. The rate at which a polymer solution undergoes gelation is controlled by the gelation chemistry. Two main types of crosslinkers, metal ions and organic systems (particularly phenol-formaldehyde) have been employed in the field with polyacrylamide and acrylamide copolymers (Albonico et at.1995). When metal ions are added to a polymer solution, a reaction occurs between the carboxyl group and the metal ion (Al-Assi et al. 2006). For high temperature applications, phenol-formaldehyde systems are used due to their good thermal stability.

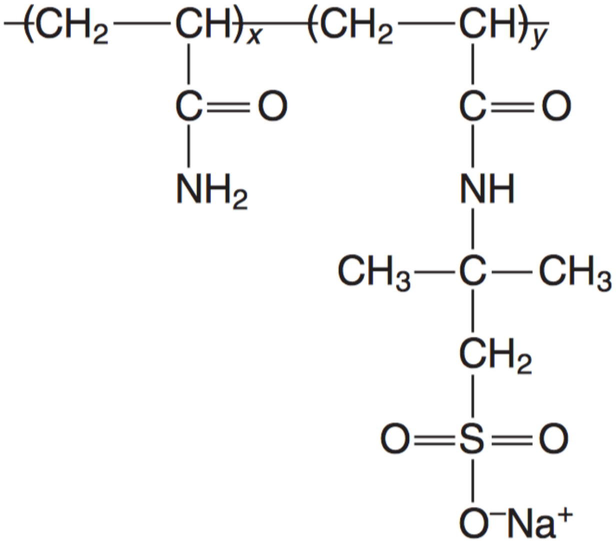


Figure 2.5. Structure of AMPS/AM copolymer (Sheng 2011).

2.4.2.1 Metal ion crosslinkers. Albonico et al. (1995) indicated Al(III) crosslinkers appear to be suitable only for low temperature applications due to their fast reaction with polymers. The crosslinking reaction is rapid if aluminum exists as a trivalent cation and the rapid crosslinking reaction make it difficult to be dispersed uniformly in polymer solution. However, by chelating the aluminum with citrate, in-depth penetration can be improved (Dovan et al 1987).

The crosslinking reactions in theses chromium(III) crosslinked polyacrylamide gel systems take place by the complexation of Cr(III) ions with carboxylate groups on the polymer chains (Reddy et al. 2002). The widely-employed Cr(III)-acetate crosslinker can provide gelation delays of up to a few hours at temperature as high as 70 °F. Bryant et al. (1998) indicated that Cr(III) acetate propagates very poorly in a porous matrix at elevated temperature.

Zirconium has been widely used in fracturing applications as a crosslinker. Zirconium can form a stable crosslinked fluid at pH levels from 3.5 to 10.5 and up to 350 °F (Alsaiari et al., 2016). Due to concerns over environmental effects of chromium crosslinkers, zirconium crosslinkers have been developed as alternative crosslinkers for gelation of polyacrylamide and the zirconium/polyacrylamide crosslinking systems possess good tolerance of high brine salinity and hardness (Moffitt et al., 1996). Both of increasing pH and adding sodium lactate result in a retardation of the crosslinking process. However, increasing pH does not change crosslink energy (Chauveteau et al., 1999). Titanium crosslinkers have also been developed due to environment concerns using chromium crosslinker.

2.4.2.2 Organic crosslinkers. A typical example of an organically crosslinked gel is the acrylamide-phenol/formaldehyde gel. It has been confirmed by Krilov et al. (1998) that the phenol-formaldehyde crosslinked polymer gelants possess good injectivity and the phenol-formaldehyde crosslinked polymer gels possess the best thermal stability. A phenol/formaldehyde polymer gel has been reported to be stable at 121 °C for 13.3 years (Al-Muntasheri et al. 2005). It has been confirmed by Krilov et al. (1998) that the phenol-formaldehyde crosslinked polymer gelants possess good injectivity and the phenol-formaldehyde crosslinked polymer gels possess the best thermal stability. Phenol-formaldehyde crosslinked polymer gels exhibit excellent stability at high temperature (60-140 °C) and insensitive to pH and the lithology of the porous media (Bryant et al. 1998).

However, gelation time is strongly influenced by temperature and nature of polymers (Albonico et al., 1995).

The partitioning of phenol into crude oil is found to be a significant issue for propagation of the gelants prepared by phenol-formaldehyde. However, the use of a phenol pre-flush of the formation can be a viable solution for the problem (Albonico et al., 1995).

3. DATA COLLECTION AND ANALYSIS

3.1. STATISTICAL ANALYSIS TOOLS

3.1.1. Bar Chart. A bar chart is a chart that displays grouped data with rectangular bars with heights proportional to the values that they represent. It is used for categorical variables to show comparisons among categories and can be plotted vertically or horizontally. Bars can be arranged in any order. An example of a bar chart is shown in Figure 3.1.

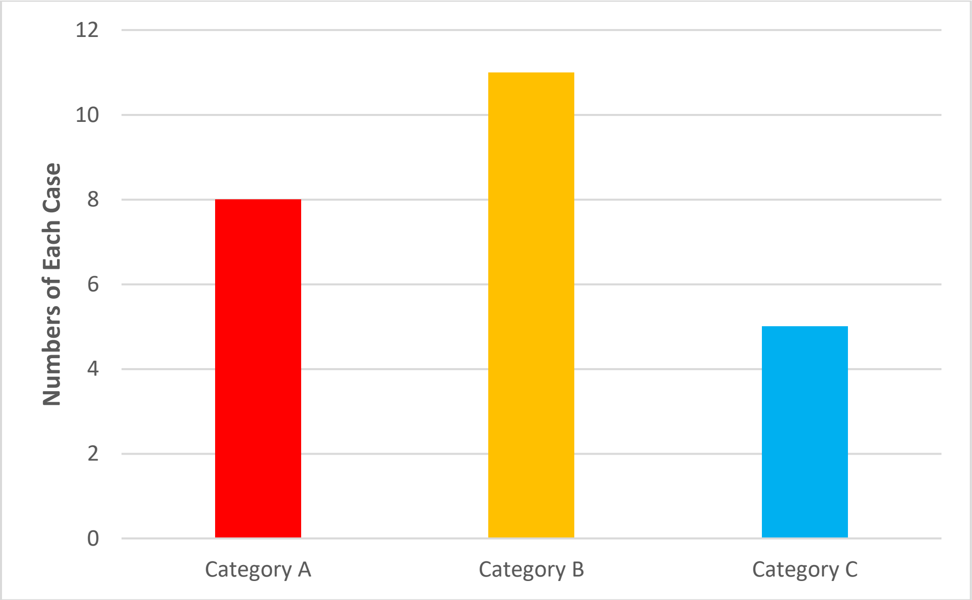


Figure 3.1. Example of a bar chart.

3.1.2. Histogram. A histogram is a particular type of bar chart that presents the frequency of occurrence of values. Histograms use what are called bins to collect values that are in given ranges. The heights of bins show the number of cases fall into each of the bins. The bins are usually specified as consecutive, non-overlapping intervals of a variable. The bins in a histogram need not be of the same width. But the bins must be adjacent. The disadvantage of using a histogram is that choice of number and width of bins can heavily influence the appearance of a histogram. An example of a histogram is shown in Figure 3.2.

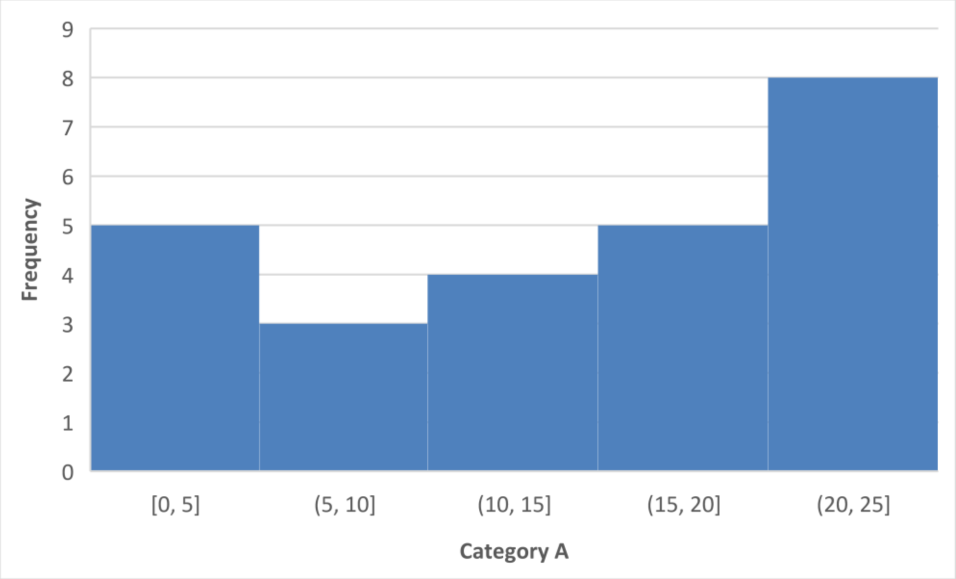


Figure 3.2. Example of a histogram.

3.1.3. Box Plot. A box plot is a quick way of graphically examining and depicting one or more sets of numerical data through their quartiles. The bottom and top of the box are the first and third quartiles and the line inside the box is the second quartile (the median). A box plot shows sample skewness if the median is not centered in the box. The distance between the top and bottom is the interquartile range, which is noted as IQR. The point inside the box represents the mean of the data. The upper limit and the lower limit are 1.5 times the interquartile range away from the top and bottom of the box, respectively. An outlier is a value that is above the upper limit or below the lower limit. A schematic of a box plot is shown in Figure 3.3.

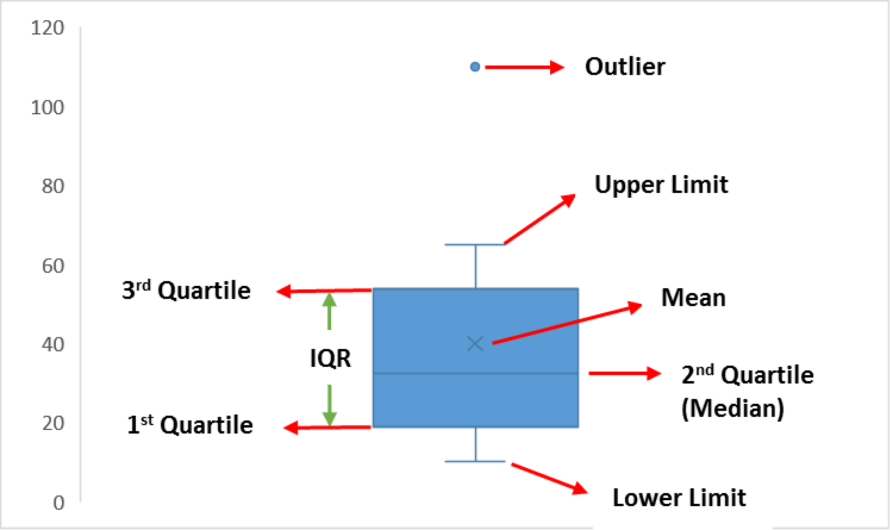


Figure 3.3. Schematic description of a box plot.

3.1.4. Scatter Plot. A scatter plot is a type of plot using Cartesian coordinates to display values of typically two variables for one or more sets of data. The data is displayed as a collection of points. The values of the variables of each point determine the position on the horizontal axis and vertical axis. An example of a scatter plot is shown in Figure 3.4.

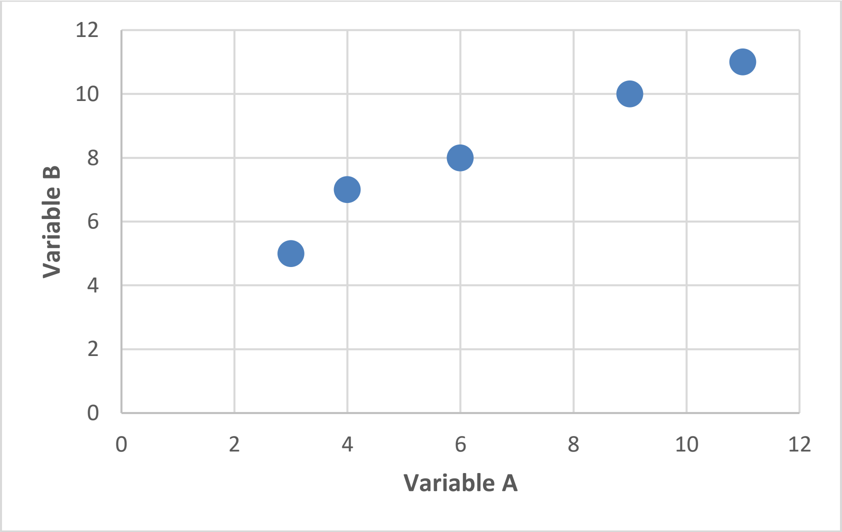


Figure 3.4. Example of a scatter plot.

3.2. DATA COLLETION

3.2.1. Data Resource. China has the largest amount of chemical-based conformance control treatments and a series of new technologies have been successfully developed and deployed in recent years (Liu et al.,2006). This research is based on the projects reported in China Academic Journals Full-text Database from 2001 to 2010. The database is the largest and continuously updated Chinese journal database in the world, focuses on academy, technology, policy guidance, popular science and education journals and covers science, engineering technology, agriculture, philosophy, medicine, humanities, and social sciences, etc.

3.2.2. Dataset Description. The data set consists of the data collected from 76 field applications and laboratory experiments conducted from 2001 to 2010. Totally, there are 31 field applications conducted for evaluating gel properties and 45 laboratory experiments conducted for studying the feasibility of applying weak gel treatment for a certain oil field based on the reservoir properties and gel formulations. The parameters collected and analyzed include reservoir properties, gel proprieties and production data. The reservoir properties include porosity, permeability, temperature, net thickness, depth, water salinity, divalent cation concentration, PH, Dykstra-Parsons Coefficient, and oil viscosity. Gel properties include polymer type, polymer concentration, polymer molecular weight, polymer degree of hydrolysis, crosslinker type, crosslinker concentration and injected PV. Production data includes oil recovery before treatment, water cut before treatment, water cut after treatment and water cut decrease. Table 3.1 shows the parameters collected and analyzed in the research. The blanks in Table 3.1 indicate that those data are not available, because those data are field data.

Table 3.1. Parameters collected and analyzed in the research.

Type	Parameter	Lab	Field
Reservoir Properties	Porosity	X	X
	Permeability	X	X
	Temperature	X	X
	Net Thickness		X
	Depth		X
	Salinity	X	X
	Divalent Cation Concentration	X	X
	pH	X	X
	Dykstra-Parsons Coefficients		X
	Oil Viscosity	X	X
Gel Properties	Polymer Type	X	X
	Concentration	X	X
	Molecular Weight	X	X
	Hydrolysis Degree	X	X
	Crosslinker Type	X	X
	Crosslinker Concentration	X	X
	Injected PV	X	X
Production Data	Oil Recovery Before Treatment	X	X
	Water Cut Before Treatment		X
	Water Cut After Treatment		X
	Water Cut Decrease		X

3.2.2.1 Types of projects. Figure 3.5 shows the types of projects. In this research, data from 45 laboratory experiments and 31 field applications are collected to display the distributions of reservoir and oil properties, gel properties and production data, which give a significant guidance in designing a new weal gel treatment project in the future.

3.2.2.2 Numbers of projects in each year. Numbers of laboratory experiments and field applications collected in each year are shown in Figure 3.6.

3.2.2.3 Numbers of field applications in each oilfield. Figure 3.7 shows the numbers of field applications in each oilfield in China. From Figure 3.7, it shows that there are more applications in Liaohe oilfield reported compared to other oilfields in China.

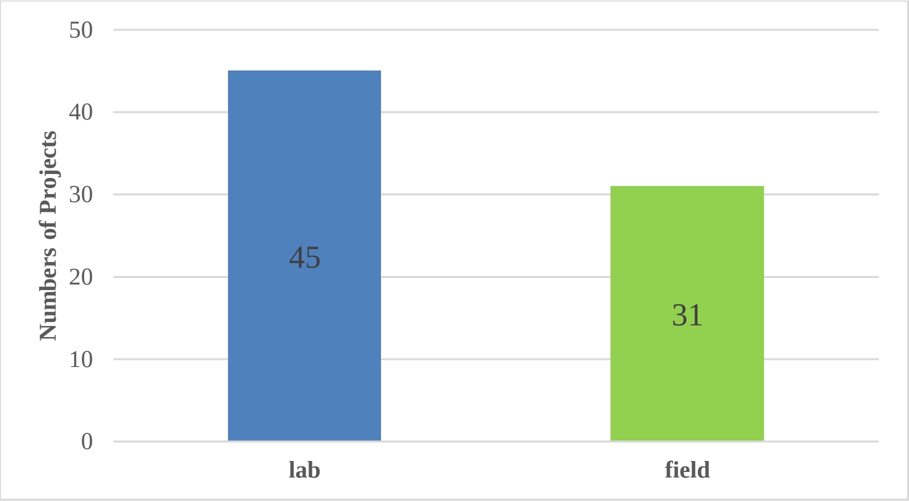


Figure 3.5. Types of projects.

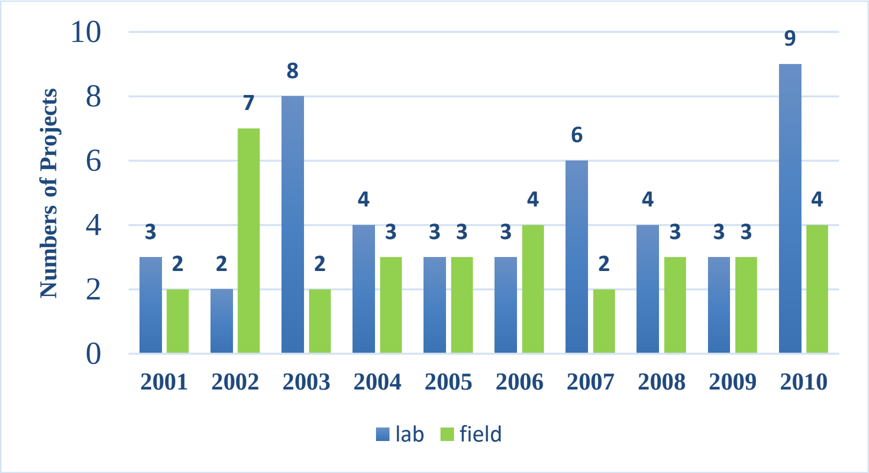


Figure 3.6. Numbers of laboratory experiments and field applications in each year.

3.3. DATA DISPLAY AND ANALYSIS

3.3.1. Porosity. Statistical analysis of porosity laboratory data and field data are illustrated in this part, where the range and distribution of porosity data are shown.

3.3.1.1 Porosity of laboratory data. A box plot and histogram are generated to display the distribution of porosity laboratory data, which are shown in Figure 3.8.

The maximum of porosity lab data is 31.8%, the minimum is 16.4%, the median is 25.1% and the mean is 25.1%. Figure 3.8 (B) shows that the porosity laboratory data in the intervals of 20-25% and 25-30% have the highest frequency. Most porosity laboratory data fall into the range of 20-30 %.

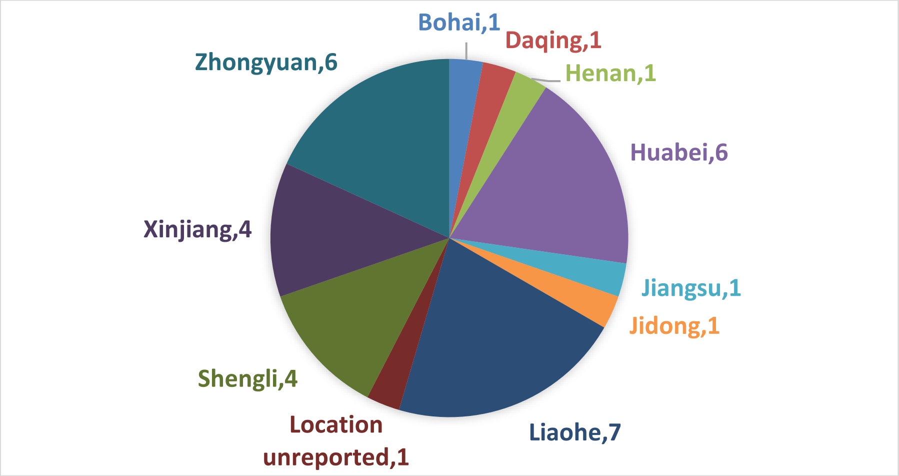


Figure 3.7. Numbers of field applications in each oilfield.

