

**The Laboratory Investigation of the Viscosity of EOR Polymers at
Various Salinity and Temperature**

BY:

IZZUL ASYRAF BIN MOHAMAD SALIM

15011

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons.)
(Petroleum Engineering)

January 2015

Universiti Teknologi PETRONAS
32610 Bandar Seri Iskandar,
PERAK DARUL RIDZUAN
MALAYSIA

CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Sia Chee Wee)

UNIVERSITI TEKNOLOGI PETRONAS
32610 BANDAR SRI ISKANDAR, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

IZZUL ASYRAF BIN MOHAMAD SALIM

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ABSTRACT

Several experiments were conducted to verify the effect of salinity and temperature to EOR polymer solutions viscosity. The viscosity of these hydrolysed polyacrylamide solution A, B and C was affected by salinity and testing temperature. The flow behaviour index, n and flow consistency index, k and viscosity of these hydrolysed polyacrylamide solutions were systematically determined over a wide range of temperatures (25 - 90°C) and salinity (5000 – 70000 ppm), using a rotational rheometer Model 1100 Pressurized Viscometer. The outcomes of these measurements suggest that the rheological behaviour of 1000 ppm polymer solution behaves like a non-Newtonian fluid at all the set ranges.

The flow behaviour index of these polymer solutions exhibited shear-thinning non-Newtonian fluid (pseudoplastic) character as it is lower than unity. The effect of temperature on the consistency coefficient and flow behaviour index of polymer solution of the different salinity followed an Arrhenius-type relationship. The viscosity of all polymer solution decreased at most increasing temperature and salinity.

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Special thanks go to Hibri Hafiz for the help in obtaining more information about the background of this project. Last but not least, many thanks go to the project coordinators, Mr. Titus Ntow Ofei and Dr. Syahrir Ridha for their time and effort in managing the occurrence of this project. Lastly, I would like to thank my family and friends for their support throughout this project.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Polymers are widely used in oil and gas industries such as in polymer flooding in Enhanced Oil Recovery (EOR). In field, polymer solution is made by mixing polymer powder with brine.

One of the techniques for increasing the amount of oil that can be extracted from an oilfield is Enhanced Oil Recovery (EOR). Chemical EOR is one of the methods in extracting remaining oil from the oilfield. According to Kirk (2011), chemical EOR is the most applicable method to increase the sweep efficiency of the oil in the offshore environment, primarily due to logistics and energy requirement.

One of the most assuring EOR processes in any reservoirs is polymer flooding due to its affordable cost (Da Silva *et. al.*, 2007). In year 2011, the cost of polymer is around USD 1.5/bbl to USD 3/bbl. Exponential increment of polymer flooding projects is because of polymer's affordable price in the U.S.A. In 2011, for mobility-control EOR purpose, nearly 1 billion lbs of polymer was used (Pope, 2011).

Water soluble polyacrylamide (HPAM), Xhantan Gum (Xc), and associative polymer (AP) are the polymers that are mainly used in oilfields. In contrast to water, polymer solution shows rheological behaviour of non-Newtonian fluid, such as shear thickening and shear thinning effects which lead to various viscosity properties in a reservoir.

As polymer solution is injected into a reservoir from an injection well, flow velocity will change. Polymer rheology is affected by molecular weight, polymer type, concentration, water salinity in the reservoir, and reservoir permeability in a porous media. According to Yong *et. al* (2012), polymer rheology and retention behaviour of the polymer solutions through a porous media are complex subjects.

Viscosity for different shear rate can be measured or it can be calculated by Darcy law which describes the effect of porous media towards fluid flow. The viscosity in coreflooding experiment is usually not constant since polymer solution used in EOR is a non-Newtonian fluid type. In polymer flooding, apparent viscosity is often used. (Yong *et. al.*, 2012).

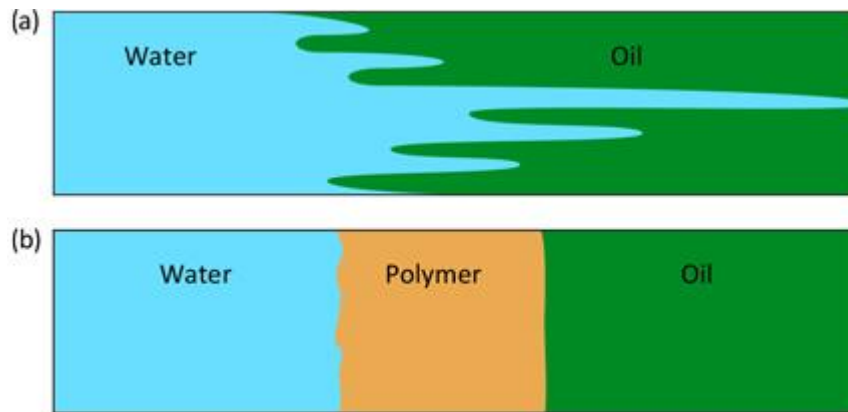


Figure 1.1. Comparison of Water and Polymer Injection (Hanssens, 2014)

Figure 1.1 shows the comparison of water and polymer injection. After the secondary stage, large amount of oil remains in the reservoir due to poor sweep and capillary trapping. Poor sweep occurs for some reasons, and one of the main causes is “Fingering Effect “(Sydansk & Romero-Zerón, 2011). The fingering effect displacement was shown in Figure 1.1. Severe fingering effect occurs due to high mobility ratio, M .

1.2 Problem Statement

The apparent viscosity of polymer is important in polymer flooding process as the viscosity of the polymer affects the mobility ratio of the flooding. Mobility ratio is the ratio of water mobility to oil mobility. As the ratio increases, sweep efficiency decreases.

$$\text{Mobility ratio, } M = \frac{\lambda_{\text{water}}}{\lambda_{\text{oil}}} \quad \dots\dots\dots\text{Equation 1}$$

Mobility of Water, $\lambda = \frac{k_{rw}}{\mu_w}$ **Equation 2**

Mobility ratio is an indication of the stability of a displacement process. When M is greater than 1.0, flow tends to become unstable (non-uniform displacement front or viscous fingering). Thus, a large mobility ratio (unfavourable M) is generated due to large viscosity contrast between the displacing fluid (*i.e.* water) and the displaced fluid (*i.e.* oil). This will promote the fingering of water through the more viscous oil and reduces the oil recovery efficiency (Sydansk & Romero-Zerón, 2011).

However, the rheological properties of polymer solutions could not be used directly to predict the pressure-to-flow relationship in porous media since it is measured by conventional rheological instruments which strive to produce pure shear flow (Yong *et. al.*, 2012).

The main concerns regarding polymer flooding applications are the effects of salinity and temperature of formation's water on the stability of polymer solutions. Stability of polymer solutions in high salinity and high temperature reservoirs is challenging to be sustained.. Therefore, implementing polymer flood requires critical evaluations on the subject matter (Levitt *et. al.*, 2013). Hence, the behaviour of a particular polymer solution in high temperature and high salinity water should be investigated upon the execution of the matter.

It is unknown whether the flow behaviour of polymer solution conforms to power law for a wide range of shear rates. The power law is given as in **Equation 3**,

$\tau = K \gamma^n$ **Equation 3**

Where, τ is the shear stress (N.m⁻²); K is the consistency coefficient (Pa.s ^{n}); γ is the shear rate (s⁻¹); n is flow behaviour index (dimensionless). The flow behaviour index, n is a measure of the non-Newtonian behaviour.

The value of n is less than unity for shear thinning substances while flow consistency index, K is a function of the viscosity of the solution. These constants can be used as an estimate of the polymer solution viscosity when there are no experimentally determined values (Shawki, 1979).

1.3 Objectives

This project focuses on few objectives, which are:

1. To study the viscosity of polymers in different range of salinity (0 – 70000 ppm) and temperature (25 to 90°C).
2. To measure and study the trend of flow behaviour index, n and flow behaviour index, k for each polymer.

1.4 Scopes of Study

This laboratory investigation focuses on the effect of temperature and salinity towards the apparent viscosity of polymer solutions respectively. Hence, the optimum temperature and salinity of the polymer solution were obtained. Additionally, the study of the flow constants, (n & K) of the polymer solutions would be analysed to classify the solutions as non-Newtonian fluid or otherwise.

Specific classification of these polymer solutions is determined as the flow behaviour index, n is less than unity for a shear thinning substances. Concurrently, n is larger than unity for a shear thickening substances. This laboratory investigation relates the temperature effect and flow constants using the Arrhenius relation.

CHAPTER 2

LITERATURE REVIEW

As this laboratory investigation is mainly about polymer, a non-Newtonian fluid, the factor that might affect the rheology properties should be conceded to achieve accurate results. The rheology term refers to fluid matter study, liquid state as the primary fluid, or solids under conditions in which rather than deforming elastically in response to an applied force they respond with plastic flow. (Schowalter, 1978).

2.1 Shear Rate

Shear rate is the rate of deformation of fluid (Darby, 2001). Since most of polymer solutions are non-Newtonian fluids, they are not follow-on in linear relationship between shear rate versus viscosity. Shear rate should be defined for any given viscosity. Fluid actual velocity, permeability and porosity are related to the average porous media's shear rate.

2.2 Apparent viscosity

In Measurement and Impact Factors of Polymer Rheology in Porous Media, Rheology, by Juan De Vicente, he stated that one of the most popular theoretical calculations that explain solution flow via porous media is Darcy's law as shown in **Equation 4**:

$$Q = \frac{kA\Delta P}{\mu L} \dots\dots\dots \text{Equation 4}$$

Where, Q is the volume of the liquid at time interval in $\text{cm}\cdot\text{s}^{-1}$; L is the length of sample in macroscopic flow in cm; A is the cross-sectional area in cm^2 ; μ represents viscosity of a flowing fluid via porous media in $\text{mPa}\cdot\text{s}$; ΔP is pressure drop across porous media in atm; k represents absolute permeability in Darcy for the porous media.

Since polymer solution which is favourable in EOR process is a non-Newtonian fluid; therefore, viscosity μ in Eq.3 is unlikely to remain constant. Apparent viscosity, μ_{app}

in polymer flooding, is formulated as follow:

$$\mu_{app} = \frac{kA\Delta P}{QL} \dots\dots\dots \text{Equation 5}$$

In pore surfaces polymer retained and reduces the porous media permeability. Thus, in **Equation 5**, μ_{app} is changing as it is affected by flow rate and rock permeability.

2.3 Polymer Mechanical Degradation

The tests involve high shear rate which is applied on the polymer solution. Mechanical degradation formed is inevitable. Sufficiently high-flow shear rate degrade all dissolved polymers mechanically. Even before the flooding of polymer process start, high- flow shear rates formed in surface-injection equipment such as orifices, pumps, valves, and tubing. Also, at downhole constrictions for example perforations, tubing orifices, or screens. Also in the injection well at formation face (Lake 1989). Due to the degradation, each sample is only valid for one test to avoid the error caused mechanically.

2.4 Viscosity

As shown in **Equation 6**, viscosity can be defined as the ratio of the imposed shear stress(force F , applied tangentially, divided by the area A), and times the shear rate (velocity V , divided by the gap h).

$$\mu = \frac{F}{A} \times \frac{h}{v} \dots\dots\dots \text{Equation 6}$$

Meanwhile, in fluid flowing via round tube or between two flat plates, the shear stress varies linearly from zero along the central axis to a maximum value along the wall. The shear rate change nonlinearly starting from zero along the central axis to a maximum along the wall. The velocity profile is quasi-parabolic with a maximum at the plane of symmetry and zero at the wall as shown in Figure 2.1, for flow between two flat plates.

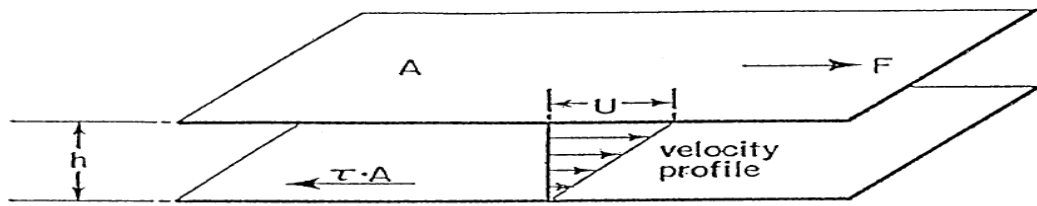


Figure 2.1. Simple Shear Flow (Strutt, 2014)

2.5 Flow Behavior Index

In order to determine the flow behaviour index, n , of a pseudoplastic behavior shown by sample, from different measurements of the stability at various speeds with the exact same spindle and at the same temperature (Durgueil, 1987). This statement explained that, the flow behaviour index for each polymer solutions would vary with different temperature.

2.6 Effect of temperature on the rheological characteristics

The relationship between the temperature and rheological characteristics (i.e. consistency coefficient and flow behavior index) is expressed by the following Arrhenius relationship is shown in **Equation 7** and **Equation 8**.

$$n = n_o e^{\left(\frac{-E_a}{RT}\right)} \dots\dots\dots \text{Equation 7}$$

$$K = K_o e^{\left(\frac{E_a}{RT}\right)} \dots\dots\dots \text{Equation 8}$$

Where, n_o and k_o represent constants; E_a represents the activation energy ($\text{cal}[\text{g}\cdot\text{mole}]^{-1}$), R represents the gas constant ($\text{cal}[\text{g}\cdot\text{mole}\cdot\text{K}]^{-1}$), and T is the absolute temperature, K. As shown in **Equation 7** and **Equation 8**, an increase in the temperature leads to decrease in a consistency coefficient and increase in flow behavior index. Currently, it is best seen as an empirical relationship. It can be used to model the temperature variation of diffusion coefficients, population of crystal vacancies, creep rates, and many other thermally-induced processes or reactions. (Kenneth, 1990).

2.7 Salinity

According to Chinese Oceanic Information Network, on March 2015, the minimum salinity of southern China Sea occurs at the northern coast Malaysia, less than 31000 ppm. When the northeast monsoon prevails, the surface temperature is low and salinity is high. When the southwest monsoon prevails, the surface temperature is high and salinity is low. Thus, the selected salinity amount for this experimental ranging from 0 ppm to 70000 ppm, mimic the average salinity amount of northern coast Malaysian seawater which is 31000 ppm especially at 30000 ppm.