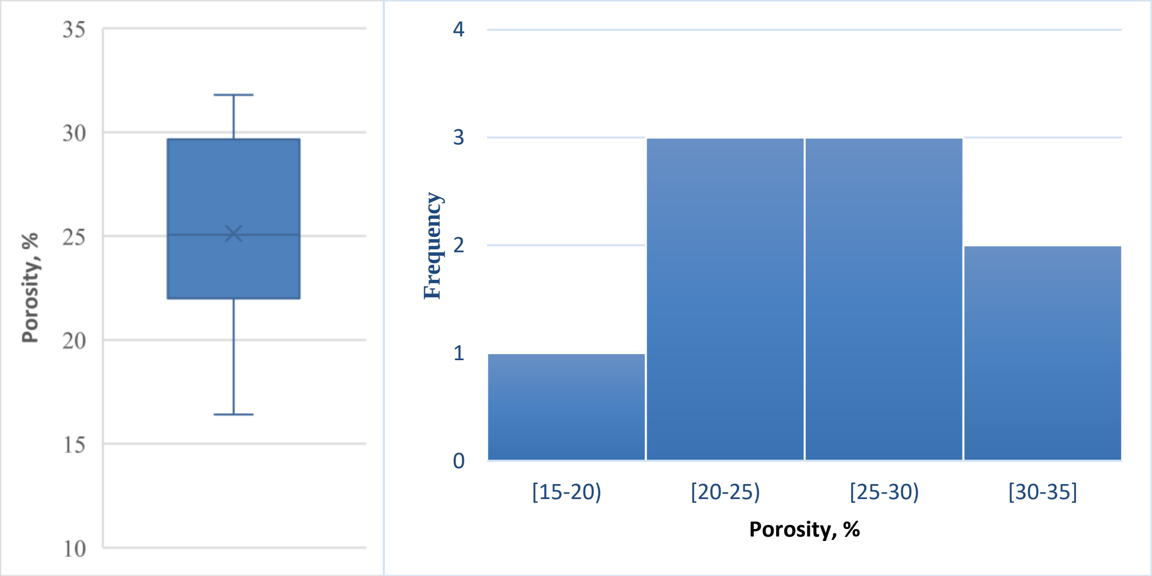


Figure 3.8. Box plot (A) and histogram (B) of porosity laboratory data.

3.3.1.2 Porosity of field data. The box plot and histogram of porosity are generated to depict the distributions of porosity laboratory data and are shown in Figure 3.9.

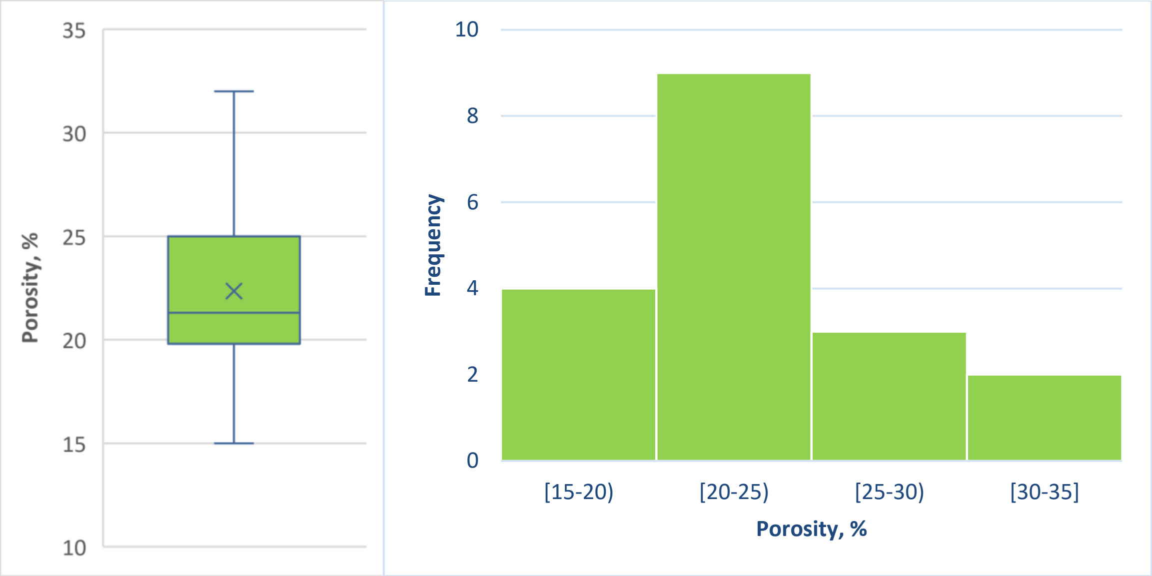


Figure 3.9. Box plot (A) and histogram (B) of porosity field data.

The minimum of porosity field data is 15 % and the maximum is 32 %. The median is 21.3 % and the mean is 22.4%. Figure 3.9 (B) displays that the porosity field data in the range of 20-25 % have the highest frequency.

3.3.2. Permeability. Statistical analysis of permeability laboratory data and field data are illustrated in this part.

3.3.2.1 Permeability of laboratory data. A box plot and frequency histogram of permeability laboratory data are shown in Figure 3.10.

The maximum observation of the permeability laboratory data is 2100 md and the minimum observation is 51 md. The median is 955 md and the mean is 822.5 md. Figure 3.10 (B) displays that the permeability laboratory data in the interval of 1000-1500md have the highest frequency. Most permeability laboratory data fall into the range of 0-1500 md. It means most laboratory works used cores with permeability in the range of 0-1500 md.

3.3.2.2 Permeability of field data. A box plot and frequency histogram of permeability field data are shown in Figure 3.11.

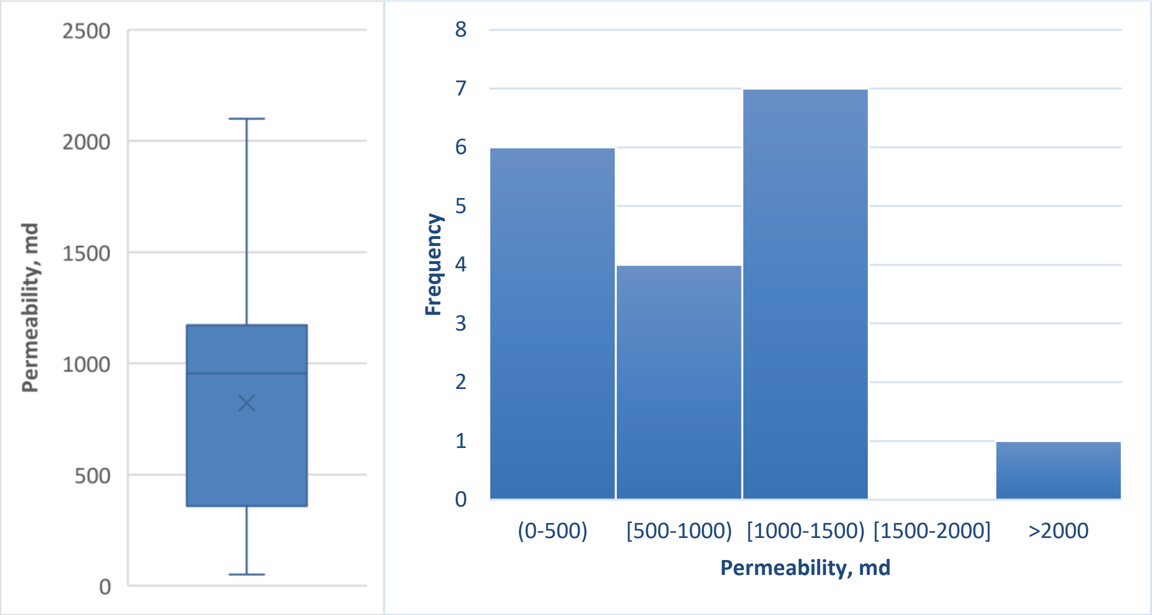


Figure 3.10. Box plot (A) and histogram (B) of permeability laboratory data.

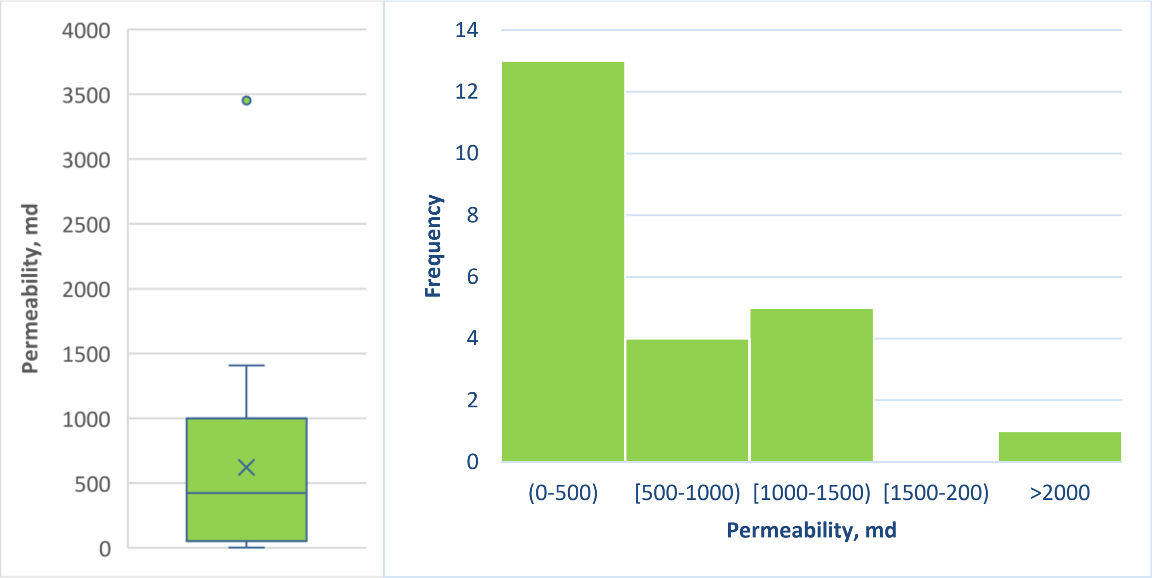


Figure 3.11. Box plot (A) and histogram (B) of permeability field data.

Using the box plot to display the distribution of permeability field data, a special case is detected, which is shown in Figure 3.11 (A). The special case comes from a pilot test in the Bohai SZ-1 oilfield, which is an offshore oilfield in China. The formation was unconsolidated and poorly cemented and gravel packing was completed. The average permeability was 3452 md and the oil viscosity varied from 13-380 cp, with an average of 70 cp. Seawater with a TDS of 32,423 mg/l was injected. This pilot test used the comb-shape polymer KYPAM, which is salinity-tolerant polyacrylamide and can be used to deal with high salinity environments. The average polymer concentration was 2250 mg/l and phenol-formaldehyde was used as crosslinker with a concentration of 450 mg/l.

The range of the permeability field data is from 2.2 to 3452 md. The median is 424 md and the mean is 621.9 md. Also, it indicates weak gel treatments can be applied in reservoirs with low permeability. The permeability can be lower than 20 md.

Figure 3.11 (B) displays a right-skewed distribution. And it indicates the field applications conducted in reservoirs with permeability in the range of 0-500 md have the highest frequency. Furthermore, the histogram of the permeability field data also illustrated most permeability data fall into the range of 0-1500 md.

3.3.3. Temperature. High temperature results in fast crosslinking reaction and low temperature results in low gel strength.

3.3.3.1 Temperature of laboratory data. The box plot and histogram of temperature laboratory data are presented in Figure 3.12.

The temperature laboratory data start from 68 °F to 230 °F. The median of temperature laboratory data is 158 °F and the mean is 148 °F. Tang et al. (2005) suggests that the polymer gels are very sensitive to temperature. When the temperatures are very low for crosslinking reactions, it’s very hard to acquire the gel strength required and the gels formed will be too weak. So, even though very high temperature is not favorable for weak gel treatments, very low temperature is also not desired. Figure 3.12 (B) illustrates the temperature laboratory data in the intervals of 140-160 °F and 160-180 °F have the highest frequency. Furthermore, it indicates weak gels have been applied in high temperature environments with temperatures higher than 200 °F.

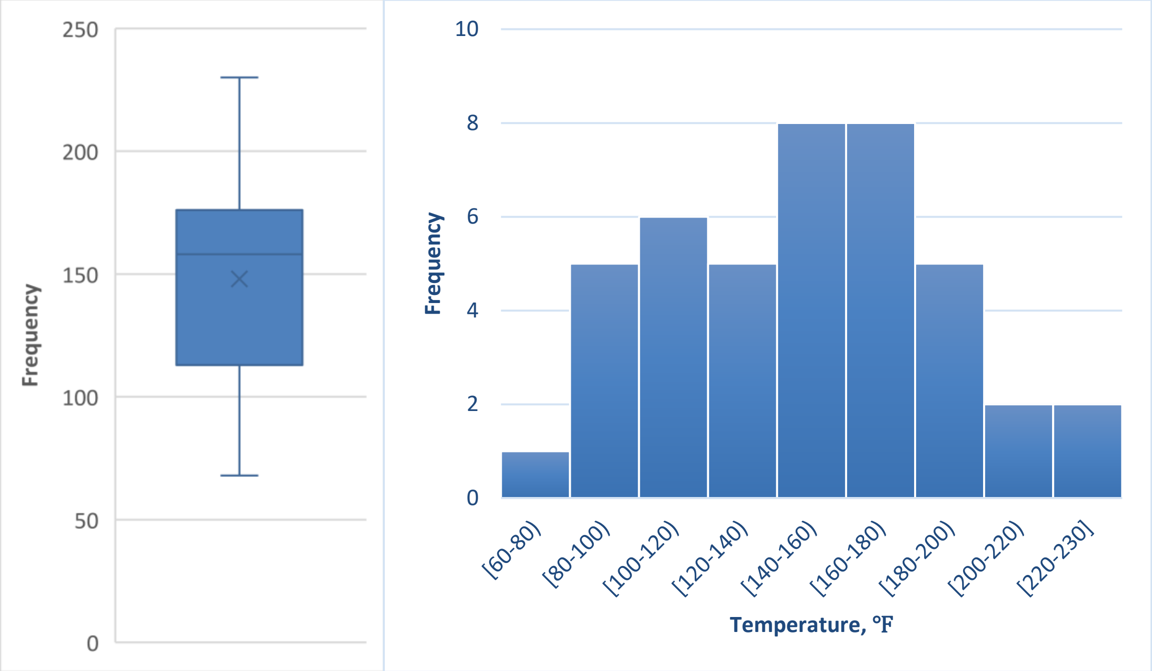


Figure 3.12. Box plot (A) and histogram (B) of temperature laboratory data.

3.3.3.2 Temperature of field data. The box plot and histogram of temperature field data are illustrated in Figure 3.13.

The temperature field data fall into the range of 100.4-237.2 °F. The median is 159.1 °F and the mean is 165.1 °F. Figure 3.13 (B) illustrates the temperature filed data fall into the interval of 140-160 °F have the highest frequency. It also shows weak gels have been applied in high temperature reservoirs with temperatures higher than 200 °F.

3.3.4. Reservoir Net Thickness. Statistical analysis of reservoir net thickness data is illustrated in this part and the box plot and histogram of reservoir net thickness data are illustrated in Figure 3.14.

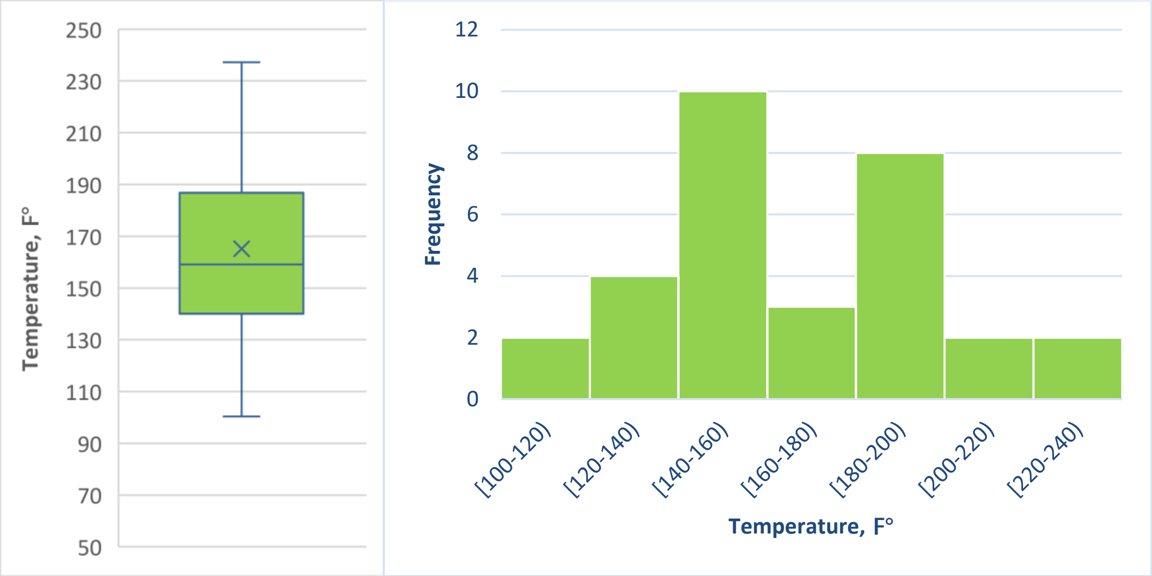


Figure 3.13. Box plot (A) and histogram (B) of temperature field data.

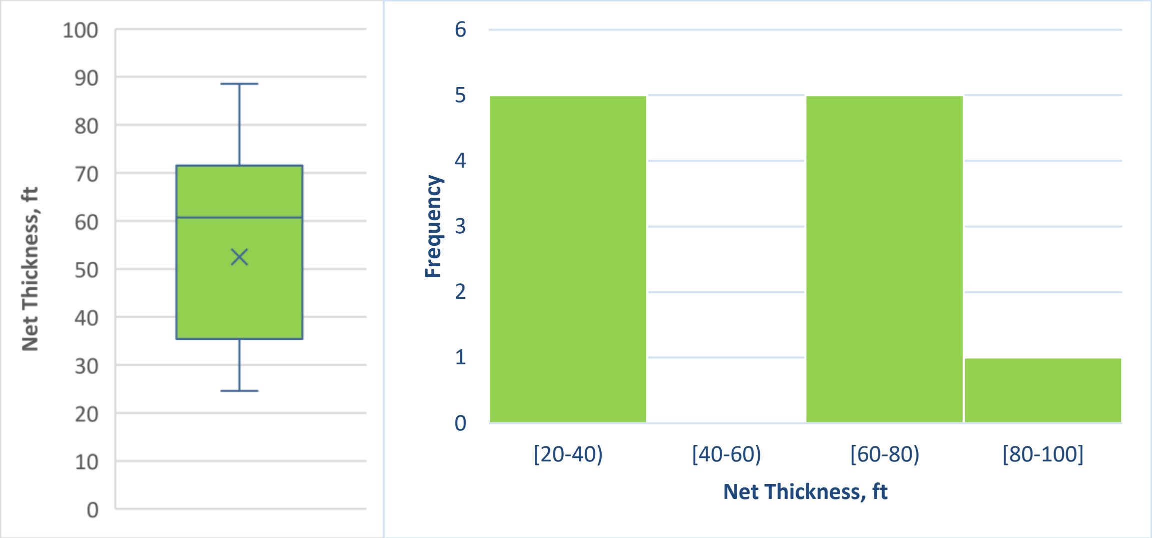


Figure 3.14. Box plot (A) and histogram (B) of reservoir net thickness.

The minimum of reservoir net thickness is 24.6 ft and the maximum is 88.6 ft. The mean is 52.5 ft and the median is 60.7 ft. Figure 3.14 (B) shows that most net thickness data fall into the intervals of 20-40 ft and 60-80 ft.

3.3.5. Reservoir Depth. Statistical analysis of reservoir depth data is illustrated in this part and the box plot and histogram of reservoir depth are illustrated in Figure 3.15.

The reservoir depth falls into a wide range of 1640.4-9406.2 ft. The mean of reservoir depth is 5843.7 ft and the median is 5905.5 ft. Figure 3.15(B) indicates that the reservoir depth data in the intervals of 4000-5000 ft and 5000-6000 ft have the highest frequency and about 79% of reservoir depth data fall into the range of 4000-8000 ft. Also, weak gel treatments can be applied for both shallow and deep reservoirs.

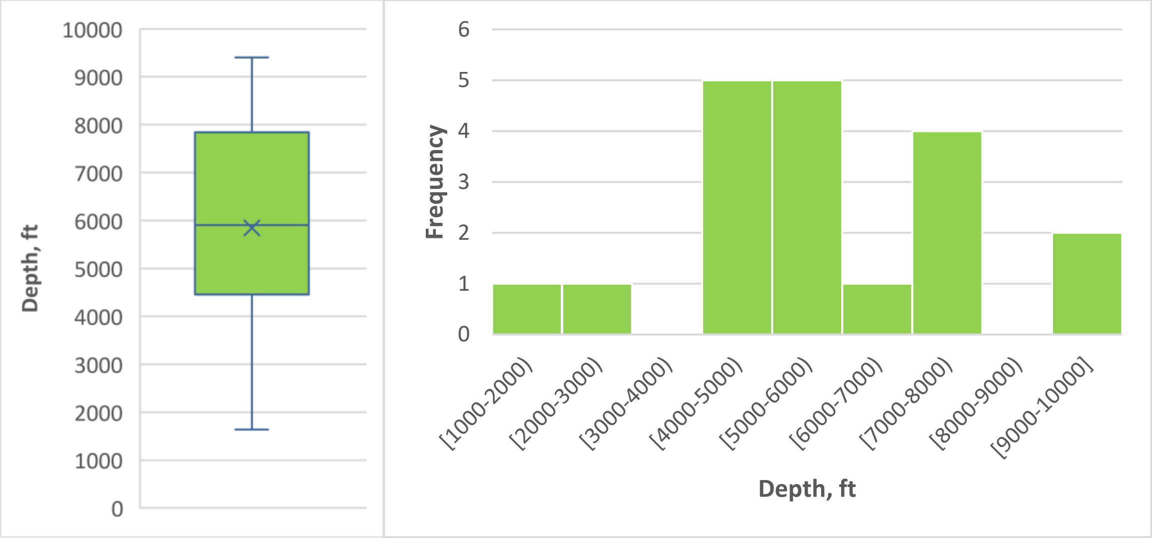


Figure 3.15. Box plot (A) and histogram (B) of reservoir depth.