2.8 Temperature

Since EOR process is time-consuming, hereby polymer stability is an important factor. Basically, hydrolysis level is required not to go more than 40% after three months. However, in case of polyacrylamide, hydrolysis goes very fast under acidic and basic conditions. At high temperature levels, the hydrolysis occurs fast under neutral conditions as well. Hereby it becomes obvious that HPAM is not being tolerant to high temperature or high salinity (Wang *et al.*, 2003). It is consistent with the founding of recent tests result that in some high-temperature (over 90°C) reservoirs, normal polymer product HPAM will degrade and cease to be effective (Youyi *et. al*, 2012). Thus, the temperature for this experimental was ranging from 25°C to 90°C to observe the tolerance of the polymer solutions.

2.9 Polymer Concentration

In 2013, a simulation study has been run by Pasha Huseynli in the Norne Field E-Segment on three different concentration values to investigate polymer concentration effect. The graphs below show the results of study with polymer concentration of 300, 600, 900 ppm. In this case water is injected for the first eight years from 1997 to 2005 then polymer injection lasts from 2006 to 2009 and finally from 2009 to 2017 water is injected.

Total oil, water and polymer production, the production rate of oil and water, reservoir pressure and bottom-hole pressure of injection well (F-3H) have been plotted for analysis.

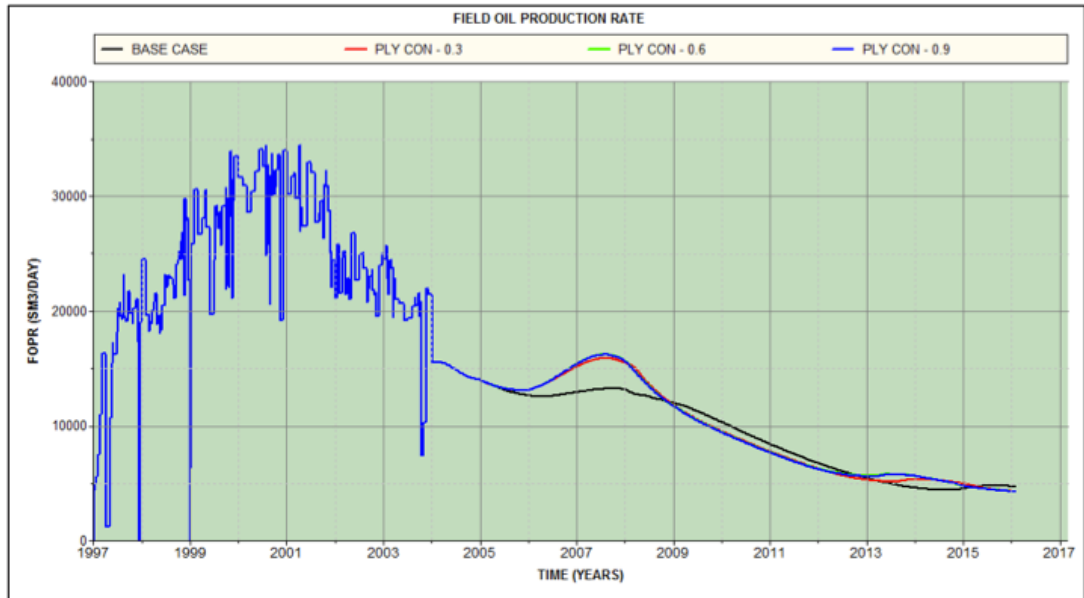


Figure 2.2. Oil production rate at different polymer concentrations.

Figure 2.2 illustrates that polymer flooding causes higher oil recovery as compare to water flooding where red line curve shows the result of polymer flooding at concentration of 300 ppm green line curve injection at concentration of 600 ppm while blue one injection of chemical at concentration of 900 ppm.

From the figure above it is obvious that after applying the polymer flooding in 2006, increasing oil production rate and the highest oil production for all injected polymer concentrations is attained between 2007 and 2009, then hydrocarbon production rate came down the base case.

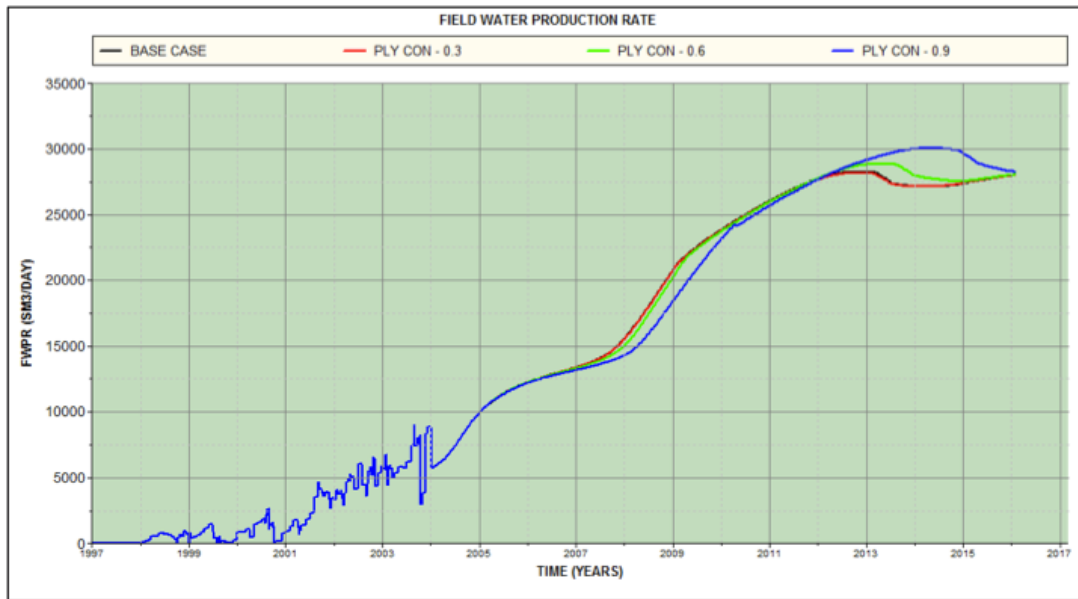


Figure 2.3. Water production rate at different polymer concentrations.

From figure 2.3 it is clear that the polymer injection has a great effect on sweep efficiency. Polymer flooding at concentration of 900 ppm causes enhanced sweep efficiency and less field water production compare to base case. Despite the fact that the water production rate is lower at early stage, it increases faster over other cases after 2012.

It can be concluded that 900 ppm of polymer solution is the preferred amount of concentration in obtaining great sweep efficiency for Norne Field E-Segment. Hence, 1000 ppm of polymer solution was selected as the concentration of polymer in the experimental.

2.10 Hydrolyzed polyacrylamide

Wide specter of EOR applications includes HPAM as the one, which is widely used (Manrique *et al.*, 2007). This type of polymers for improved recovery is that HPAM solutions have better viscoelasticity, compared to xanthan solutions (Wang *et al.*, 2006). Polyacrylamide is able to adsorb strongly on mineral surfaces. Hereby, the polymer is being partially hydrolysed in order to reduce adsorption through the reaction of polyacrylamide with a base, like sodium or potassium hydroxide as well as sodium carbonate. Hydrolysis process converts some of amide groups (CONH^2) into carboxyl groups (COO^-). Figure 2.4 demonstrates this process.

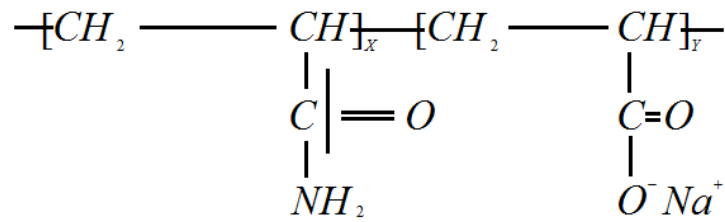


Figure 2.4. Hydrolysis process of HPAM.

The degree of hydrolysis represents the mole fraction of amide groups, which have been converted by hydrolysis. Its value usually ranges from 15 up to 35% for commercial products.

The process of polyacrylamide hydrolysis introduces negative charges on the backbones of polymer chains. This results in a significant effect on the rheological properties of the polymer solution itself. At low values of salinities, the negative charges on the polymer backbones tend to repel each other and, as result, polymer chains stretch. In case of addition of an electrolyte, such as sodium chloride, the repulsive forces are being shielded by a double layer of electrolyte and that reduces the chain stretch.

When the values of hydrolysis go above 40%, the flexible chains are being significantly compressed as well as distorted, and that results in viscosity reduction. For example, in hard waters (with high contents of calcium and magnesium ion), as hydrolysis goes beyond 40%, flocculation may occur. Flocculation represents the process where colloids leave the suspension in the form of floc or flake. This may happen both spontaneously and as a result of clarifying agent addition. This action is different from precipitation, because before the flocculation occurs, colloids are simply being suspended in a liquid and not dissolved in a solution.

Since EOR process is time-consuming, hereby polymer stability is an important factor. Basically, hydrolysis level is required not to go more than 40% after three months. However, in case of polyacrylamide, hydrolysis goes very fast under acidic and basic conditions. At high temperature levels, the hydrolysis occurs fast under neutral conditions as well. Hereby it becomes obvious that HPAM is not being

tolerant to high temperature or high salinity (Wang *et al.*, 2003).

2.11 Extensional thickening time

Extensional thickening time is the time required for the polymer molecules to pass through the pores (Kaminsky *et al.*, 2007). It can be measured in coreflooding tests since the polymer solutions are flowing through pores unlike the rheometer. Different type of polymer would have different extensional thickening.

CHAPTER 3

METHODOLOGY

Different findings, observations and methodologies are gathered from the research works of other researchers, who were dealing with topics related to the present study. These findings are to be studied in details and incorporated in this project.

The relevancy of findings should be verified in order to ensure that the entire project has been accomplished according to anticipated plan. Initially, various journals as well as technical papers have to be read through to get the general understanding of the project and obtain the major factors that influence polymeric solution during polymer flooding. The steps of this laboratory investigation are as below:

Literature Review

- Preliminary research on existing studies on the topic from articles.
- Understand the rheological properties of polymers.

Polymer solution preparation

- Select polymers with suitable rheological properties which is hydrolysed polyacrylamide type. The reason to select this type of polymers for EOR is because of HPAM solutions have better viscoelasticity compared to xanthan solutions. This is also due to the fact that it has low adsorption rate to mineral surfaces compared to polyacrylamide solution as it undergoes hydrolysis process (Wang *et al.*, 2006).
- It is concluded that 900 ppm of polymer solution is the preferred amount of concentration in obtaining great sweep efficiency for Norne Field E-Segment. However, as consulted by Siti Rohaida from PETRONAS Research Sdn. Bhd., 1000 ppm of polymer solution was selected for the experimental study. 1000 ppm of polymer solution would enhance the sweeping efficiency with reasonable cost factor.

Experiment

- Viscosity of the polymer solutions are measured in different ranges of temperature. HPAM is not being tolerant to high temperature or high salinity since at high temperature levels, the hydrolysis occurs fast under neutral conditions as well (Wang *et al.*, 2003). Thus, the temperature for this experimental study was ranging from 25°C to 90°C to observe the tolerance of the polymer solutions.
- The viscosity of polymer solutions is measured in different ranges of salinity. According to Chinese Oceanic Information Network, salinity occurs at the northern coast Malaysia, is less than 31000 ppm. Thus, the selected salinity for this experimental ranging from 0 ppm to 70000 ppm, mimic the average salinity amount of northern coast Malaysian seawater which is 31000 ppm.
- The flow constants of polymer solution are measured.

Data Collection

- The results are exported.
- The data collected is analysed.

Conclusion

- Explain the effect of temperature and salinity amount of polymer solutions towards its apparent viscosity.
- Classify each type of polymer solutions.
- Explain the trend of the flow constant with the Arrhenius relations.

3.1 SAMPLES AND EQUIPMENT

3.1.1 Equipment

Equipment used in this project is Model 1100 Pressurized Viscometer. Viscometer is one of the conventional rheological instruments that measure viscosity of fluids. This system precisely measures the fluid behavior of fracturing fluids and drilling fluids which involve shear stress, shear rate, time, and temperature at pressure up to 2500 psi and it is fully-automated. It capable to conduct test up to 2,500 psi (17.2 MPa) with temperature up to

500°F (260°C). It operates by using traditional Bobs and Rotor for measurements that are easy-to-translate (shear stress range 0 - 4000 dynes/cm²) which enabled rheograms (shear stress versus shear rate diagram) to be constructed.

3.1.2 Polymer Preparation.

Polymers used in this experiment were obtained from PETRONAS Research Sdn. Bhd. The materials and preparation of polymer are briefly explained in the next section. Three different polymers are chosen to undergo the tests.

Table 1. Characteristics of polymer solutions of A, B and C

Polymer Solution	Type	Molecular Weight (10 x 10 ⁶ Dalton)
A	HPAM	12
B	HPAM	18
C	HPAM	12

The polymers are prepared in stock solution that in concentration of 5000 ppm. After that it will be diluted in concentrations that are needed. The steps to prepare polymer stock solution are:

1. The amount of brine and polymer were calculated as follow:
 - i. Example, prepare 200ml of 5000ppm Polymer A.
 - ii. Amount polymer;
 $5000 \text{ ppm} = 5000 \text{ mg/L}$
 $5000 \text{ mg/L} \times 0.2 \text{ L} = 1000 \text{ mg} = 1 \text{ g}$
 - iii. Amount brine;
 $200 \text{ ml} = 200 \text{ g}$
 $200 \text{ ml} - 1 \text{ g} = 199 \text{ g}$
2. Then the dry polymer and the calculated weigh of the brine was put into a beaker.
3. The brine was stir using overhead stirrer at 400 rpm.



Figure 3.1 Typical polymer mixing.

4. The polymer powder was sprinkled into the vortex over 30 seconds. The solution, was observed make sure there is no fish-eye should present.

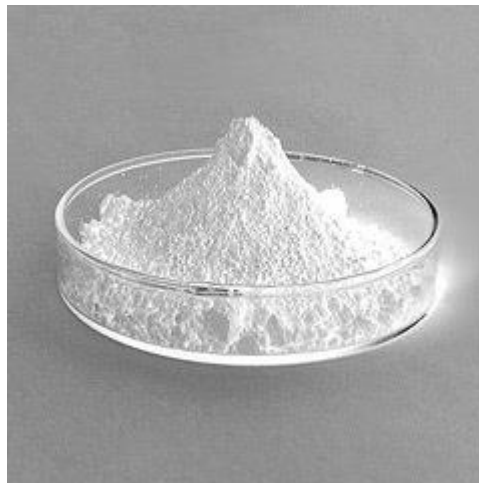


Figure 3.2 Typical polymer powder.