3.3.6. Water Salinity. Statistical analysis of water salinity laboratory data and field data are illustrated in this part, where the range and distribution of water salinity data are shown.

3.3.6.1 Water salinity of laboratory data. The box plot and histogram of water salinity of laboratory data are illustrated in Figure 3.16.

Figure 3.16 (A) shows that special cases are detected. Zhang et al. (2003) reported using their own product, JCH-M, as crosslinking promoter to control the gelation time of HPAM/phenol-formaldehyde weak gel system at the salinity of 160,000 mg/l and 194 °F. They indicated that the gelation time of phenol-formaldehyde based gelant system should be between 1 and 200 hours and should be controllable as well. And under high salinity condition, the gelation time should be less than 100 hours in regarding to gel stability concern. Because of high temperature and salinity condition, which caused long gelation time of HPAM/PF system, crosslinking promoter was added to decrease the gelation time. Chen et al. (2003) conducted the research on the factors that influence the behaviors of polymer weak gels in high salinity condition and found out that 1200 mg/l AMPS terpolymer crosslinking with 1000 mg/l phenol-formaldehyde crosslinker has better performance than other formulations using HPAMs in the high salinity condition with a TDS of 110,000 mg/l and a divalent cation concentration of 3000 mg/l. 200 mg/l thiourea was added as deoxidizer. The temperature was 167 °F. Chen et al. (2003) conducted another research with the proposed formulation (1200mg/l AMPS terpolymer+1000 mg/l phenol-formaldehyde crosslinker) on the influence of metallic ions and total salinity on weak gels and observed that forming the weak gels using saline water that has salinities of 3300-110,000 mg/l and divalent cation concentrations of 900-3000 mg/l have better stability than using fresh water. Chen et al. (2008) reported using AMPS terpolymer with a concentration of 1500 mg/l to crosslink with phenol-formaldehyde (PF) crosslinker with a concentration of 1200 mg/l at a salinity of 100,000 mg/l and temperature of 185 °F. and indicated that low salinity is not favorable for forming the weak gel based on that research.

The maximum of the available water salinity laboratory data is 160,000 mg/l and the minimum observation is 991.1 mg/l. The mean of water salinity laboratory data is 24442.5 mg/l and median is 8432 mg/l.

Figure 3.16 (B) displays a right-skewed distribution and it shows that 70% of water salinity laboratory data fall into the interval of 0-20000 mg/l. Most laboratory experiments are conducted under low salinity environments. It also indicates weak gel treatments can be used in reservoirs with high salinity environments.

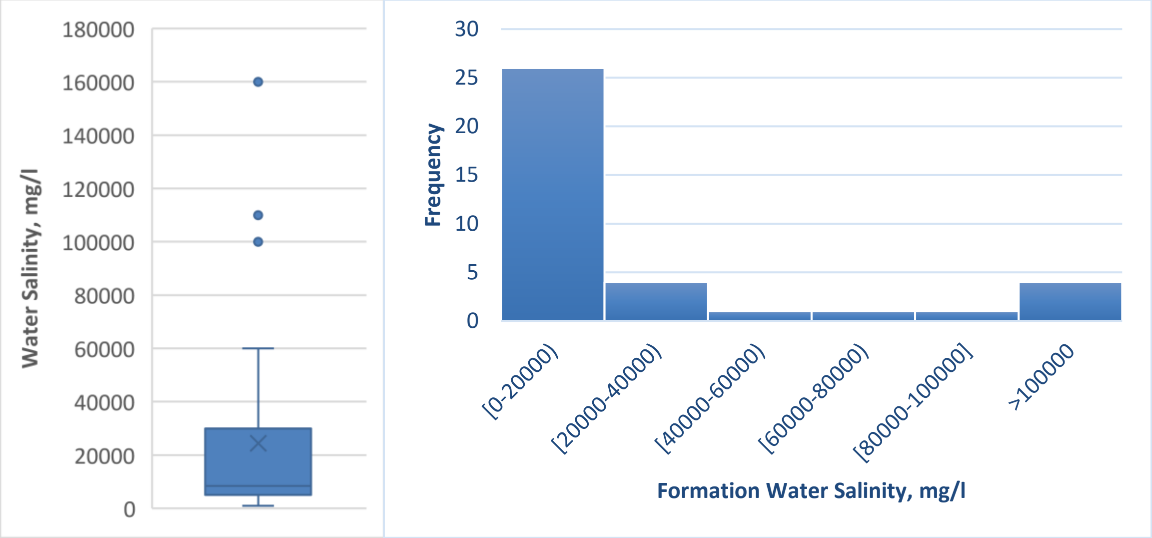


Figure 3.16. Box plot (A) and histogram (B) of water salinity laboratory data.

3.3.6.2 Water salinity of field data. The box plot and histogram of water salinity field data are displayed in Figure 3.17.

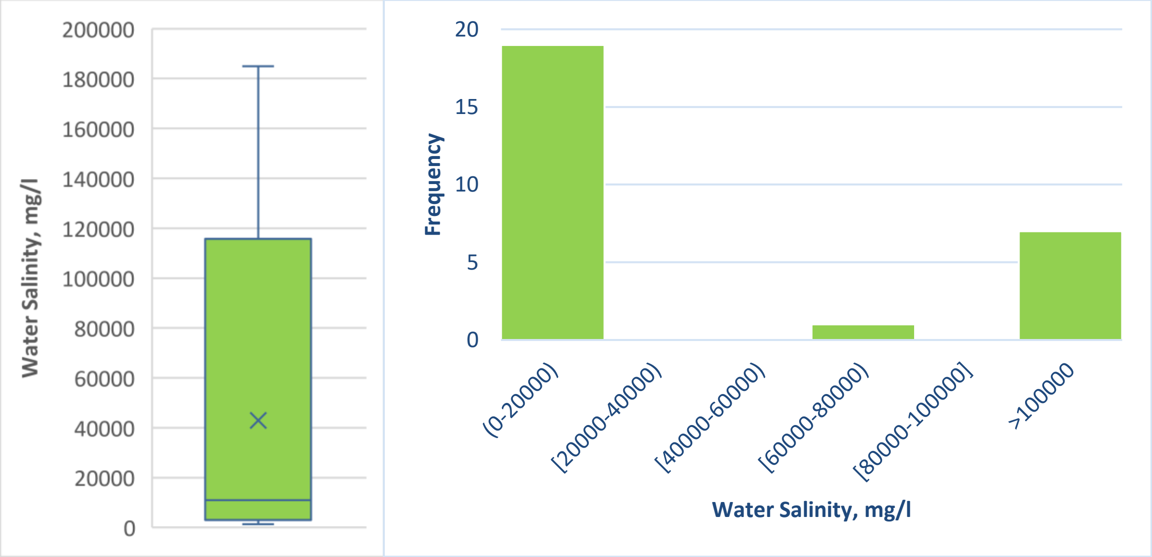


Figure 3.17. Box plot (A) and histogram (B) of water salinity field data.

3.3.7. Divalent Cation Concentration. Statistical analysis of divalent cation concentration data and field data are illustrated in this part, where the range and distribution of divalent cation concentration data are shown.

3.3.7.1 Divalent cation concentration of laboratory data. The box plot and histogram of divalent cation concentration laboratory data are illustrated in Figure 3.18.

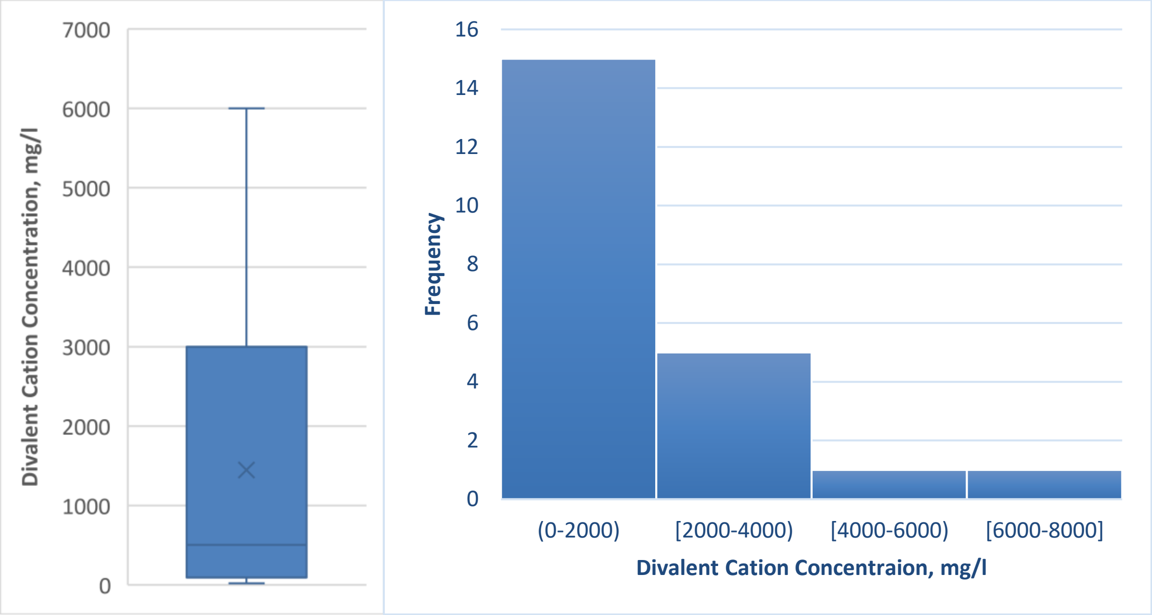


Figure 3.18. Box plot (A) and histogram (B) of divalent cation concentration lab data.

Divalent cations also affect the performance of the weak gels. Albonico et al. (1993) suggests that for polymer gels, significant polymer hydrolysis in the presence of divalent cations leads to syneresis. Severe syneresis can lead to a reduction of 90% or more of the original gel volume, can have a significant impact of a gel within porous reservoir rock.

The maximum of divalent cation concentration laboratory data is 6000 mg/l and the minimum is 22.7 mg/l. The median is 506 mg/l and the mean is 1446.4 mg/l. Figure 3.18 (B) displays a right-skewed distribution. Most divalent cation concentration data fall into the interval of 0-2000 mg/l. It indicates that low divalent cation concentration is preferable for weak get treatments.

3.3.7.2 Divalent cation concentration of field data. The box plot and histogram of divalent cation concentration field data are illustrated in Figure 3.19.

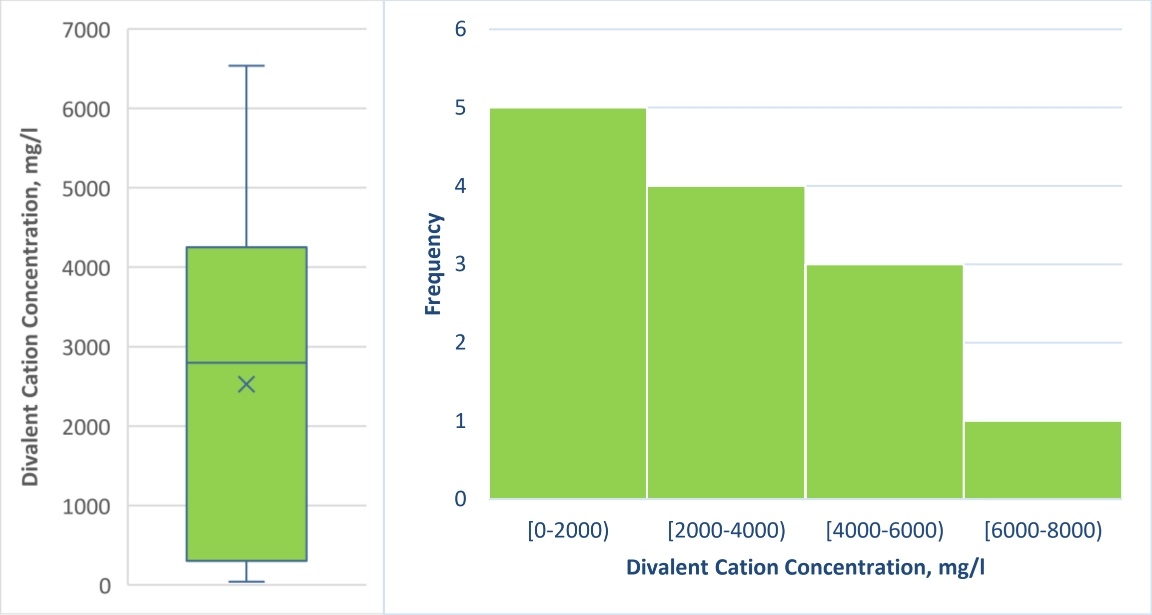


Figure 3.19. Box plot (A) and histogram (B) of divalent cation concentration field data.

The maximum of divalent cation concentration field data is 6535 mg/l and the minimum is 39.4 mg/l. The median is 2796.5 mg/l and the mean is 2528.1 mg/l.

Figure 3.19 (B) displays a right-skewed distribution as well. It shows that the divalent cation concentration field data in the interval of 0-2000 mg/l have the highest frequency.

3.3.8. pH. It has been indicated that the pH has an obvious effect on the viscosity of polymer solutions, which affects the properties and performance of weak gels. Levitt et al. (2008) indicates the kinetics of hydrolysis of polymers are a strong function of pH. Zhao et al. (2004) indicated that pH value of AP systems has an obvious effect on the viscosity of the polymer solution.

3.3.8.1 pH of laboratory data. The box plot and histogram of pH laboratory data are illustrated in Figure 3.20.

The pH of laboratory data is in the range is 6-7.5. The mean of pH laboratory data is 6.8 and the median is 7. Figure 3.20 (B) displays that the pH of 7 is the highest frequency for the laboratory data.

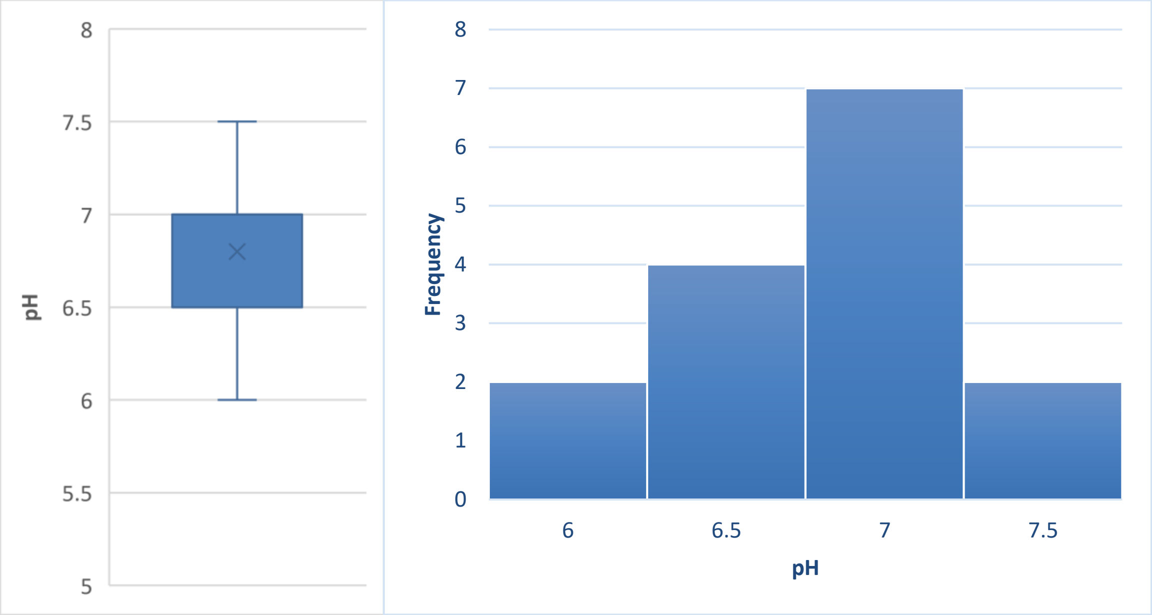


Figure 3.20. Box plot (A) and histogram (B) of pH laboratory data.

3.3.8.2 pH of field data. The box plot and histogram of pH field data are illustrated in Figure 3.21.

The maximum observation of pH field data is 8.5 and the minimum observation of pH field data is 5.5. The mean of pH field data is 7.1 and the median is 7. Figure 3.21 (B) displays that most pH field data fall into the range of 6.5-7.5.

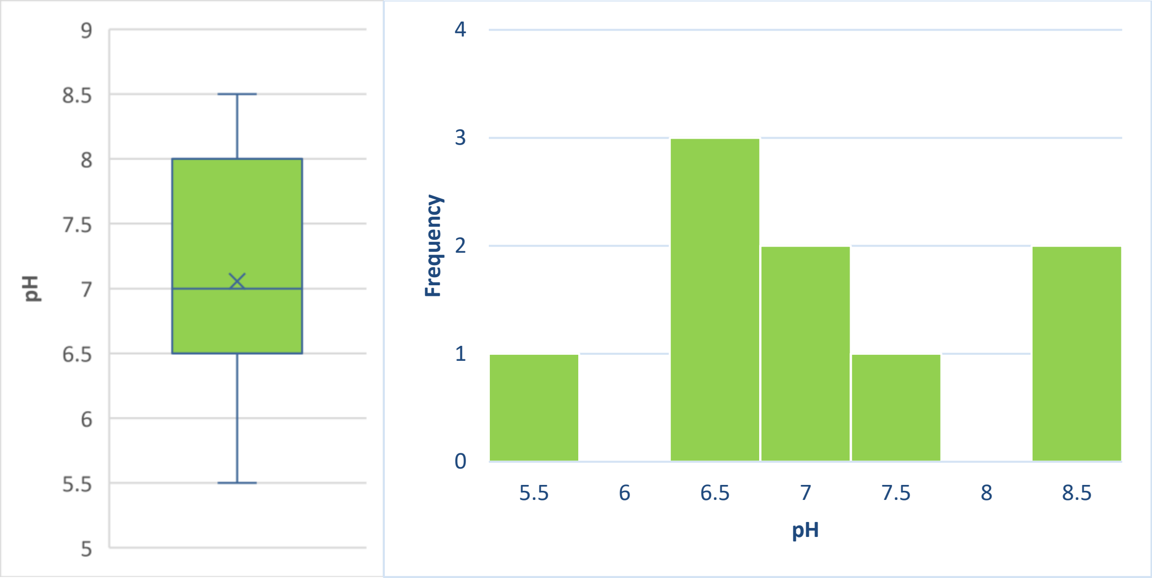


Figure 3.21. Box plot (A) and histogram (B) of pH field data.

3.3.9. Dykstra-Parsons Coefficient. Dykstra-Parsons coefficient of permeability variation is used to describe the vertical permeability variations of reservoirs. The box plot and histogram of Dykstra-Parsons coefficient are illustrated in Figure 3.22.

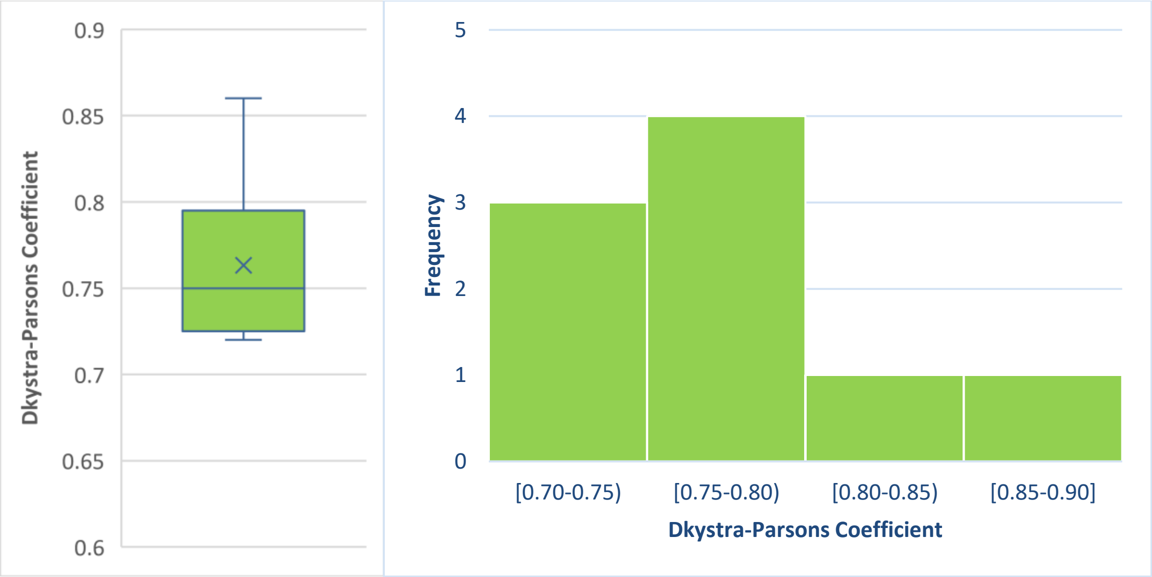


Figure 3.22. Box plot (A) and histogram (B) of DP coefficient.

The maximum observation of Dykstra-Parsons coefficient is 0.86 and the minimum observation is 0.72. The mean of Dykstra-Parsons coefficient is 0.76 and the median is 0.75. Figure 3.22 (B) displays that most Dykstra-Parsons coefficient are in the range of 0.7-0.8. The Dykstra-Parsons coefficient data in the interval of 0.75-0.80 have the highest frequency.