5. The solution was stir for 2 hours. Then let the solution overnight before dilute it.
6. Un-dissolved particles was checked, presence of un-dissolved particles requires a start over

Figure of polymer stock solution A, B and C are shown below; no precipitation or fish-eye observed:

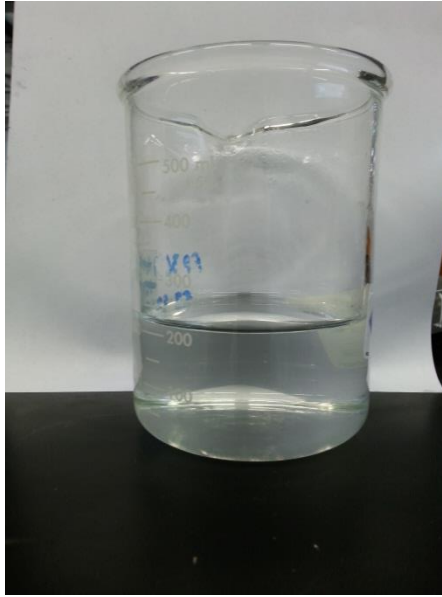


Figure 3.3 5000 ppm of polymer stock solution A

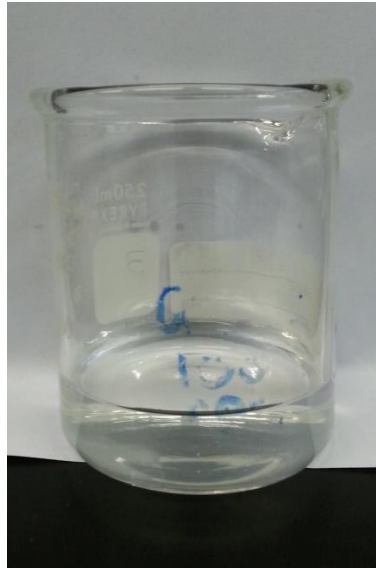


Figure 3.4 5000 ppm of polymer stock solution B



Figure 3.5 5000 ppm of polymer stock solution C

3.1.3 Polymer Mixing.

The steps for polymer dilution are:

Amount of polymer and saline water was calculated as follow:

Example, prepare 50g of 1000mg/L Polymer A in saline water. For a polymer with an active ingredient is 88.2%.

Amount of polymer A, V_1 ;

$$M_1V_1 = M_2V_2$$

$$(5000)(0.882)V_1 = (1000)(50)$$

$$V_1 = 11.34 \text{ g}$$

Amount of saline water;

$$50 \text{ ml} = 50 \text{ g}$$

$$50.00 \text{ g} - 11.34 \text{ g} = 38.66 \text{ g}$$

1. The weight of the polymer and amount of brine was measured. It was put into the beaker and stirred.
2. The polymer was stirred for ½ hour to get homogenous solution.
3. Solution is ready to be used for screening.

3.2 Viscosity Measurement

3.2.1 Viscosity and flow constant measurement:

1. 52 cm³ of fluid was placed into the viscometer slowly to avoid producing bubbles. This volume is sufficient to fully cover the bob.
2. Each new shear rate shall be attained within the first 5 s after completing data collection at the previous shear rate.
3. The shear rates during a ramp shall occur in the sequence specified, however the sequence of rates may be either monotonically increasing or decreasing.
4. The data recorded was exported.



Figure 3.4 OFITE Model 1100 Pressurized Viscometer

3.2.2 Calculation of shear stress and shear rate of rotational viscometer :

$$\tau = \frac{M}{2\pi.R^2.L} \dots\dots\dots\text{Equation 9}$$

In Eq. 9, M is the torque, in newton metres (lbf.ft), L is the stationary inner cylinder length, in metres (feet), R is the radius of the stationary cylinder, in metres (feet).

$$\gamma = \frac{2\omega}{\left[1 - \left(\frac{R_i}{R_o}\right)^2\right]} \dots\dots\dots\text{Equation 10}$$

In Eq. 10, γ is the nominal shear rate at the surface of the stationary inner cylinder, in reciprocal seconds; ω is the angular velocity of the rotating outer cylinder, in radians per second; R_i is the radius of the inner stationary cylinder, in metres (feet); R_o is the inner radius of the outer rotating cylinder, in metres (feet).

This method of calculations are retrieved from the Recommended Practice for the Measurement of Viscous Properties of Completion Fluids ANSI/API Recommended Practice 13M First Edition, July 2004 Identical to ISO 13503-1: 2003

3.3 GANTT CHART

Table 2. Project Gantt chart

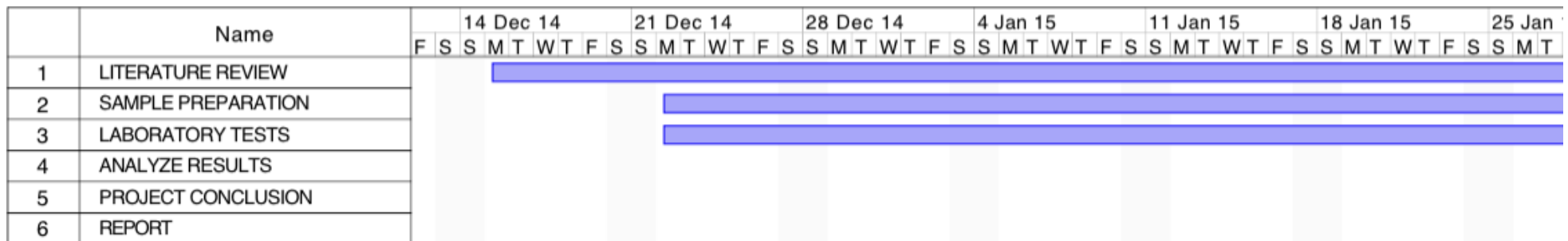
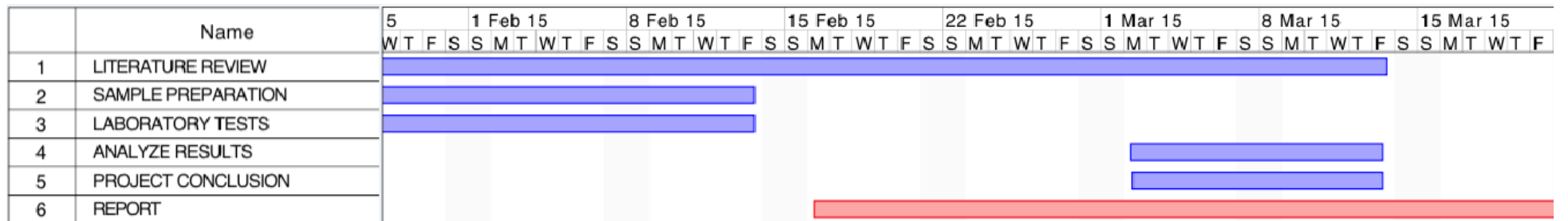


Table 3. Project Gantt chart



CHAPTER 4

RESULTS AND DISCUSSION

The expected result for the test is the polymer show variety range of viscosity but still exhibits non – Newtonian fluid characteristics. The purpose of this laboratory investigation is to observe the behaviour of polymer solution at different range of salinity and temperature.

The polymer solution that could maintain low viscosity in high temperature is desirable and at the same time not degraded due to the temperature effect (thermal degradation). High salinity solution might affect the effectiveness of the polymer.

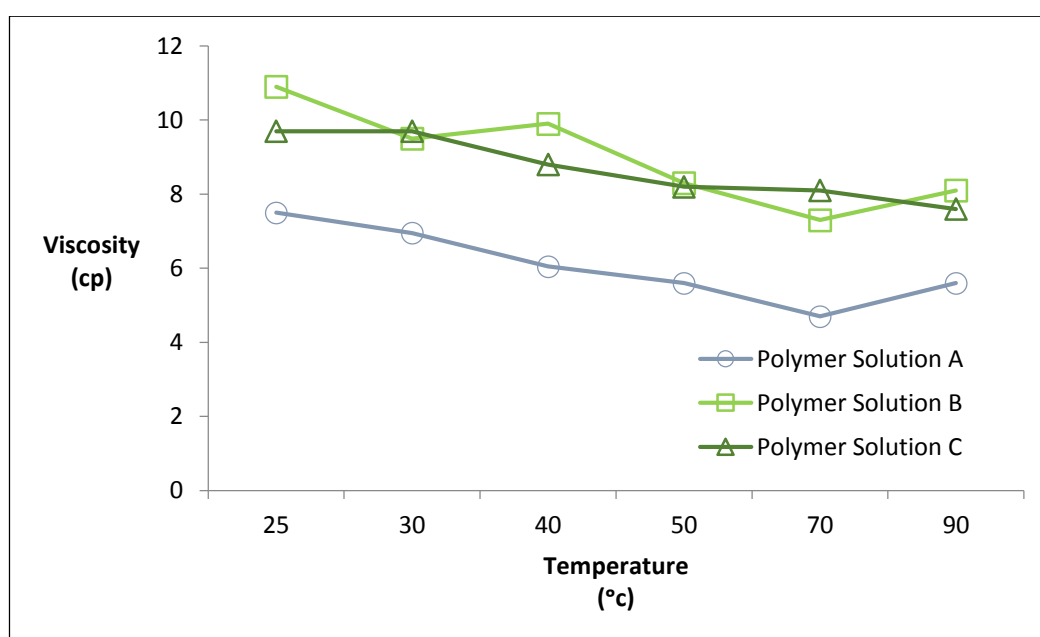


Figure 9. Apparent Viscosity against Temperature of 1000 ppm Polymer A, B and C Solutions

Figure 9 shows apparent viscosity of polymer solutions at rpm of 600 of each test. The polymer solution of 1000 ppm shows significant drop of apparent viscosity with increasing temperature. It can be seen from Figure 9 that at temperature 25 to 90°C, viscosity of all three polymer solutions decreased from 7.8cp to 6cp, 11cp to 8cp and 9.5cp to 8cp for polymer solution A, B and C respectively. Overall, it can be

concluded that polymer solution B and C exhibit higher viscosity compared to polymer solution A at the temperature range. It was expected that the viscosity is dropping as the temperature increased. The finding from this investigation is consistent with the expectation as shown in Figure 9.

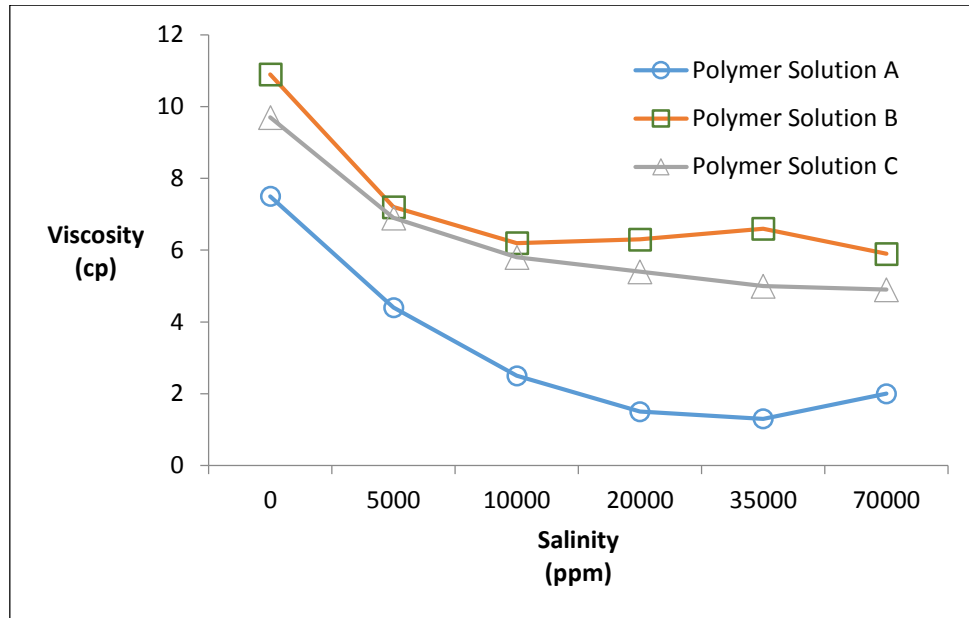


Figure 10. Apparent Viscosity against Salinity of 1000 ppm Polymer A, B and C Solution

Figure 10 shows the apparent viscosity Polymer A, B and C solutions of 1000 ppm ran at 600 rpm,. The apparent viscosity drops significantly with increasing salinity. It can be seen from Figure 10, at increasing salinity from 0 ppm to 70000 ppm, viscosity of all three polymer solution decreased. Obviously, the polymer solutions perform best at 0 ppm salinity. A swift drop of viscosity for all three polymer solutions can be observed at the salinity of 5000 ppm. From the plot, the viscosity stabilises at 10000 ppm of salinity.

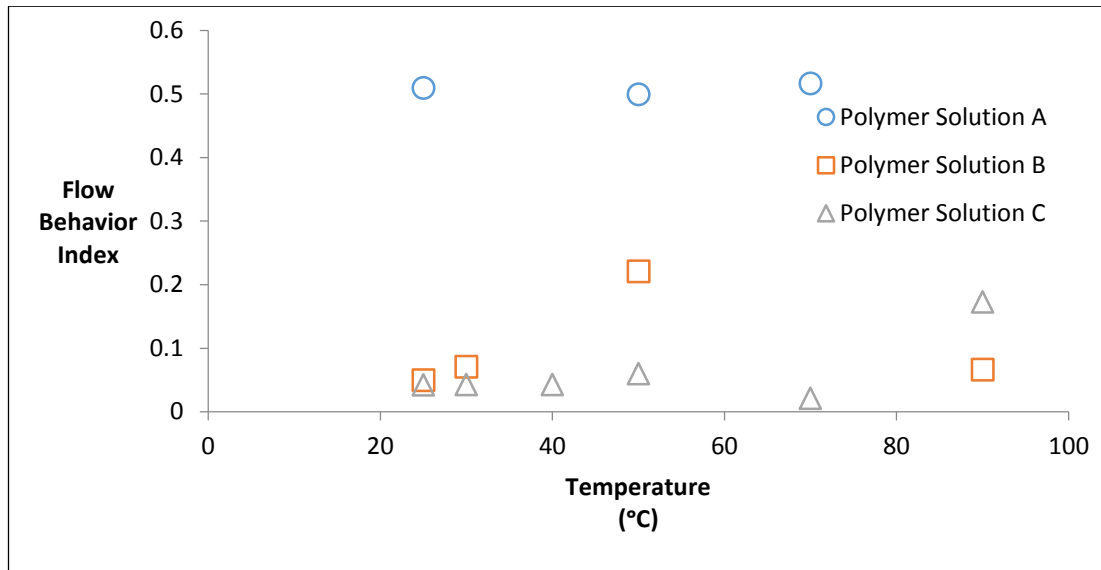


Figure 11. Flow Behaviour Index against Temperature of 1000 ppm Polymer A,B and C Solutions

Figure 11 illustrates that the flow behaviour index of these polymer solutions increase with increasing temperature which is consistent with the Arrhenius relations. In addition, these polymer solutions exhibit shear-thinning characteristic as the flow behaviour index less than unity. It can be concluded that the apparent viscosity of these polymer solutions would decrease as the injection rate increased in the porous media. It is possible that these polymer solutions have low extensional thickening time since the viscosity decrease upon injection through the porous media. As the polymer solutions flow deeper in the reservoir, the viscosity would decrease hence, the sweeping efficient would decrease.