3.3.10. Oil Viscosity. Statistical analysis of oil viscosity data and field data are illustrated in this part, where the range and distribution of oil viscosity data are shown.

3.3.10.1 Oil viscosity of lab data. The box plot and histogram of oil viscosity laboratory data are displayed in Figure 3.23.

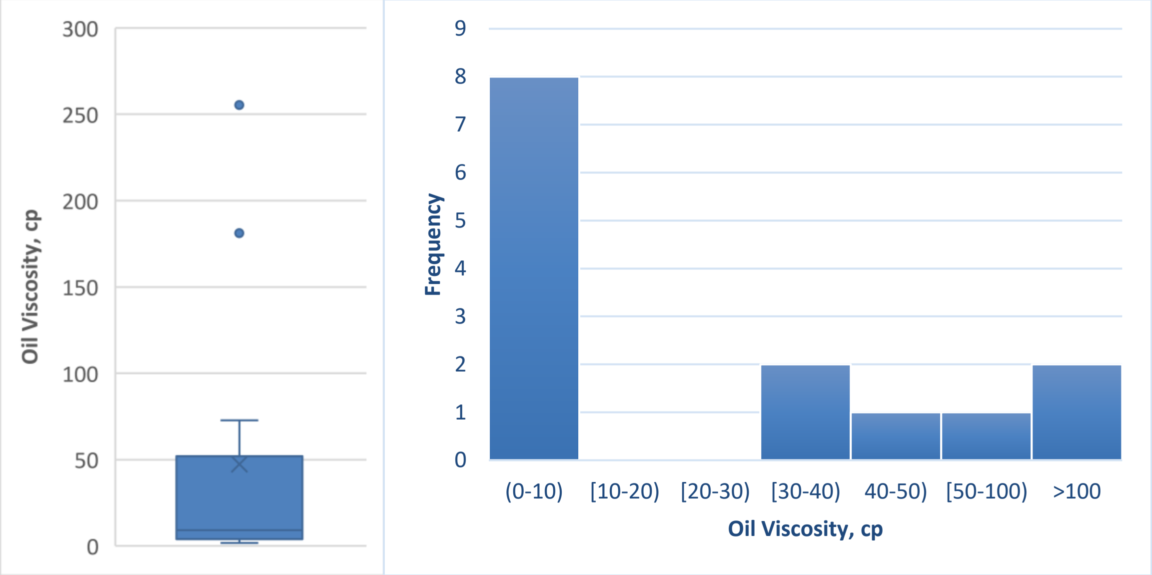


Figure 3.23. Box plot (A) and histogram (B) of oil viscosity laboratory data.

It can be seen from Figure 3.23 (A) that two special cases are detected. Ren et al. (2007) did the research on the selection of movable gel system using the heavy oil with a viscosity of 255.4 cp at 100.4 °F. Different polymer concentrations and different crosslinkers were compared. The proposed weak gel system was made of 800 mg/l HPAM and 17.8 mg/l chromium crosslinker. The tested core permeability was 639 md and 0.3 PV of the weak gel was injected. Zhang et al. (2009) conducted a laboratory study on enhancing oil displacement efficiency of heavy oil using chromium gel system. The oil viscosity was 181.2 cp at 123.8 °F and the water salinity was 2813 mg/l. The core permeability was 535 md and the porosity was 25.4%. A total of 0.3 PV of the weak gel was injected. The weak gel was made of 1000 mg/l HPAM that has 2×10^7 molecular weight and 500 mg/l chromium crosslinker.

Figure 3.23 (A) also shows that weal gels have been applied for heavy oil. The minimum oil viscosity lab data is 1.7 cp and the maximum oil viscosity is 255.4 cp. The median of oil viscosity lab data is 9.1 cp and the mean of oil viscosity is 47.3 cp. Figure 3.23 (B) shows that the oil viscosity lab data in the interval of 0-10 cp have the highest frequency.

3.3.10.2 Oil viscosity of field data. The box plot and histogram of oil viscosity field data are illustrated in Figure 3.24.

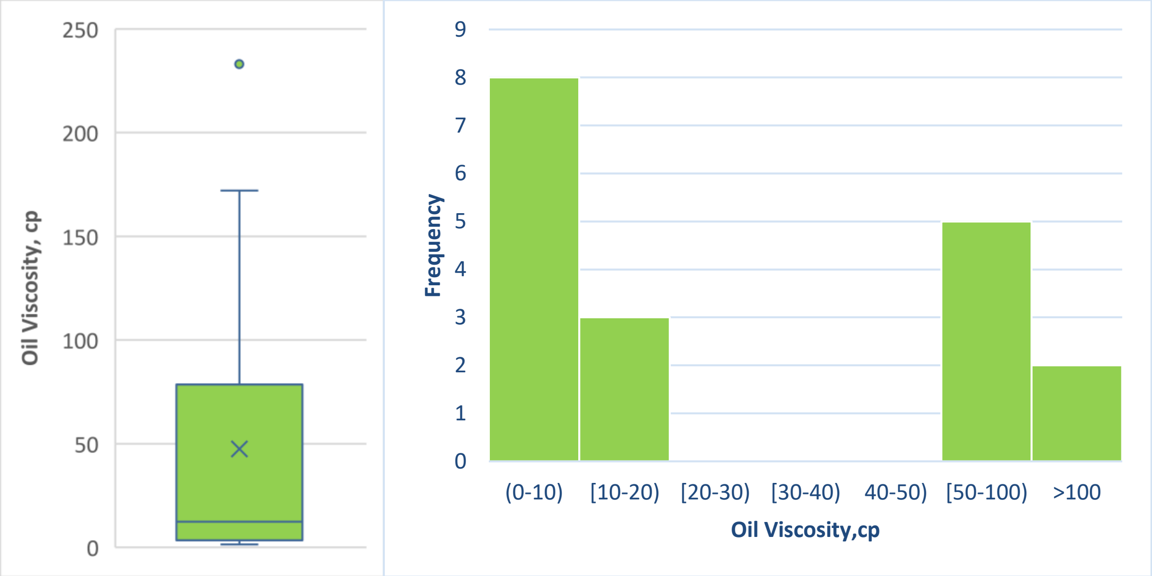


Figure 3.24. Box plot (A) and histogram (B) of oil viscosity field data.

Figure 3.24 (A) displays that a special case is detected. Du et al. (2008) conducted the research on application of movable gel in conventional heavy oil reservoirs. Based on Menggulin field properties, the weak gel system was selected. The weak gel was made of 1000 mg/l HPAM with 16.5% degree of hydrolysis and 40 mg/l chromium crosslinker. The average reservoir depth was 2657.5 ft, the reservoir temperature was 100.4 ℉, the oil viscosity was 233 cp at the formation water salinity was 1301 mg/l. A total of 0.08 PV of the weak gel was injected.

Figure 3.24 (B) also shows that weak gels have been applied to heavy oil reservoirs. The maximum value of oil viscosity field data is 233 cp and the minimum value is 1.4 cp. The median of oil viscosity field data is 12.4 cp and the mean is 47.5 cp. Figure 3.24 (B) also indicates that oil viscosity in the interval of 0-10 cp have the highest frequency.

3.3.11. Polymer Type and Concentration. In this part, polymers that are commonly used in weak gel treatments are studied and range and distribution of polymer concentration are illustrated.

3.3.11.1 Polymer type and concentration of lab data. The box plot and histogram of polymer concentration and the bar chart of types of polymers of lab experiments are illustrated in Figure 3.25 and polymer type and polymer concentration of laboratory experiments are shown in Figure 3.26.

Figure 3.25 (A) displays that two special cases are detected. Wang et al. (2001) reported choosing 2500 mg/l KYPAM with a molecular weight of 9.5×106 and a degree of hydrolysis of 10% among different polymer products to crosslink with chromium crosslinker. Changqing oilfield produced water was used, which had a salinity of 40,000 mg/l and a divalent cation concentration of 6000 mg/l. The weak gel formed using KYPAM had a better stability at the temperature of 149 °F than using other HPAM products. Zhang (2007) studied the effect of polymer concentration, pH and temperature on gel stability using HPAM with the molecular weight of 1.2×10^7 and the degree of hydrolysis of 20% crosslinking with phenol-formaldehyde. Orthogonal array test was used and found out the optimal gel formulation with 3000 mg/l HPAM and 450 mg/l phenol-formaldehyde. The temperature was 176 °F and the core permeability was 988 md. The gel stability was tested at 113 over 10 months and the viscosity only decreased 20%.

The maximum polymer concentration of lab data is 3000 mg/l and the minimum polymer concentration is 600 mg/l. The median polymer concentration of lab data is 1200 mg/l and the mean is 1279.6 mg/l.

From 3.25 (B) displays a left-skewed distribution. The polymer concentration lab data in the interval of 1000-1500 mg/l have the highest frequency. And the polymer concentrations that most lab works chose are from 600-2000 mg/l.

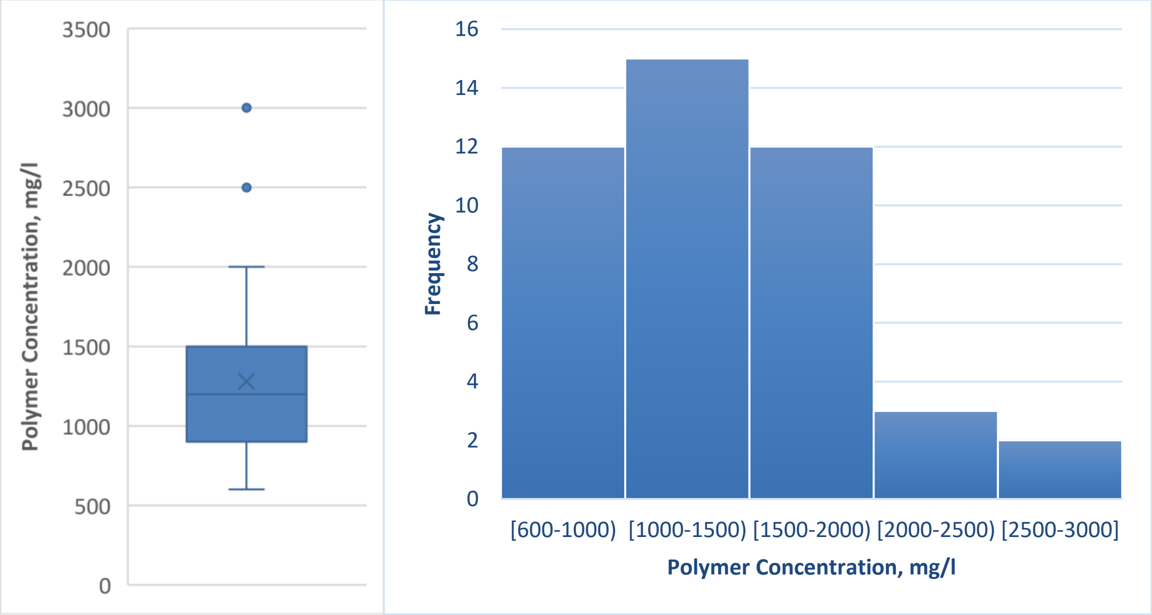


Figure 3.25. Box plot (A) and histogram (B) of polymer concentration laboratory data.

It can be seen from Figure 3.26 (A), four types of polymers have been used for lab experiments, including HPAM, AP, AMPS and KYPAM. There are 35 lab experiments using HPAM, 4 lab experiments using AP, 3 lab experiments using AMPS and 3 lab experiments using KYPAM. HPAM has been more widely used than other types of polymer. Also, the range of the polymer concentration of HPAM is broader than other types of polymers, which is shown in Figure 3.26.

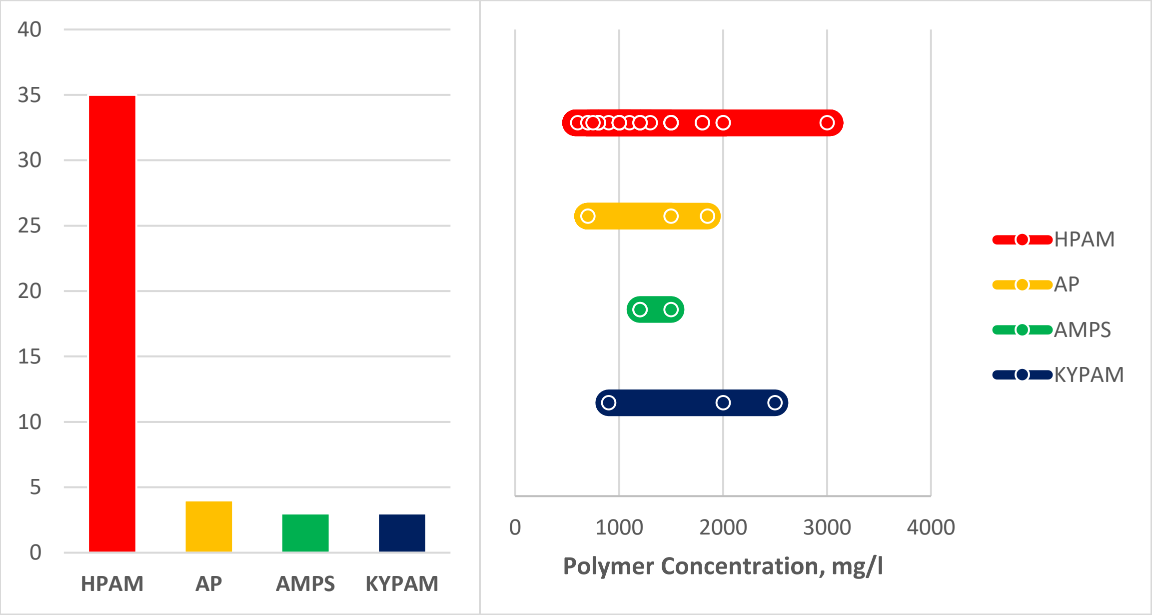


Figure 3.26. Polymer type (A) and polymer concentration (B) of lab experiments.

3.3.11.2 Polymer type and concentration of field data. The box plot and histogram of polymer concentration field data and the bar chart of types of polymers of field applications are illustrated in Figure 3.27 and polymer type and polymer concentration of field applications are shown in Figure 3.28.

The maximum of polymer concentration field data is 3000 mg/l and the minimum is 700 mg/l. The median of polymer concentration field data is 1500 mg/l and the mean is

1657.1 mg/l. Figure 3.27 (B) shows that polymer concentration data in the interval of 1000-1500 mg/l have the highest frequency. For field applications, most polymer concentration data range from 1000-2500 mg/l.

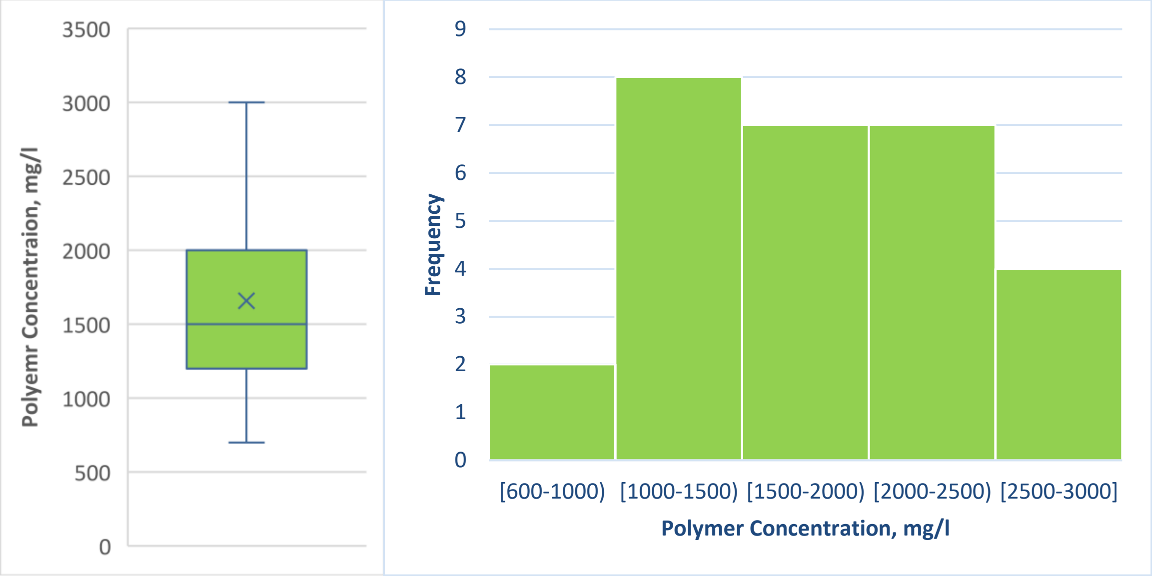


Figure 3.27. Box plot (A) and histogram (B) of polymer concentration field data.

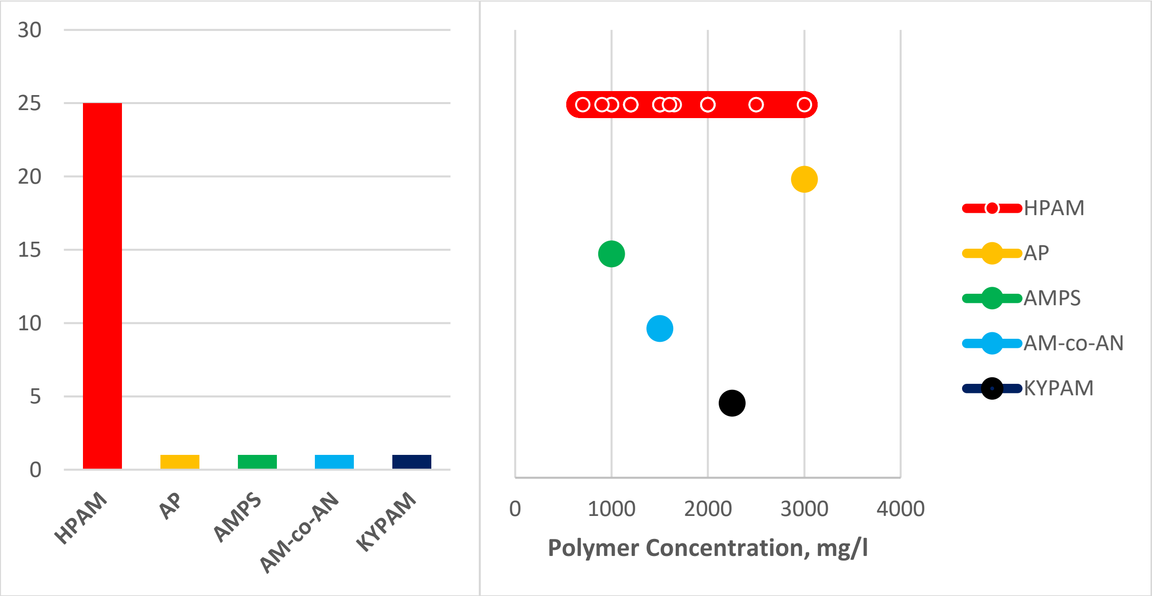


Figure 3.28. Polymer type (A) and polymer concentration (B) of field applications.

For field applications, there are 25 field applications using HPAM, 1 application using AP, 1 application using AMPS copolymer, 1 application using AM/AN copolymer and 1 application using KYPAM. HPAM has been most widely used, which can be seen in Figure 3.28 (A). However, other polymers are not widely used due to the fact that their flow properties and long term chemical stability have not been tested to nearly the extend of HPAM (Levitt and Pope, 2008).

3.3.12. Polymer Molecular Weight. Statistical analysis of polymer molecular weight data and field data are illustrated in this part, where the range and distribution of polymer molecular weight data are shown.

3.3.12.1 Polymer molecular weight of lab data. The box plot and histogram of polymer molecular weight lab data are illustrated in Figure 2.29 and molecular weight of each kind of polymer of laboratory experiments is shown in Figure 2.30.

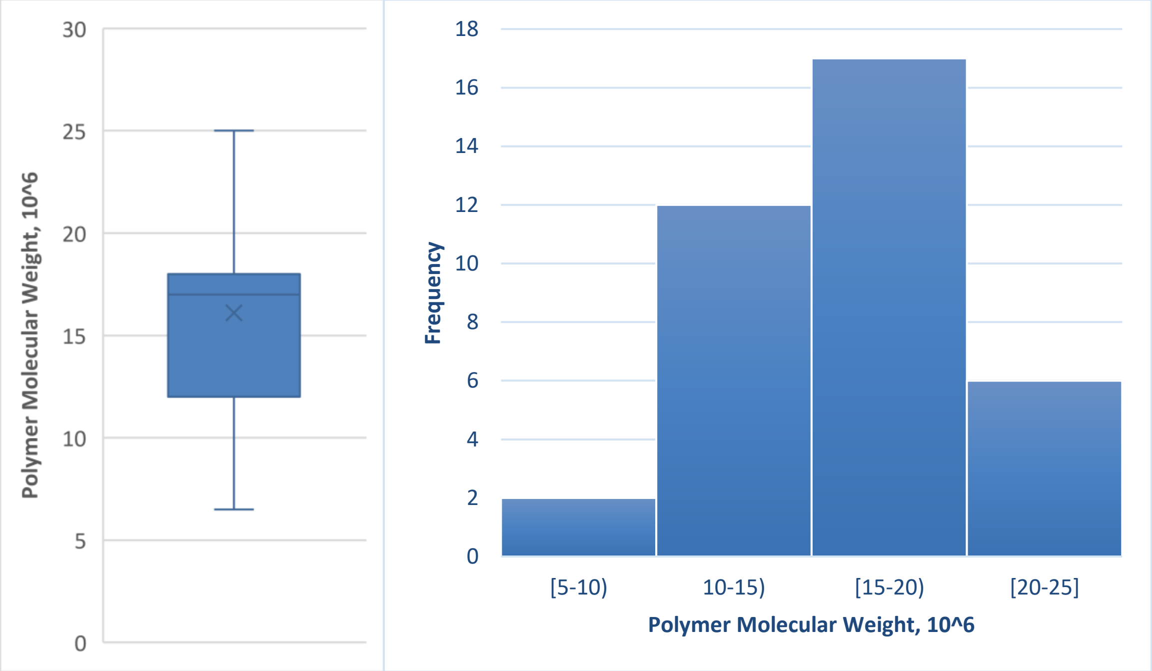


Figure 3.29. Box plot (A) and histogram (B) of polymer molecular weight lab data.

The maximum of polymer molecular weight lab data is 25(10^6) and the minimum is 6.5(10^6). The median of polymer molecular weight lab data is 17(10^6) and the mean is 16.1(10^6). Figure 3.29 (B) shows that the polymer molecular weight lab data in the interval of 15-20 (10^6) have the highest frequency.

The polymer molecular weight of HPAM has a broader range compared to other polymers, which is shown in Figure 3.30. Even though lab experiments using AMPS has been collected in the database, the polymer molecular weight data of using AMPS are not available. Also, Figure 3.30 indicates that the range of polymer molecular weight of HPAM is broader than other kinds of polymers and the molecular weights of other polymers are lower than using HPAM.

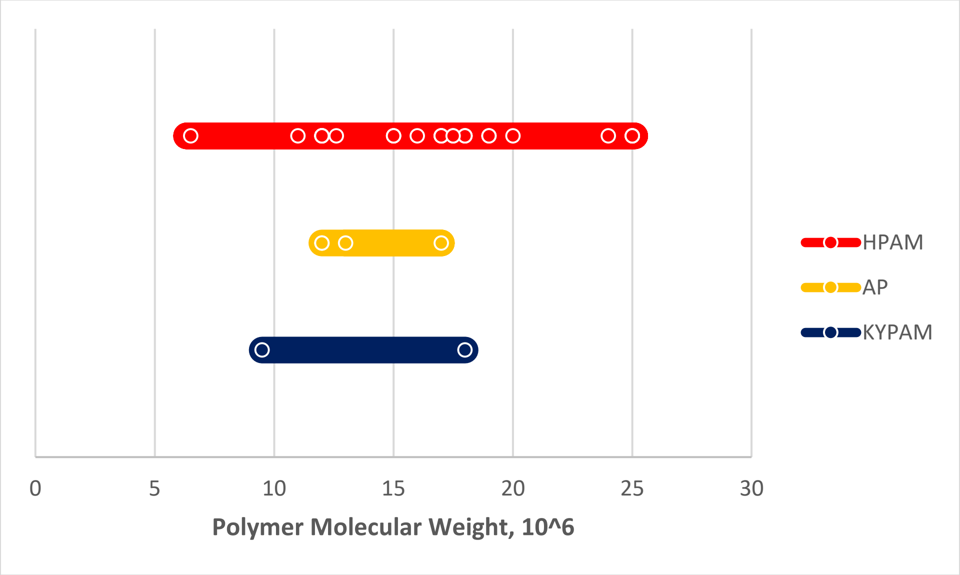


Figure 3.30. Molecular weight of each kind of polymer of lab experiments.

3.3.12.2 Polymer molecular weight of field data. The box plot and histogram of polymer molecular weight of field data are illustrated in Figure 3.31 and the molecular weight of each kind of polymer of field applications is shown in Figure 3.32.

The maximum observation of polymer molecular weight field data is $25(10^6)$ and the minimum observation is $2(10^6)$. The median of polymer molecular weight field data is $18(10^6)$ and the mean is $15(10^6)$.

Figure 3.31 (B) shows a right-skewed distribution. It can be observed that polymer molecular weight field data in the range of $15\text{-}20(10^6)$ have the highest frequency.

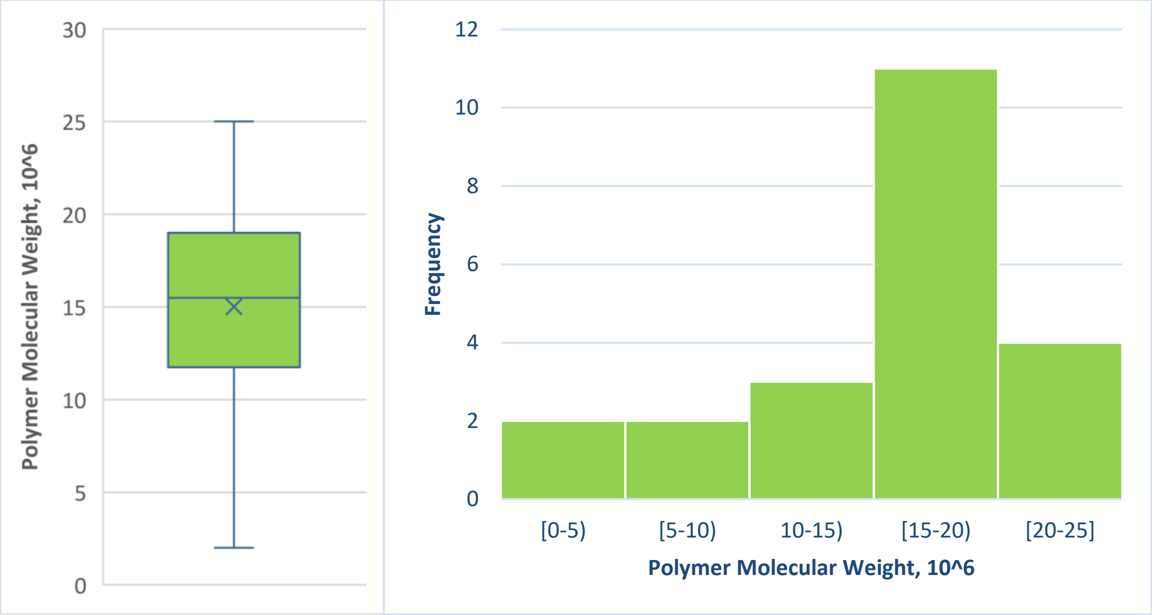


Figure 3.31. Box plot (A) and histogram (B) of polymer molecular weight field data.

The polymer molecular weight of HPAM tends to be higher than that of other polymers, which can be seen in Figure 3.32. Only 1 polymer molecular weight data of using AP and 1 molecular weight data of using AM-co-AN are available. The field application of weak gel using AP with low molecular weight was conducted in Zhongyuan oilfield and reported by Chen et al. (2004). The temperature was 203 °F and the water salinity was 115,672.5 mg/l with a divalent cation concentration of 2161 mg/l. The polymer molecular weight of the application using AP was 2×10^6 and the concentration was 3000 mg/l. The weak gel using Am-co-AN was applied in Huabei oilfield in 2002 with a polymer molecular weight of 3.4×10^6 and a concentration of 1500 mg/l. Based on geological statistical data, the effective permeability was 16.7-72 md and the average was 41 md. The reservoir temperature was 237.2 °F. The salinity was 131,926 mg/l with a divalent cation concentration of 6535 mg/l. Also, Figure 3.32 indicates that HPAM weak gels are more widely used in oilfields.

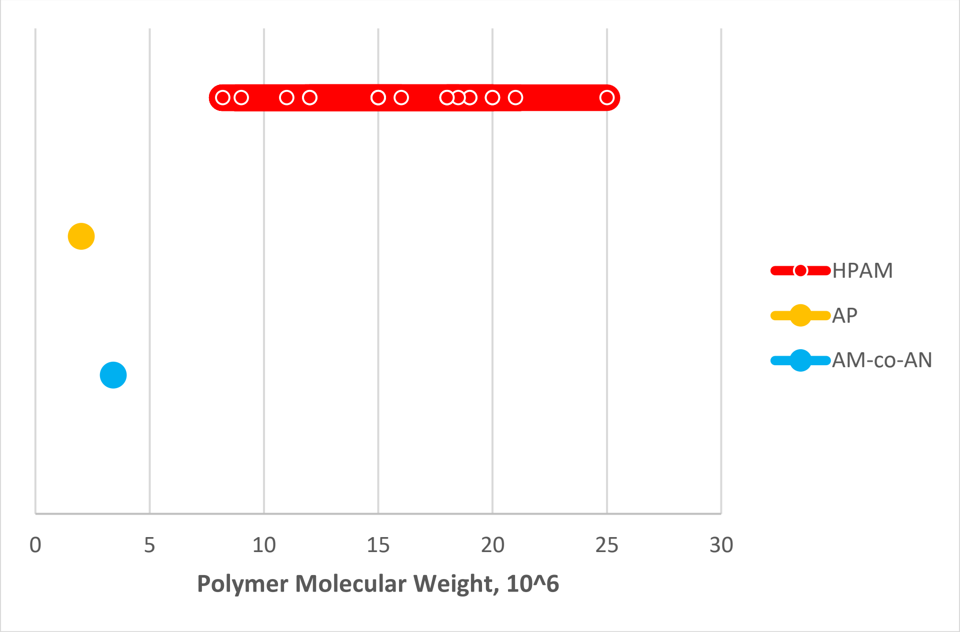


Figure 3.32. Molecular weight of each kind of polymer of field applications.

3.3.13. Degree of Hydrolysis. Statistical analysis of polymer degree of hydrolysis data and field data are illustrated in this part, where the range and distribution of polymer degree of hydrolysis data are shown.

3.3.13.1 Degree of hydrolysis of lab data. A box plot and histogram of degree of hydrolysis laboratory data are illustrated in Figure 3.33 and Figure 3.34 illustrates degree of hydrolysis of each kind of polymer of laboratory data.

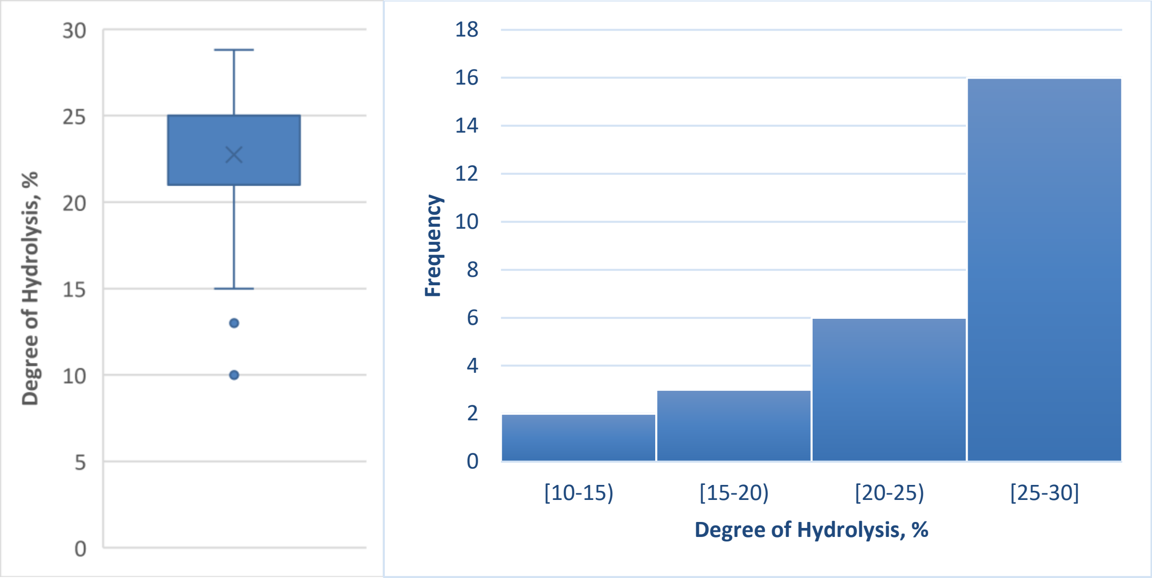


Figure 3.33. Box plot (A) and histogram (B) of degree of hydrolysis lab data.

From Figure 3.33 (A), it can be observed that two special cases are detected. Wang et al. (2001) did the research on preparation weak gels for permeability control using KPAYM. The weak gel is prepared with low degree of hydrolysis (10%) and moderate molecular weight (9.5×10^6) 2500 mg/l KYPAM and 2000 mg/l chromium crosslinker at the temperature of 123.8°F, the salinity of 40,000 mg/l and the divalent cation concentration of 6000 mg/l.

Li et al. (2005) conducted the research on forming weak gel using produced water. The water salinity of the produced water was 8800 mg/l. The temperature of the lab experiment was 158°F. 1800 mg/l HPAM with a polymer molecular weight of 1.75×10^7 and a degree of hydrolysis of 13%. The crosslinker was 500 mg/l aluminum crosslinker.

The maximum degree of hydrolysis lab data is 28.8% and the minimum is 10%. The median of degree of hydrolysis lab data is 25% and the mean is 22.7%. Figure 3.33 (B) displays a right-skewed distribution. The degree of hydrolysis lab data in the interval of 25-30 % have the highest frequency.

Wu et al. (2004) conducted a lab experiment to find out the optimal gel formulation at a temperature of 172.4°F, which consists of 1850 mg/l AP with the degree of hydrolysis of 18.2% crosslinking with 60 mg/l chromium crosslinker. The water salinity was not high, which was 1683 mg/l. Guo et al. (2007) conducted a laboratory study on heat resistant weak gel using AP. The temperature was 183.2 °F and water salinity was 9339.97 mg/l. The weak gel was made of 1500 mg/l AP with the degree of hydrolysis of 18.2 and molecular weight of 1.2×10^7. Two cores were used with permeability of 1173 and 1097 md respectively. For the application of using KYPAM, the degree of hydrolysis was 10%. It can also be observed when HPAM was used, it has a broader range of degree of hydrolysis and HPAM has been most widely used to form a weak gel.

3.3.13.2 Degree of hydrolysis of field data. A box plot and histogram of degree of hydrolysis field data are illustrated in Figure 3.34 and Figure 3.35 displays degree of hydrolysis of each kind of polymer of field data.

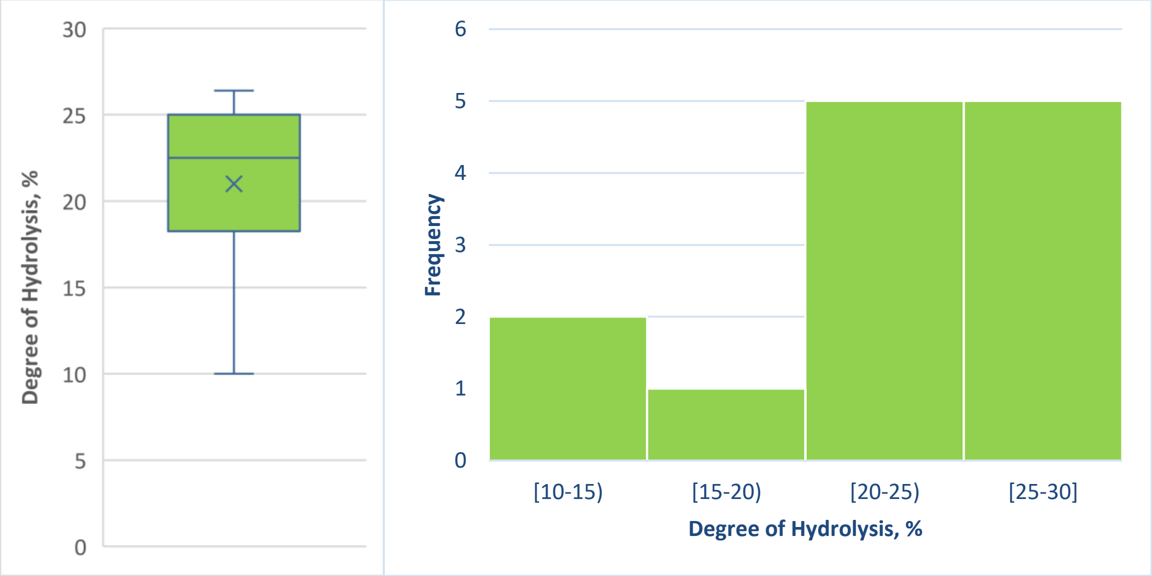


Figure 3.34. Box plot (A) and histogram (B) of degree of hydrolysis field data.

The maximum observation of degree of hydrolysis field data is 26.4% and the minimum observation is 10%. The median of degree of hydrolysis field data is 22.5% and the mean is 21.0%. Figure 3.34 (B) indicates most degree of hydrolysis data fall into the intervals of 20-25% and 25-30%.

From Figure 3.35, it can be observed that only the degree of hydrolysis data of HPAM are available. Even though the applications of using AP, AMPS, AM-co-AN and KYPAM are collected for the analysis, the degree of hydrolysis data were not reported.

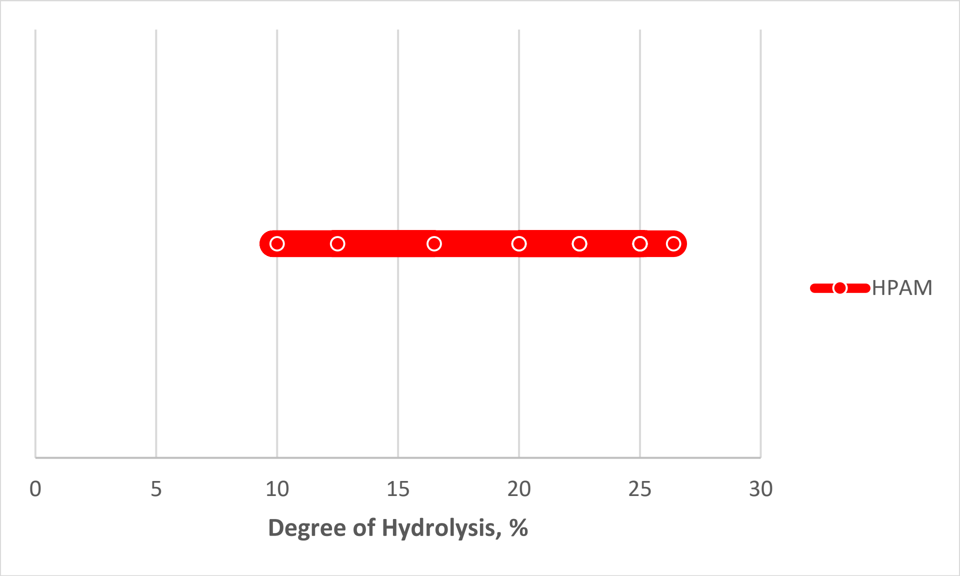


Figure 3.35. Degree of hydrolysis of each kind of polymer of field data.

3.3.14. Crosslinker Type and Concentration. Crosslinkers that are commonly used in weak gel treatments are studied and range and distribution of crosslinker concentration are illustrated.

3.3.14.1 Crosslinker type and concentration of lab data. Figure 3.36 illustrates the numbers of each kind of crosslinker in lab experiments. Figure 3.37 illustrates the concentration of each kind of crosslinker used in the lab experiments.

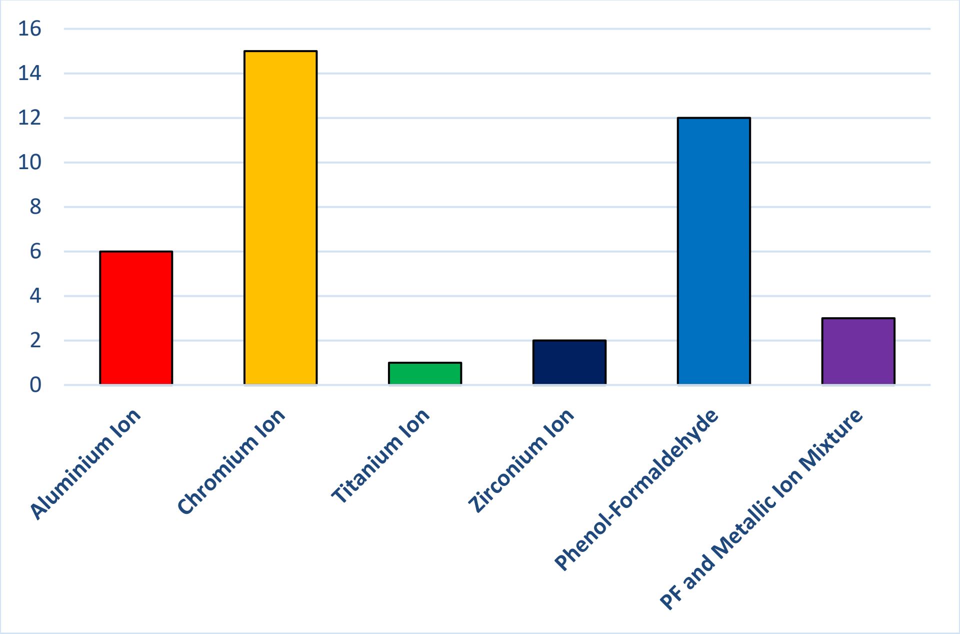


Figure 3.36. Bar chart of crosslinker type of lab experiments.