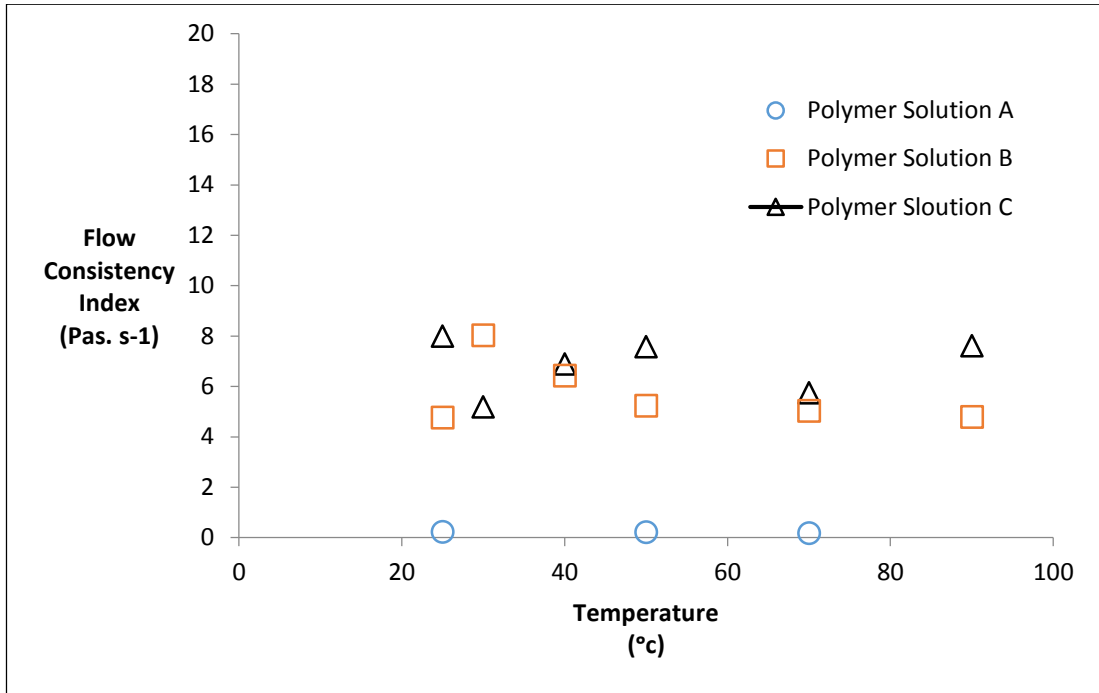


Figure 12. Flow Consistency Index against Temperature of 1000 ppm Polymer A, B and C Solutions

Figure 12 shows that the flow consistency index of polymer solution decreased with increase in temperature. However, the effect of temperature towards the flow consistency indexes of Polymer solutions B and C are not stable. There are two outliers found for Polymer solution C at 30 and 90 °C. These outliers probably occur due to error during the sample preparation or testing process. The flow consistency index for polymer solution A approaches zero at all temperature set. Overall, it was found that the effect of temperature on the consistency coefficient of polymer solution of the different salinity followed Arrhenius type relationship. Based on the measurement and with the aid from Fig. 12, it can be concluded that the flow consistency index, K is about constant. Further analysis using F -Test analysis should be conducted to verify this visual inspection.

One-Way ANOVA test was done on the flow behaviour index of Polymer Solution A, B and C.

The null and alternative hypotheses of this F -test are

Null hypothesis, H_o = the effect of temperature on the flow behaviour index of polymer solution is insignificant;

$$H_o : n_{\text{polymerA}} = n_{\text{polymerB}} = n_{\text{polymerC}}$$

Alternative hypothesis, H_o = notable difference on flow behaviour index of polymer solution when temperature changes;

$$H_o : \text{at least one flow behaviour index is different}$$

Reject if $F > F_{crit}$, otherwise do not reject and the probability to commit type 1 error is 0.05, ($\alpha = 0.05$).

Table 4. ANOVA Test for Flow Behaviour Index of Polymer Solution A, B and C

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	92.10275	2	46.05137	37.60048	6.79E-06	3.885294
Within Groups	14.69706	12	1.224755			
Total	106.7998	14				

Based on One-Way ANOVA with 95% confidence, there is no proof of statistical evidence that the flow behaviour index is constant.

One-Way ANOVA test was also done on the flow consistency index of Polymer Solution A, B and C.

The null and alternative hypotheses of this F -test are

Null hypothesis, H_o = the effect of temperature on the flow consistency index of polymer solution is insignificant;

$$H_o : n_{\text{polymerA}} = n_{\text{polymerB}} = n_{\text{polymerC}}$$

Alternative hypothesis, H_o = notable difference on flow consistency index of polymer solution when temperature changes;

$$H_o : \text{at least one flow consistency index is different}$$

Reject if $F > F_{crit}$, otherwise do not reject and the probability to commit type 1 error is 0.05, ($\alpha = 0.05$).

Table 5. ANOVA Test for Flow Consistency Index of Polymer Solution A, B and C

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.429448	2	0.214724	62.58307	2.22E-06	4.102821
Within Groups	0.03431	10	0.003431			
Total	0.463759	12				

Based on One-Way ANOVA with 95% confidence, there is no proof of statistical evidence that the flow consistency index is constant.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The effect of temperature and concentration on rheological behaviour of polymer solution were examined in the temperature range 25 - 90°C and salinity range 5000 – 70000 ppm, using a rotational rheometer. The rheological behaviours of 1000 ppm concentration of all three polymer solutions behave as non-Newtonian, shear-thinning fluid.

Polymer solution B & C was found more stable as the temperature increase compared to polymer solution A. The salinity test results show that the reduction of viscosity of polymer solution B & C is not significant from 5000 ppm to 70000 ppm. However, viscosity of polymer solution A decreased significantly as salinity increased.

The consistency coefficient of polymer solution decreased and flow behaviour index of polymer solution increased with increase in temperature. It was found that the effect of temperature on the consistency coefficient and flow behaviour index of polymer solution of the different salinity followed Arrhenius type relationship.

5.2 Recommendation

Several recommendations for the laboratory tests:

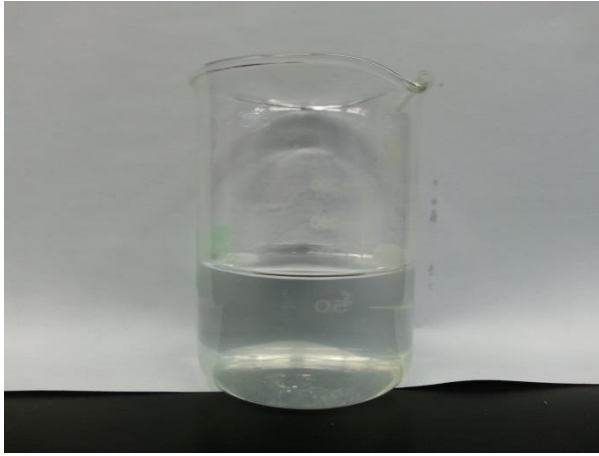
1. The mother stock of polymer should be left overnight to achieve stability.
2. Polymer solution that able to retain high shear rate should be selected to avoid mechanical degradation.
3. The mother stock polymer should not be mixed with brine consisting high contents of Calcium ion and Magnesium ion, to avoid flocculation occur as mentioned in the literature review section.
4. The test should be extended to higher temperature to observe the degradation point of the polymer solutions.