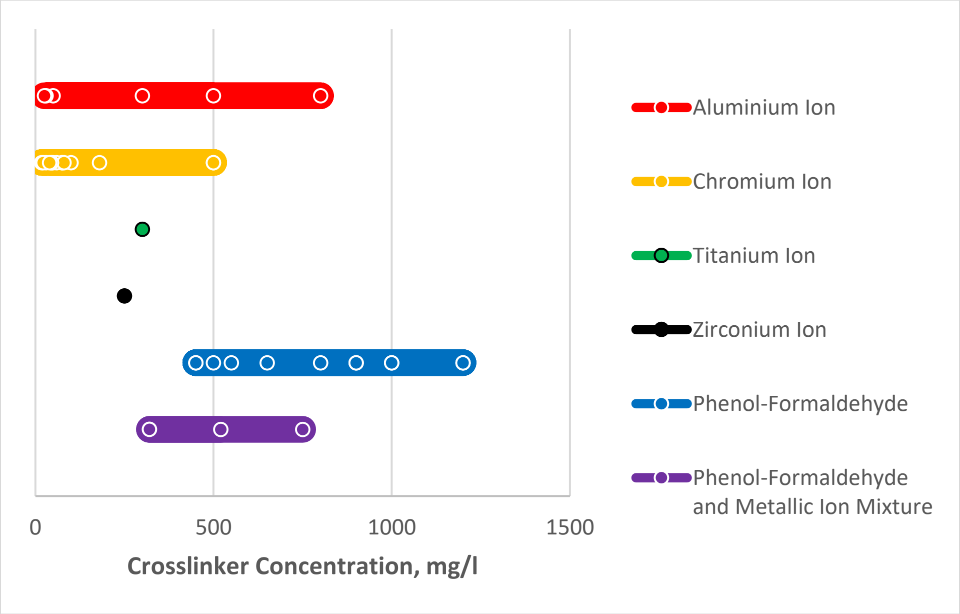


Figure 3.37. Crosslinker concentration of lab data.

Figure 3.36 displays that for lab experiments collected, chromium ion crosslinker is the most widely used. Phenol-formaldehyde crosslinker is widely used as well. However, there is only one lab work reported using the titanium ion crosslinker and two using zirconium crosslinker. But for those two laboratory experiments using zirconium crosslinker, only one of them reported the crosslinker concentration used. Figure 3.37 shows aluminum ion crosslinker and phenol-formaldehyde crosslinker have wider concentration ranges compared to other kinds of crosslinkers.

3.3.14.2 Crosslinker type and concentration of field data. Figure 3.38 illustrates the numbers of each kind of crosslinker in field applications. Figure 3.39 illustrates the concentration of each kind of crosslinker used in field applications.

Figure 3.38 displays that for field applications, chromium ion crosslinker and phenol-formaldehyde are widely used. There is only one field application reported using aluminum ion crosslinker. Figure 3.39 shows the range of phenol-formaldehyde concentration is wider than other kinds of crosslinkers.

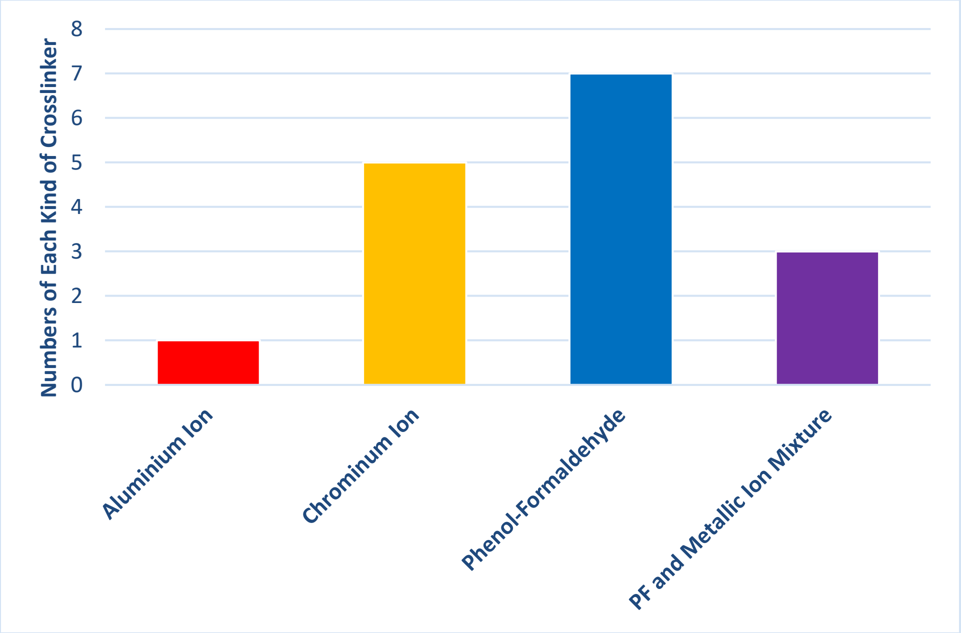


Figure 3.38. Bar chart of crosslinker types of field applications.

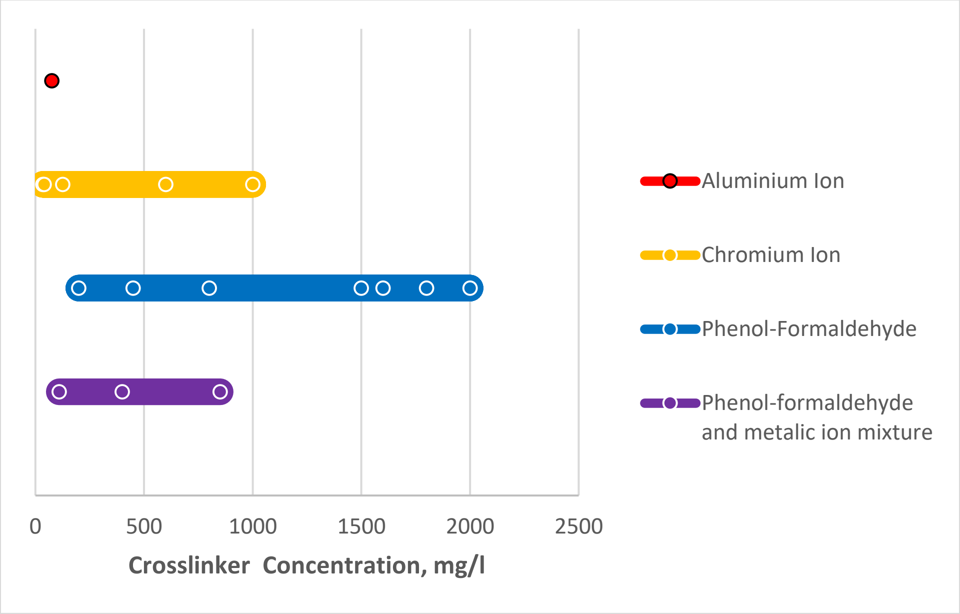


Figure 3.39. Crosslinker concentration of field data.

3.3.15. Injected PV. Statistical analysis of injected PV laboratory data and field data are illustrated in this part, where the range and distribution of injected PV data are shown.

3.3.15.1 Injected PV of lab data. A box plot and histogram of injected PV lab data are illustrated in Figure 3.40.

It can be seen from Figure 3.40 (A) that two special cases are detected. Hu et al. (2010) conducted the lab experiment on thermal-stable deep profile control agent. 2 PV of weak gel, which was made of 1500 mg/l HPAM with a molecular weight of 2.5×10^7 and a degree of hydrolysis of 25%, 500 mg/l phenol-formaldehyde crosslinker, 20 mg/l chromium crosslinker and 100 mg/l deoxidizer, was injected to cores with permeability of 119, 245 and 306 md. The weak gel had good stability at 230 °F and the weak gel system was still strong movable at the high temperature. Cui et al. (2006) injected 3 PV of weak gel that was made of 2000 mg/l 2×10^7 molecular weight 20% degree of hydrolysis HPAM, 1000 mg/l chromium crosslinker and 300 mg/l stabilizer at 167 °F. The water salinity was 11,000 mg/l.

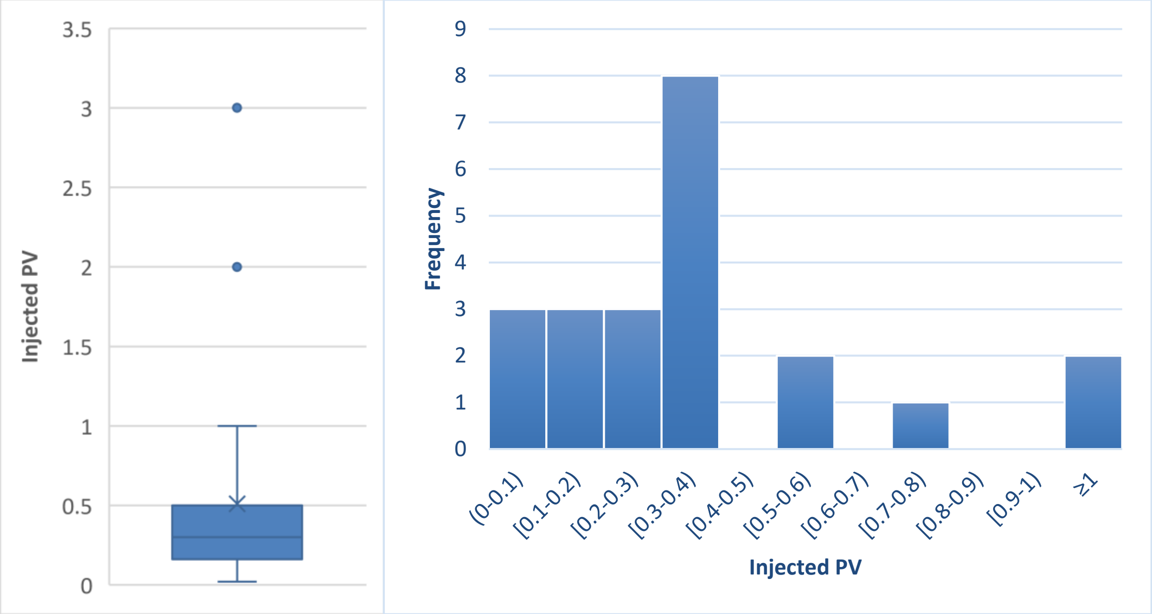


Figure 3.40. Box plot (A) and histogram (B) of injected PV lab data.

The injected PV varies from 0.02-3 PV. The median is 0.3 PV and the mean is 0.51 PV. Figure 3.40 (B) shows that the injected PV data in the interval of 0.3-0.4 PV have the highest frequency.

3.3.15.2 Injected PV of field data. The box plot and histogram of injected PV field data are illustrated in Figure 3.41.

It can be seen from Figure 3.40 and Figure 3.41 that injected pore volumes of laboratory experiments are larger than those of filed applications.

The maximum of injected PV field data is 0.35 PV, the minimum is 0.01 PV, the median is 0.12 PV and the mean is 0.14 PV. The injected PV field data in the interval of 0-0.1 PV have the highest frequency.

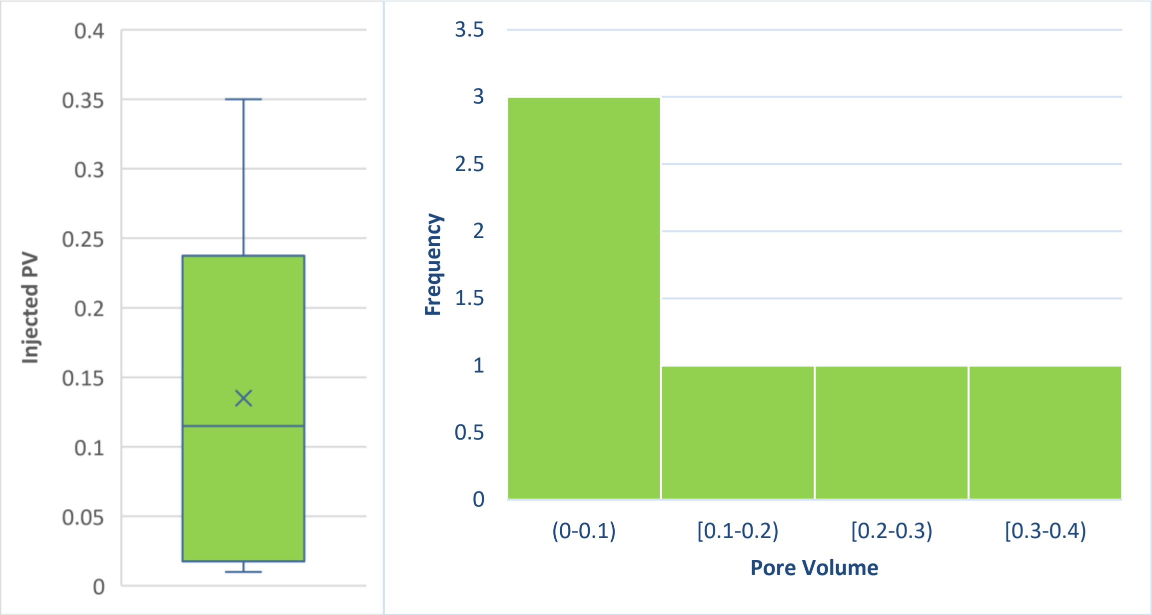


Figure 3.41. Box plot (A) and histogram (B) of injected PV field data.

3.3.16. Oil Recovery Before Treatment. Statistical analysis of oil recovery before treatment laboratory data and field data are illustrated in this part, where the range and distribution of oil recovery before treatment data are shown.

3.3.16.1 Oil recovery before treatment of lab data. The box plot and histogram of oil recovery before treatment lab data are illustrated in Figure 3.42.

The maximum of oil recovery before treatment lab data is 59.0%, the minimum is 7.8%, the median is 28.3% and the mean is 32.9%. Weak gel can be applied in early, middle, and late stage of oil recovery. Figure 3.42 shows that oil recovery before treatment lab data in the interval of 20-30% have the highest frequency.

3.3.16.2 Oil recovery before treatment of field data. The box plot and histogram of oil recovery before treatment of field data are illustrated in Figure 3.43.

It can be observed from Figure 3.43 (A) that one special case is detected. Zhu (2001) designed the weak gel system that was made of 3000 mg/l HPAM, 2000 mg/l phenol, 2000 mg/l formaldehyde for Zhen 12 block operated by Jiangsu oilfield. The oil recovery was 47.88% and the water cut was 93.8%. The weak gel was applied to reduce water production and to increase oil production.

The combination of high viscous oil and heterogenous formation result in low oil recovery. Thus, profile control has been carried out by injecting weak gel. Weak gel can be applied in early, middle, and late stage of oil recovery. The maximum of oil recovery before treatment field data is 47.9%, the minimum is 17.3%, the median is 24.5% and the mean is 27.2%.

Figure 3.43 (B) shows that oil recovery before treatment field data in the interval of 20-30% have the highest frequency.

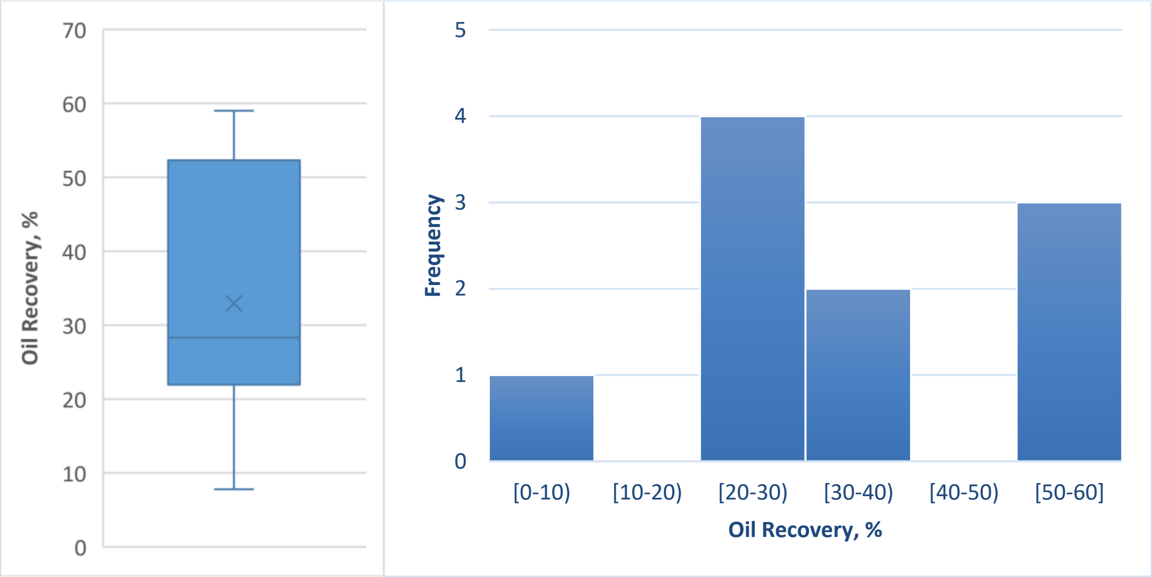


Figure 3.42. Box plot (A) and histogram (B) of oil recovery before treatment lab data.

3.3.17. Water Cut. Weak gels have been applied to reduce high water cut caused by water breakthrough. The box plot and histogram of water cut are illustrated in Figure 3.44 and Figure 3.45.

The maximum of water cut before treatment is 96.1%, the minimum is 16.0%, the median is 93.1% and the mean is 81.6. The maximum of water cut after treatment is 94.5%, the minimum is 14.9%, the median is 88.6% and the mean is 75.9%.

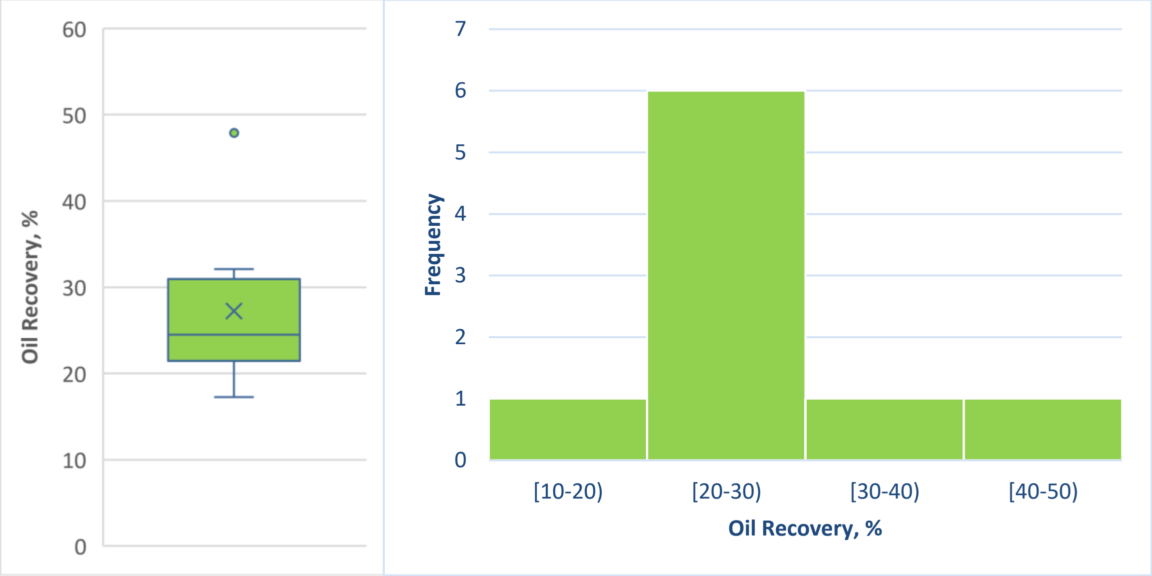


Figure 3.43. Box plot (A) and histogram (B) of oil recovery before treatment field data.

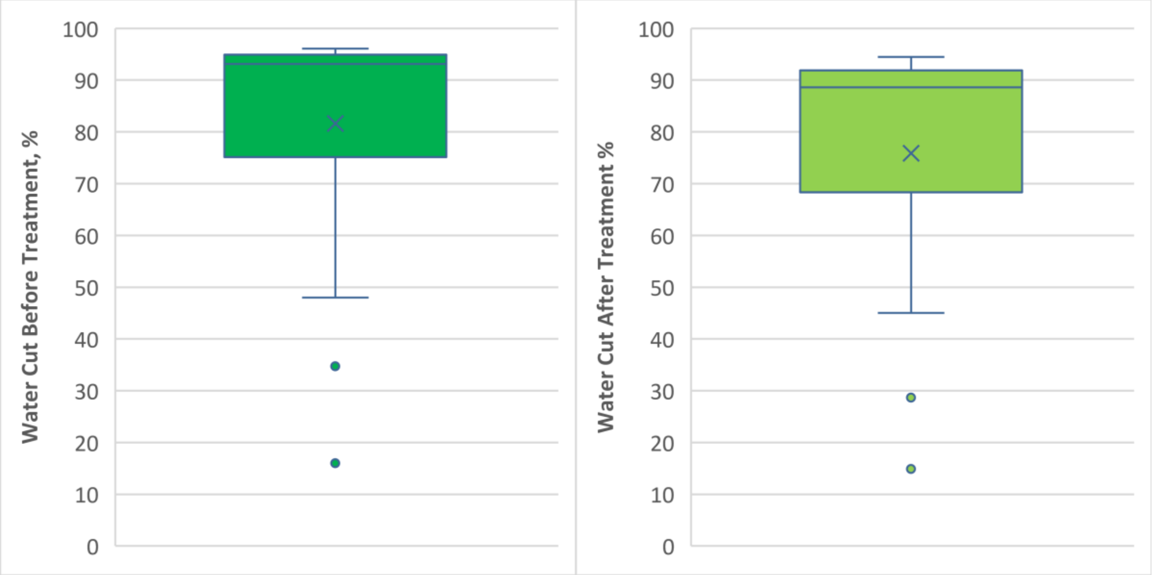


Figure 3.44. Box plot of water cut before and after treatment.

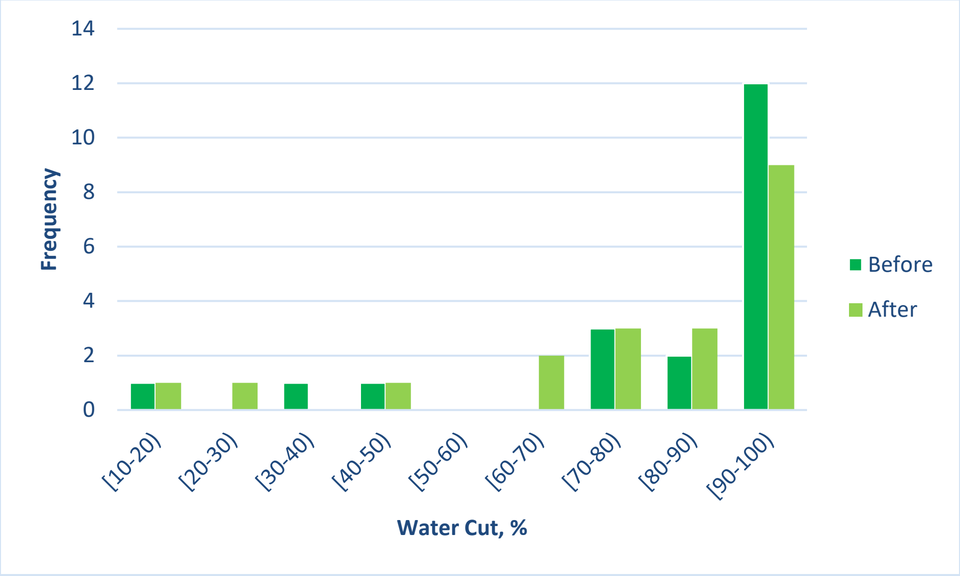


Figure 3.45. Histogram of water cut before and after treatment.

3.3.18. Water Cut Decrease. The box plot and histogram of water cut decrease are illustrated in Figure 3.46. Successfully applying weak gel treatments in early stage of oil recovery can significantly reduce water cut, which is shown in Figure 3.46 (A).

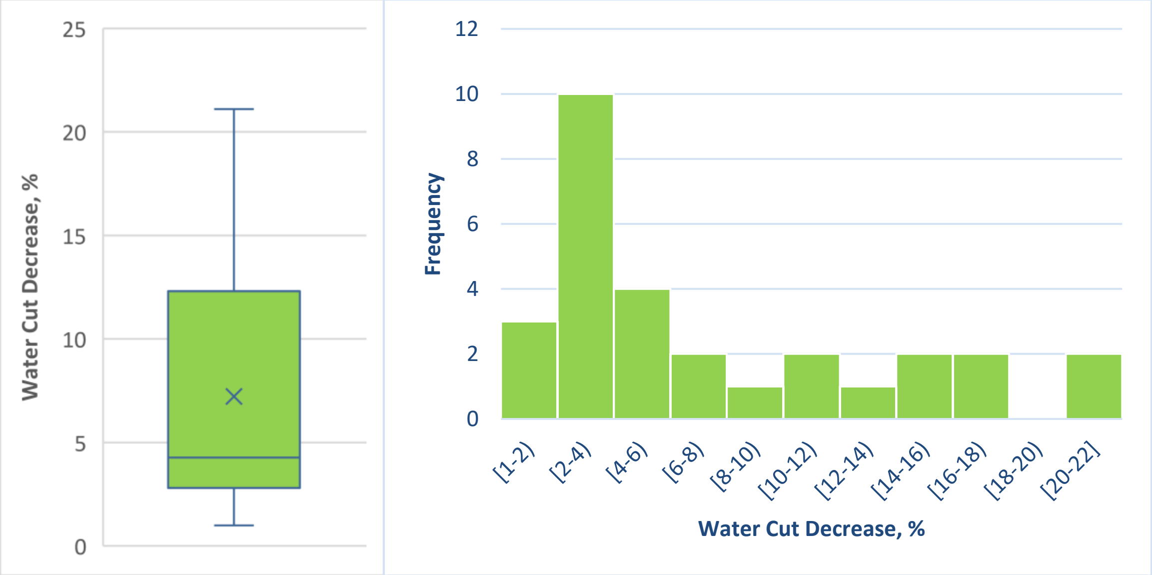


Figure 3.46. Box plot (A) and histogram (B) of water cut decrease.

The maximum of water cut decrease data is 21.1%, the minimum is 1.0%, the median is 4.3% and the mean is 7.2%.

It can be observed from Figure 3.46 (B) that water cut decrease data in the interval of 2-4% have the highest frequency.

3.3.19. Temperature vs. Crosslinker Concentration. Data distribution of temperature vs. crosslinker concentration of laboratory experiments and field applications are studied in this part.

3.3.19.1 Temperature vs. crosslinker concentration lab data. The cross plot of temperature vs. crosslinker concentration lab data is illustrated in Figure 3.47, which describes data distribution of different types of crosslinkers used over different temperatures.

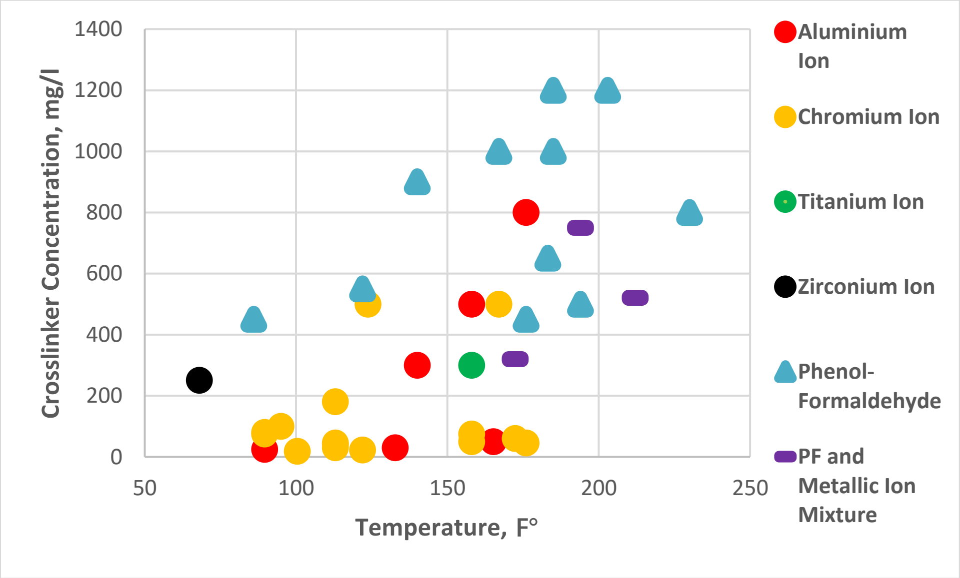


Figure 3.47. Cross plot of temperature vs. crosslinker concentration of lab data.

Figure 3.47 indicates that when phenol-formaldehyde crosslinkers are used, larger crosslinker concentrations are chosen compared to other types of crosslinkers. And phenol-formaldehyde corsslinkers are more applicable over a broad range of reservoir temperatures than other kinds of crosslinkers. Furthermore, for high temperature environments with temperatures higher than 200 °F, phenol-formaldehyde crosslinker and phenol-formaldehyde and metallic ion mixture crosslinker are used to adapt the high temperatures. Also, the concentrations of phenol-formaldehyde and metallic ion mixture crosslinkers chosen tend to be lower than just using phenol-formaldehyde crosslinker.

3.3.19.2 Temperature vs. crosslinker concentration field data. The cross plot of temperature vs. crosslinker concentration is illustrated in Figure 3.48.

Figure 3.48 also infers that phenol-formaldehyde crosslinkers are more applicable over a broad range of temperatures and the concentrations of phenol-formaldehyde crosslinkers tend to be larger than other types of crosslinkers. For high temperature reservoirs, organic crosslinkers are preferred.

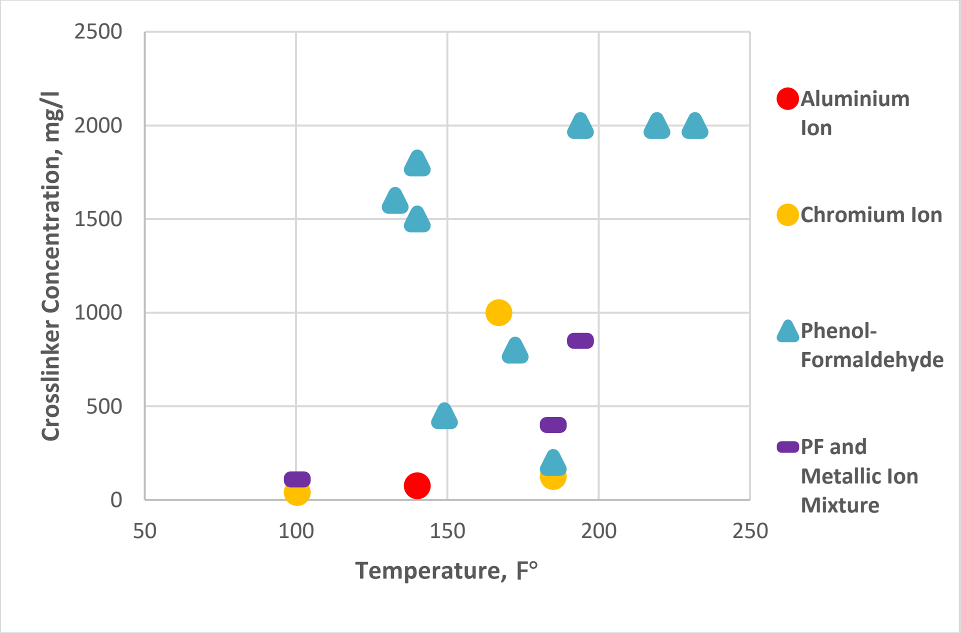


Figure 3.48. Cross plot of temperature vs. crosslinker concentration field data.

3.3.20. Temperature vs. Polymer Molecular Weight. Data distribution of temperature vs. polymer molecular weight of laboratory experiments and field applications are studied in this part.

3.3.20.1 Temperature vs. polymer molecular weight lab data. The cross plot of temperature vs. polymer molecular weight lab data is illustrated in Figure 3.49.

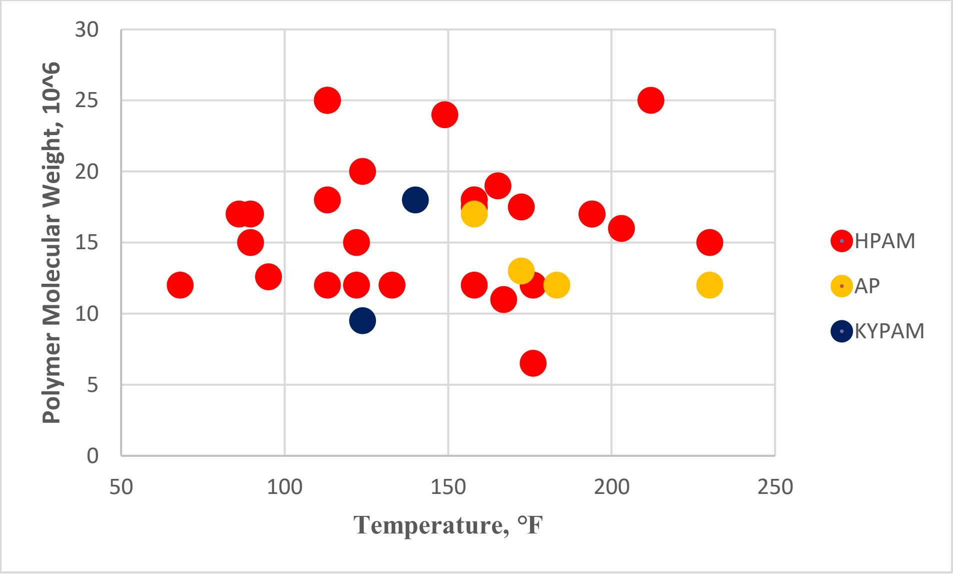


Figure 3.49. Cross plot of temperature vs. polymer molecular weight lab data.

A hydrophobically associating polymer solution can have a high viscosity with low molecular weight or low concentration and the viscosity is not necessarily relying on increasing single molecular chain size to gain a high viscosity, which makes APs able to meet the challenges of high temperature up to 120 °C (248 °F) and high salinity of 10-16(10^4) mg/l (Zhao et al., 2004). The filed application using AP were carried out at a temperature of 230 °F and zirconium crosslinker was used to adapt the high temperature. Furthermore, it can be observed that most polymers used in lab experiments have degree of hydrolysis from 10-20%. And, HPAM have been more widely and largely used over a broad range of temperatures, from low temperature to high temperatures, compared to other types of polymers.

3.3.20.2 Temperature vs. polymer molecular weight field data. The cross plot of temperature vs. polymer molecular weight field data is illustrated in Figure 3.50.

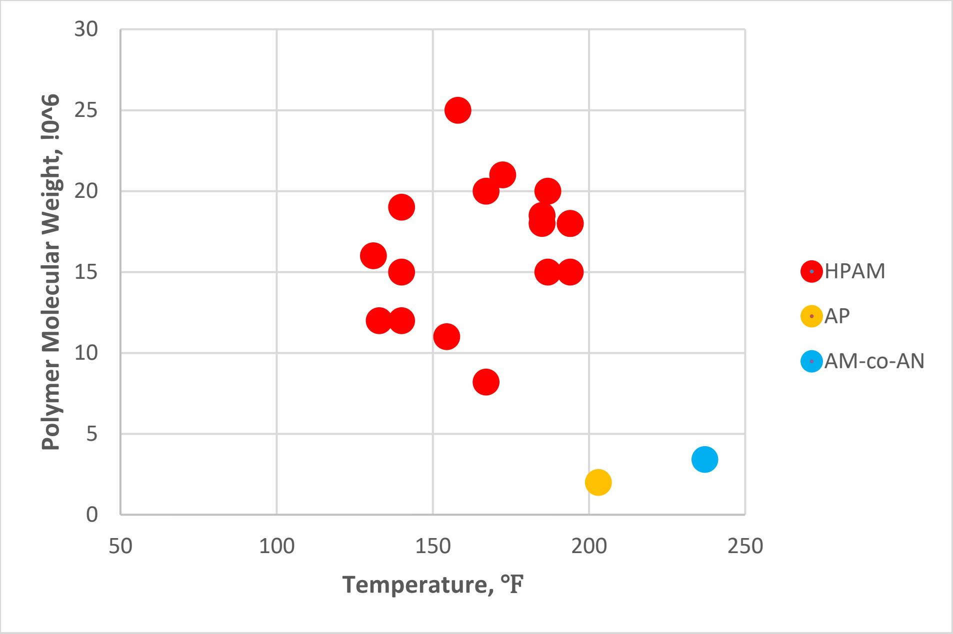


Figure 3.50. Cross plot of temperature vs. polymer molecular weight field data.

Figure 3.50. indicates that the applications using HPAMs in high temperature reservoirs are limited and HPAMs with degree of hydrolysis from 10 to 20 (10^6) have been more largely used in field applications. Furthermore, low degree of hydrolysis AP and AM/AN copolymer have been used in high temperature reservoirs. The use of low molecular weight polymers can retard the rate of gelation of gels that are applied to high temperature reservoirs (Sydansk, 2007). Furthermore, a AP solution can still have a high viscosity with low molecular weight and low concentration. Thus, the low molecular weight AP was use at the high temperature.

3.3.21. Temperature vs. Polymer Degree of Hydrolysis. Data distribution of temperature vs. polymer degree of hydrolysis of laboratory experiments and field applications are studied in this part.

3.3.21.1 Temperature vs. polymer degree of hydrolysis lab data. The cross plot of temperature vs. degree of hydrolysis lab data is illustrated in Figure 3.51.

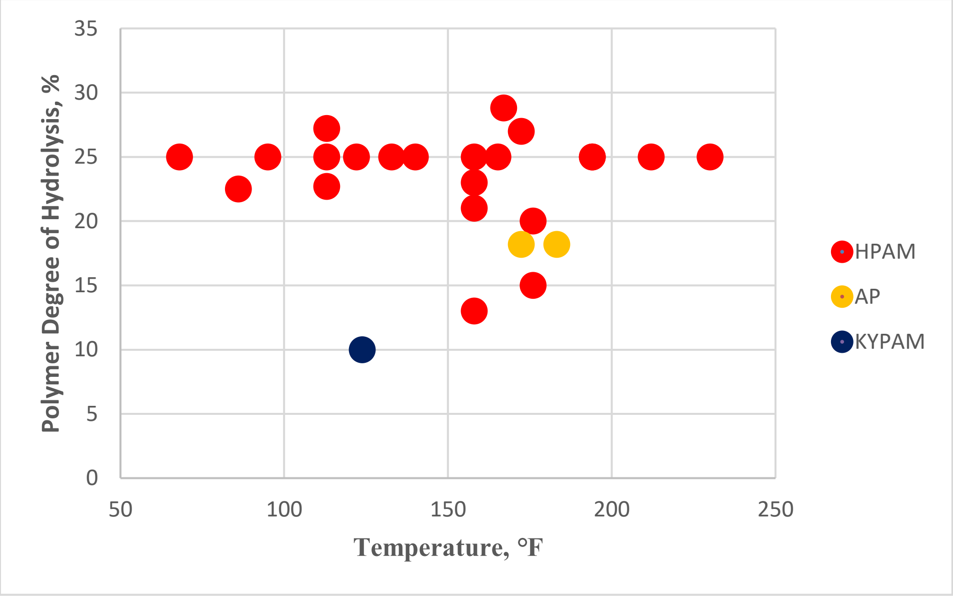


Figure 3.51. Cross plot of temperature vs. polymer degree of hydrolysis lab data.

Figure 3.51 indicates that polymers with 25% degree of hydrolysis are the most commonly used in the lab works. And polymers with 20-30% of degree of hydrolysis are widely used over a broad range of temperatures. It can also be observed from Figure 3.52 that intermediate molecular weight APs and low molecular weight KYPAM have been used in laboratory experiments.

3.3.21.2 Temperature vs. polymer degree of hydrolysis field data. The cross plot of temperature vs. degree of hydrolysis field data is illustrated in Figure 3.52.

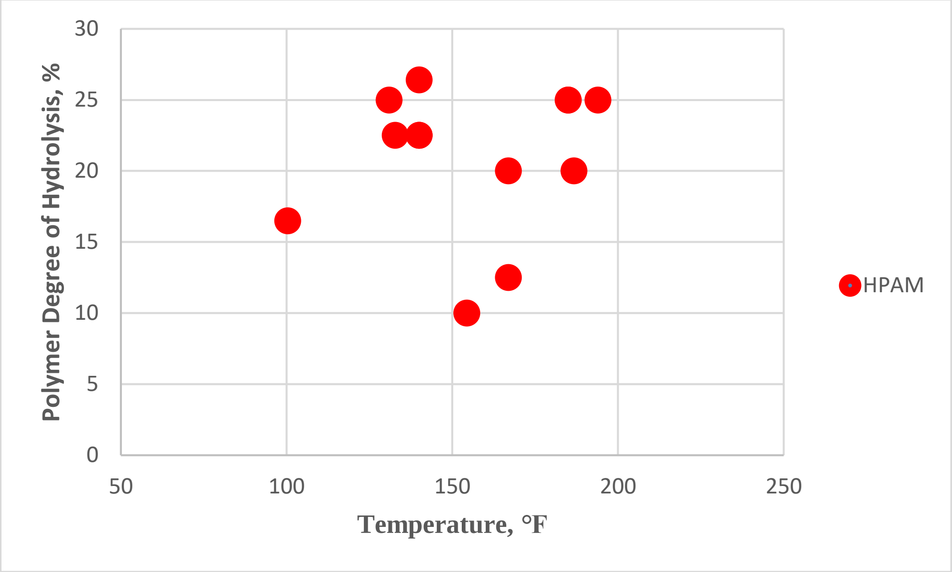


Figure 3.52. Cross plot of temperature vs. polymer degree of hydrolysis field data.

Although other kinds of polymers have been used, the temperature and polymer degree of hydrolysis data of those polymers are not available. It can be inferred from Figure 3.52 that polymers with degree of hydrolysis from 20-30% are widely used over a broad range of reservoir temperatures.

4. DATA SUMMARY

Table 4.1 presents the summary of the data ranges of reservoir properties and production data for weak gel treatments based on field applications. The maximum, minimum, median and mean of each reservoir properties and production data are listed in Table 4.1.

Table 4.1. Data ranges of reservoir properties and production data of field applications.

Data Type	Parameters	Maximum	Minimum	Median	Mean
Reservoir Properties	Porosity, %	32.0	15.0	21.3	22.4
	Permeability, md	3452.0	2.2	424.0	621.9
	Temperature, °F	237.2	100.4	159.1	165.1
	Net Thickness, ft	88.6	21.3	60.7	51.2
	Depth, ft	9406.2	1640.4	5905.5	5843.7
	Water Salinity, mg/l	185000.0	1301.0	11000.0	42893.7
	Divalent Cation Concentration, mg/l	6535.0	39.4	2796.5	2528.1
	pH	8.5	5.5	7.0	7.1
	Dykstra-Parsons Coefficient	0.86	0.72	0.75	0.76
	Oil Viscosity, cp	233.0	1.4	12.4	47.5
Production Data	Oil Recovery Before Treatment, %	47.9	17.3	24.5	27.2
	Water Cut Before Treatment, %	96.1	16.0	93.1	81.6
	Water Cut After Treatment, %	94.5	14.9	88.6	75.9
	Water Cut Decrease, %	21.1	1.0	4.3	7.2

Table 4.2 presents the summary of the data ranges of general gel properties for weak gel treatments based on field applications. The maximum, minimum, median and mean of gel properties, including polymer concentration, polymer molecular weight,

degree of hydrolysis, and injected PV are listed in Table 4.2. For different kinds of crosslinkers, the crosslinker concentration varies greatly. The concentration of metallic crosslinkers tends is much smaller than organic crosslinkers. Thus, the crosslinker properties are not include in the screening guide of general gel properties. However, in Table 4.3 that presents the data ranges of specific gel properties, the concentration of each kind of crosslinker is included.

Table 4.2. Data ranges of general gel properties of field applications.

Parameter	Maximum	Minimum	Median	Mean
Polymer Concentration, mg/l	3000	700	1500	1657
Polymer Molecular Weight,10^6	25.0	2.0	15.5	15.0
Degree of Hydrolysis, %	26.4	10.0	22.5	21.0
Injected PV	0.35	0.01	0.12	0.14

Table 4.3 presents the summary of the data ranges of specific gel properties for weak gel treatments based on field applications. From Table 4.3, it can be observed that the polymer molecular weight of AMPS and KYPAM are not available. The degree of hydrolysis of AP, AMPS, AM-co-AN and KYPAM are not available. There is only one field application reported the polymer molecular weight of AP and only one filed application reported the polymer molecular weight of AM-co-AN. Only one concentration of aluminum crosslinker is available, which is 75 mg/l, and three concentrations using PF and metallic ion mixtures are available, which are 110, 400 and 850 mg/l.

Table 4.4 presents the summary of the data ranges of reservoir properties and production data for weak gel treatments based on laboratory experiments. From Table 4.4, it can be observed that for those laboratory experiments, the net thickness, depth, Dykstra-Parsons coefficient, water cut before treatment, water cut after treatment and water cut decrease are not available because in Table 4.4 only laboratory experiments data are presented.

Table 4.3. Data ranges of specific gel properties of field applications.

Polymer Type	HPAM	AP	AMPS	AM-co-AN	KYPAM
Polymer Concentration, mg/l	700-3000	3000	1000	1500	2250
Polymer Molecular Weight,10^6	8.2-25.0	2.0	X	3.4	X
Degree of Hydrolysis, %	10-26.4	X	X	X	X
Crosslinker Type	Al	Cr	PF	PF and Metallic Ion Mixture	
Crosslinker Concentration, mg/l	75.0	35.0-1000.0	200.0-2000.0	110.0/400.0/850.0	

Table 4.4. Data ranges of reservoir properties and production data of laboratory experiments.

Data Type	Parameters	Maximum	Minimum	Median	Mean
Reservoir Properties	Porosity, %	31.8	16.4	25.1	25.1
	Permeability, md	2100.0	51.0	955.0	822.5
	Temperature, °F	230.0	68.0	158.0	148.0
	Water Salinity, mg/l	160000.0	991.1	8432.0	24442.5
	Divalent Cation Concentration, mg/l	6000.0	22.7	506.0	1446.4
	pH	7.5	6.0	7.0	6.8
	Oil Viscosity, cp	255.4	1.7	9.1	47.3
Production Data	Oil Recovery Before Treatment, %	59.0	7.8	28.3	32.9

Table 4.5 presents the summary of the data ranges of general gel properties for weak gel treatments based on laboratory experiments. The maximum, minimum, median

and mean of polymer concentration, polymer molecular weight, degree of hydrolysis, injected PV are listed in Table 4.5.

Table 4.5. Data ranges of general gel properties of laboratory experiments.

Parameter	Maximum	Minimum	Median	Mean
Polymer Concentration, mg/l	3000	600	1200	1280
Polymer Molecular Weight,10^6	25.0	6.5	17.0	16.1
Degree of Hydrolysis, %	28.8	10.0	25.0	22.7
Injected PV	3.00	0.02	0.30	0.51

Table 4.6 presents the summary of the data ranges of specific gel properties for weak gel treatments based on laboratory experiments. The polymer molecular weight and degree of hydrolysis of AMPS are not available. Only one lab experiment used titanium crosslinker.

Table 4.6. Data ranges of specific gel properties of laboratory experiments.

Polymer Type	HPAM	AP	AMPS	KYPAM		
Polymer Concentration, mg/l	600-3000	700/1600/1850	1200/1200/1500	900/2000/2500		
Polymer Molecular Weight,10^6	6.5-25.0	12.0-17.0	X	9.5/18.0		
Degree of Hydrolysis, %	13-28.8	18.2	X	10.0		
Crosslinker Type	Al	Cr	Ti	Zr	PF	PF and Metallic Ion Mixture
Crosslinker Concentration, mg/l	25.0-800.0	17.8-500.0	300.0	250.0	450.0-1200.0	320.0/520.0/750.0

5. CONCLUSIONS

HPAM is more widely used in laboratory experiments and field applications because of its low cost, although other polymers have better stability in severe conditions (high temperature or high salinity).

Overall, HPAM has broader ranges of polymer concentration, molecular weight, degree of hydrolysis than those of other kinds of polymers.

When weak gels are used for heavy oil reservoirs, low concentration HPAM crosslinking with chromium was applied because those reservoirs have low temperatures and low saline salinities.

Chromium and phenol-formaldehyde crosslinkers have more applications in lab experiments and field applications.

Weak gels can be applied in early, middle, and late stage of oil recovery.

When phenol-formaldehyde corsslinkers are used, generally higher crosslinker concentrations are chosen compared to other kinds of crosslinkers.

Phenol-formaldehyde crosslinkers are more applicable over a broad range of temperatures.

The concentrations of phenol-formaldehyde and metallic ion mixture tend to be lower than using phenol-formaldehyde crosslinker.

For high temperature environments, phenol-formaldehyde cosslinker and phenol-formaldehyde and metallic ion mixture are preferred.

For hydrophobically associating polymers, high molecular weight is not required. Intermediate molecular weight APs can be used for high temperature and high salinity reservoirs.

BIBLIOGRAPHY

Albonico, P., Bartosek, M., Lockhart, T. P. and Causin, E., New Polymer Gels for Reducing Water Production in High-Temperature Reservoirs, SPE-27609-MS (1994).

Albonico, P., Bartosek, M., Malandrino, A., Bryant, S. and Lockhart, T. P., Studies on Phenol-Formaldehyde Crosslinked Polymer Gels in Bulk and in Porous Media, SPE-28983-MS (1995).

Albonico, P. and Lockhart, T. P., Divalent Ion-Resistant Polymer Gels for High-Temperature Applications: Syneresis Inhibiting Additives, SPE-25220-MS (1993).

Albonico, P., Burrafato, G., Di, L. and Lockhart, T. P., Effective Gelation-Delaying Additives for Cr+3/Polymer Gels, SPE-25221-MS (1993).

Aldhaheri, M. N., Wei, M., Bai, B. and Alsaba, M., A Roadmap to Successfully Select a Proper Gel Treatment Technology, SPE-182795-MS (2016).

Aldhaheri, M. N., Wei, M., Bai, B. and Alsaba, M., An Advanced Selection Tool for the Application of In-Situ Gels for Undiagnosed Injection Wells, SPE-182813-MS (2016).

Alsaiari, H. A., Al-Khaldi, M., Al-Taie, I., Wang, Q., Alabedi, G., Zhang, F., Zhang, Z., Bhandari, N., Ruan, G, Yan, F., Liu, Y., Kan, A. and Tomson, M., Effect of Crosslinkers on the Performance of Calcium Sulfate Scale Inhibitors at High Temperature: Impact of Zirconium, SPE-179878-MS (2016).

Al-Assi, Willhite, G., Green, D. W. and Mccool, C., Formation and Propagation of Gel Aggregates Using Partially Hydrolyzed Polyacrylamide and Aluminum Citrate, SPE-100049-MS (2006).

Al-Muntasheri, G. A., Nasr-El-Din, H. A., Peters, J. and Zitha, P. L. J., Investigation of a High Temperature Organic Water Shutoff Gel: Reaction Mechanisms, SPE-97530-MS (2005).

Azari, M. and Soliman, M., Review of Reservoir Engineering Aspects of Conformance Control Technology.

Bai, B., Zhou, J., Liu, Y. and Tongwa, P., Thermo-Dissoluble Polymer for In-Depth Mobility Control, IPTC-16991-MS (2013).

Bai, B., Liu, Y., Coste, J. P., Li, L., Preformed Particle Gel for Conformance Control: Transport Mechanism Through Porous Media, SPE-89468-PA (2007).

Bai, B., Tang, X., Liu, G., Li, L., Wei, Z., Liang, C. and Yu, X., Weak Gel RNJ-L as Flooding Fluid for In-depth Permeability Control in Low Temperature Reservoirs, Oilfield Chemistry, 2001, Vol. 18, No.4.

Bartosek, M., Mennella, A., Lockhart, E., Rosse, E. and Passucci, C., Polymer Gels for Conformance Treatments: Propagation of Cr(III) Crosslinking Complexes in Porous Media, SPE-27828-MS (1994).

Brattekas, B., Haugen, A., Graue, A. and Seright, R. S., Gel Dehydration by Spontaneous Imbibition of Brine from Aged Polymer Gel, SPE-153118-MS (2012).

Bryant, S. L., Borghi, G. P., Bartosek, M. and Lockhart, T. P., Experimental Investigation on the Injectivity of Phenol-Formaldehyde/Polymer Gels, SPE-52980-PA (1998).

Bryant, S. L., Rabaioli, M. R. and Lockhart, T. P., Influence of Syneresis of Permeability Reduction by Polymer Gels, SPE-35446-PA (1996).

Chauveteau, G., Tabary, R., Renard, M., Omari, A., Controlling In-Situ Gelation of Polyacrylamides by Zirconium for Water Shutoff, SPE-50752-MS (1999).

Chang, H. L., Sui, X., Xiao, L., Guo, Z., Yao, Y., Yiao, Y., Chen, G., Song, K. and Mack, J. C., Successful Field Pilot of In-Depth Colloidal Dispersion Gel (CDG) Technology in Daqing Oilfield, SPE-89460-PA (2006).

Chen, H., Zhang, S., Chu, Y., Yang, H. and Liu, F., Preparation and Use of Hydrophobically Associating Polymer Gelling Fluid for Water Injectivity Profile Modification in High Temperature and High Salinity Reservoirs, Oilfield Chemistry, 2004, Vol. 21, No. 4.

Chen, G., Ye, G., Han, J., Gu, Z. and Shen, Y., Two or Three Viewpoints on the Application of Testing Data of Weak Gel Flooding Control Effect Evaluation, Well Testing, 2002, Vol. 11, No.5.

Cui, H., Cui, Z., Lei, Y. and Zhang, Z., Profile Control Optimization of Weak Gel Flooding and Application Analysis of Nanbao 35-2 Oilfield, Petroleum Geology and Engineering, 2010, Vol. 24, No.4.

Dang, J., Zheng, F., Yang, J., and Song, Z., Laboratory Study on Thermal-stable Weak Gel System, Advances in Fine Petrochemicals, 2010, Vol. 11, No. 10.

Delshad, M., Varavei, A., Goudarzi, A., Zhang, H., Sepehrnoori, K., Bai, B., Hu, Y., Water Management in Mature Oil Fields using Preformed Particle Gels, SPE-165356-MS (2013).

Dovan, H. T. and Hutchins, R. D., Development of a New Aluminum/Polymer Gel System for Permeability Adjustment, SPE-12641-PA (1987).

Feng, Q., Guo, L., Zhang, X., Gao, S., Shi, H. and Wu, S., Study of Thermal Recovery Method of Steam and Flue Gas Combined with Gel Injection, SPE-157928-MS (2012).

Han, M., Alshehri, A. J., Krinis, D. and Lyngra, S., State-of-the-Art of In-Depth Fluid Diversion Technology: Enhanced Reservoir Oil Recovery by Gel Treatments, SPE-172186-MS (2014).

Harry, D. N., Moorhouse, R., Matthews, L. and Chen, G., Rheological Responses to Variations in Aqueous-Based Zirconium Crosslinker Chemistry, SPE-37280-MS (1997).

He, E., Du, Y., Luo, C., Jiang, M. and Wu, X., Field Test on Movable Gel as Profile Control and Fooding in Huabei Oilfield, Acta Petrolei Sinica, 2003, Vol. 24, No. 6.

He, Y, and Wang, X., Study and Application of Deep Profile Modification Technology in Shuanghe Oilfield, Journal of Yanan Univerisy, 2010, Vol. 29, No.4.

Hild, G. P. and Wachowski, R.k., Reservoir Polymer Gel Treatments to Improve Miscible CO2 Flood, SPE-56008-PA (1999).

Holtsclaw, J. and Funkhouser, G. P., A crosslinkable Synthetic-Polymer System for High-Temperature Hydraulic-Fracturing Applications, SPE-125250-PA (2010).

Hu, X., Wang, J. and Liu, P., Experimental Research on Thermostable Deep Oil Profile Control Agent, Advanced in Fine Petrochemicals, 2010, Vol. 11, No. 8.

Kantzas, A., Burger, D., Pow, M., Cheung, V. and Mourits, F., Design Strategies for Improved Conformance Using Polymer Gels, PETSOC-99-13-18 (1999).

Kohler, N., Rahbari, R., Han, M. and Zairoun, A., Weak Gel Formulations for Selective Control of Water Production in High-Permeability and High-Temperature Production Wells, SPE-25225-MS (1993).

Kosztin, B., Palasthy, Gy., Udvari, F., Benedek, L., Lakatos, I., and Lakatos-Szabo, J., Field Evaluation of Iron Hydroxide Gel Treatments, SPE-78351-MS (2002).

Krilov, Z., Tomic, M., Mesic, I., Domitrovic, D. and Myers, R. R., Water Shutoff in Extreme Hostile Environment: An Experimental Approach in Geologically Comple, Gas Condensate Reservoirs Using Cross-linked Gels, SPE-39676-MS (1998).

Kumar, S., Awang, M., Ahemed, S., Dehraj, N. U. H., and Saleem, Y. S., Worm-Like Micelles as a Mobility Control Agent for Chemical Enhanced Oil Recovery, SPE-176075-MS (2015).

Lantz, M. and Muniz, G., Conformance Improvement Using Polymer Gels: A Case Study Approach, SPE-169072-MS (2014).

Levitt, D. and Pope, G. A., Selection and Screening of Polymers for Enhanced-Oil Recovery, SPE-113845-MS (2008).

Lu, X., Wang, W., Wang, R., Liu, Y. and Shan, J., The Performance Characteristics of Cr3+ Polymer Gel and Its Application Analysis in Bohai Oilfield, SPE-130382-MS (2010).

Mack, J. C. and Smith, J. E., In-Depth Colloidal Dispersion Gels Improve Oil Recovery Efficiency, SPE-27780-MS (1994).

Maya, G., Castro, R., Sandoval, J., Pachon, Z., Jimenez, R., Pinto, K., Diaz, V., Zapata, J., Perdomo, L. and Munoz, S., Successful Polymer Gels Application in a Highly Channeled Peripheral Injection Well: Tello Field Pilot, SPE-169478-MS (2014).

Meister, J., Bulk Gel Strength Tester, SPE-13567-MS (1985).

Mumallah, N. A., A Practical Method for the Evaluation of Weak Gels, SPE-15142-PA (1987).

Muruaga, E., Flores, M. V., Norman, C. and Romero, J. L., Combining Bulk Gels and Colloidal Dispersion Gels for Improved Volumetric Sweep Efficiency in a Mature Waterflood, SPE-113334-MS (2008).

Moffitt, P. D., Moradi-Araghi, A., Ahmed, I., Janway, V. R. and Young, G. R., Development and Field Testing of a New Low Toxicity Polymer Crosslinking System, SPE-35173-MS (1996).

Nguyen, T. Q., Green, D. W., Willhite, G. P. and McCool, C. S., Effect of Composition of a Polyacrylamide-Chromium(III) Acetate Gel on the Magnitude of Gel Dehydration and Disproportionate Permeability Reduction, SPE-89404-MS (2004).

Norman, C. A., Smith, J. E. and Thompson, R. S., Economic of In-Depth Polymer Gel Processes, SPE-55632-MS (1999).

Pan, G., Chen, J., Zhang, C., Liu, D., Wu, J., Li, H., Fang, Z., Qu, J. and Zhang, J., Combined Technology of Weak Gel Flooding Assisting Thermal Huff and Puff Enhances Oil Recovery for Offshore Heavy Oil Field, SPE-181626-MS (2016).

Pu, W., Zhou, M., Zhao, J., Luo, X., Yang, Y. and Wang, J., Cr3+/Phenolic Resin Crosslinked Weak Gel and Its Use as Permeability Adjusting Oil Displacing Agent in Pucheng Oilfield, Oilfield Chemistry, 2004, Vol. 21, No.3.

Reddy, B. R., Eoff, L., Dalrymple, E. D., Black, K., Brown, D. and Rietjens, M., A Natural Polymer-Based Crosslinker System for Conformance Gel Systems, SPE-75163-MS (2002).

Saez, M., Paponi, H. M., Cabrera, F. A., Muniz, G., Romero, J. L. and Norman, C., Improving Volumetric Efficiency in an Unconsolidated Sandstone Reservoir with Sequential Injection of Polymer Gels, SPE-150492-MS (2012).

Seright, R. S., Polymer Gel Dehydration During Extrusion Through Fractures, SPE-56126-PA (1999).

Shen, P., Han, D., Wei, L. and Yuan, S., Experimental Evidences for the Mobility of Weak Gel in the Porous Media, SPE-64729-MS (2000).

Sheng, J. J., Modern Chemical Enhanced Oil Recovery-Theory Practice, 2011.

Sheng, J. J., Leonhardt, B. and Azri, N., Status of Polymer-Flooding Technology, SPE-174541-PA (2015).

Shriwal, P. and Lane, R. H., Impacts of Timing of Crosslinker Addition on Water Shutoff Polymer Gel Properties, SPE-153241-MS (2012).

Suleimanov, B. A. and Veliyev, E. F., Nanogels for Deep Reservoir Conformance Control, SPE-182534-MS (2016).

Sun, Q., Liu, R. and Li, R., Application of Ground Intelligent Injection System in Water Plugging and Profile Control, Advances in Fine Petrochemicals, 2010, 11(12).

Sydansk, R. D. and Southwell, G. P., More than 12 Years' Experience with a Successful Conformance-Control Polymer-Gel Technology, SPE-66558-PA (2000).

Tang, X., Liu, Y., Bai, B., Cai, L., Jiang, R. and Xiang, W., Study and Application of Weak Gel Using for an Offshore Oilfield, PETSOC-2005-076 (2005).

Tang, X, Liu, Y., Xiang, W., Liu, G., Jiang, R., Qin, H. and Pan, W., Study and Application of Deep Profile Controlling Agent in the SZ32-1 Oilfield, Bohai Bay Basin, Petroleum Exploration and Development, 2005, Vol. 32, No.6.

Topguder, N. N. S., A Review on Utilization of Crosslinked Polymer Gels for Improving Heavy Oil Recovery in Turkey, SPE-131267-MS (2010).

Wang, H., Guo, W. and Jiang, H., Study and Application of Weak Gel System Prepared by Complex Polymer Used for Depth Profile Modification, SPE-65379-MS (2001).

Wang, H., Wang, L., Wang, L., Wang, J., Development of HPAM/ALC$_6$H$_5$O$_7$ Weak Gel System and Its Gelling Mechanism, Advances in Fine Petrochemicals, 2009, Vol. 10, No. 5.

Wang, J., Yuan, Y., Peng, X., Li, F., Gu, H. and Xu, G., Study of In-Depth Weak Gel Flooding Fluid for Conglomerate Reservoir and Its Field Application, Advances in Fine Petrochemicals, 2006, Vol. 7 No.1.

Wang, P., Luo, J., Zhang, Y. and Bai, F., Non-Ion Polymer Weak Gel Used in the Profile Modification in High Temperature and High Salt Oilfield, Oil Drilling & Production Technology, 2002, Vol. 24, No.5.

Wang, W., Gu, Y. Liu, Y., Applications of Weak Gel for In-Depth Profile Modification and Oil Displacement, PETSOC-2002-168 (2002).

Welton, T. D., Bryant, J. and Funkhouser, G. P., Anionic Surfactant Gel Treatment Fluid, SPE-105815-MS (2007).

Yuan, S., Han, D., Wang, Q., and Yang, H., Numerical Simulation Study on Weak Gel Injection, SPE-64291-MS (2000).

Zhang, H., Colloidal Dispersion Gel Oil Flooding Technique Suitable for High-Temperature and High-Salinity Reservoirs of Zhongyuan Oilfield and Its Applications, Petroleum Geology & Oilfield Development in Daqing, 2005, Vol. 24, No. 2.

Zhao, H., Zhao, P., Bai, B., Xiao, L. and Liu, L., Using Associated Polymer Gels to Control Conformance for High Temperature and High Salinity Reservoirs, PETSOC-06-05-04 (2006).

Zheng, W., Li, W., Li, K., Liu, Z., Guo, B. and Wang, K., Application of Modulation and Displacement with Weak Gel in 2+3 Zones of the Upper Second Section of Shahejie Formation in Western Regions in Pucheng Oilfield, Fault-Block Oil & Gas Field, 2002, Vol.9, No.3.

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