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APPENDICES



Appendix 1. 1000 ppm of polymer solution A with 0 ppm of salinity



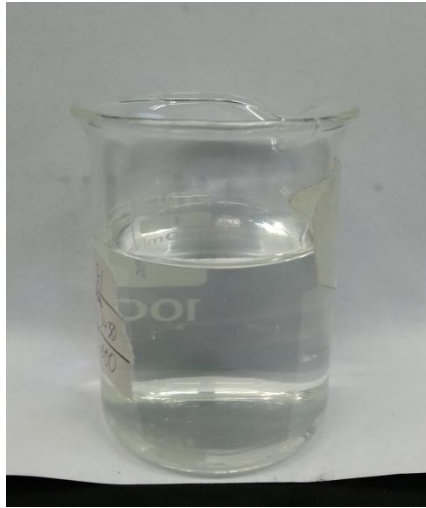
Appendix 2. 1000 ppm of polymer solution A with 5000 ppm of salinity



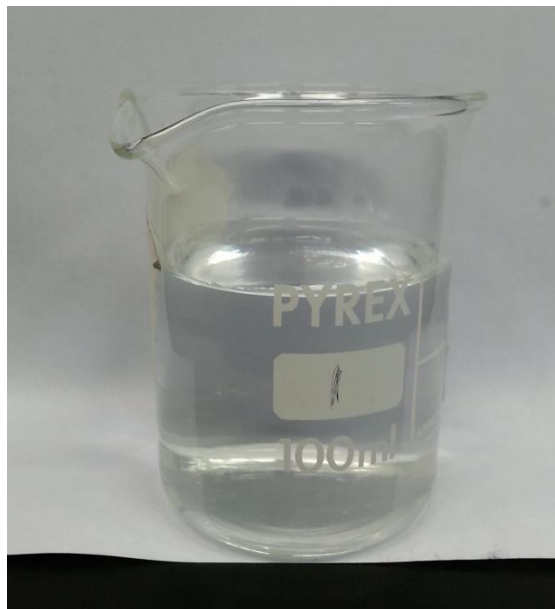
Appendix 3. 1000 ppm of polymer solution A with 10000 ppm of salinity



Appendix 4. 1000 ppm of polymer solution A with 20 000 ppm of salinity



Appendix 5. 1000 ppm of polymer solution A with 35 000 ppm of salinity



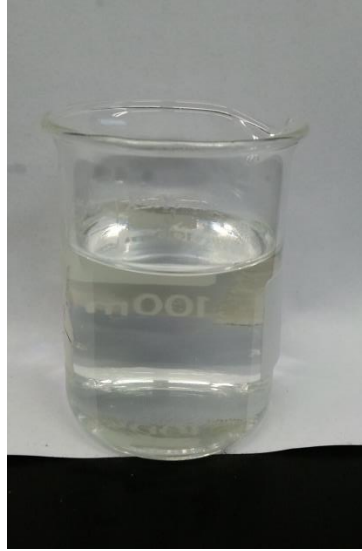
Appendix 6. 1000 ppm of polymer solution A with 70000 ppm of salinity



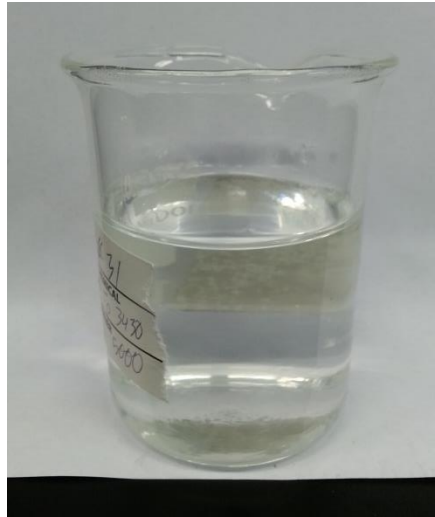
Appendix 7. 1000 ppm of polymer solution B with 0 ppm of salinity



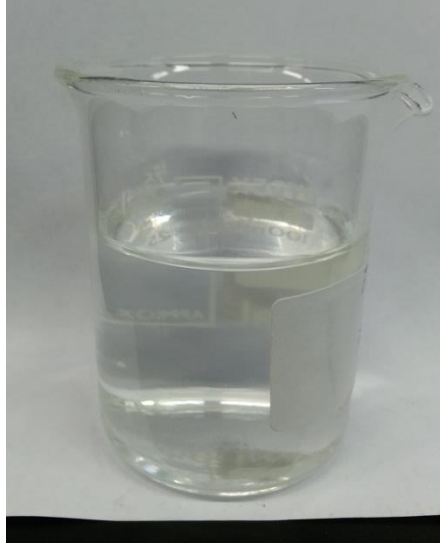
Appendix 8. 1000 ppm of polymer solution B with 5000 ppm of salinity



Appendix 9. 1000 ppm of polymer solution B with 10 000 ppm of salinity



Appendix 10. 1000 ppm of polymer solution B with 20 000 ppm of salinity



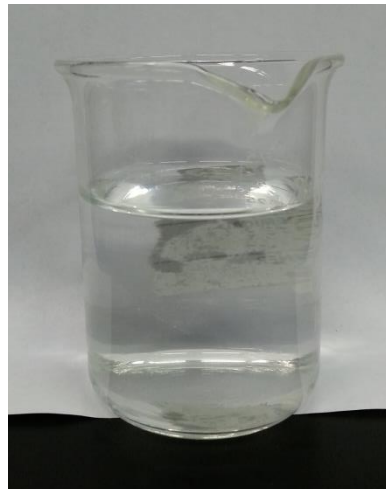
Appendix 11. 1000 ppm of polymer solution B with 35 000 ppm of salinity



Appendix 12. 1000 ppm of polymer solution B with 70000 ppm of salinity



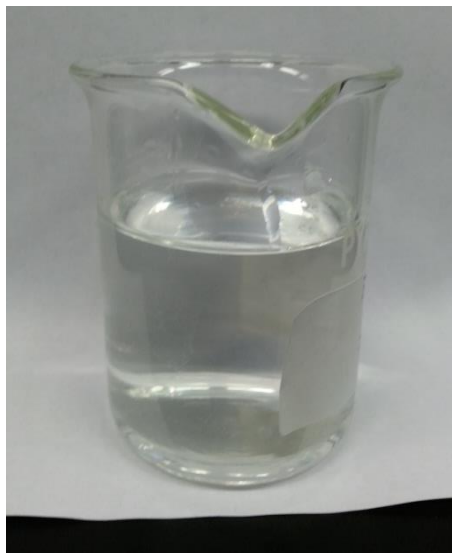
Appendix 13. 1000 ppm of polymer solution C with 0 ppm of salinity



Appendix 14. 1000 ppm of polymer solution C with 5000 ppm of salinity



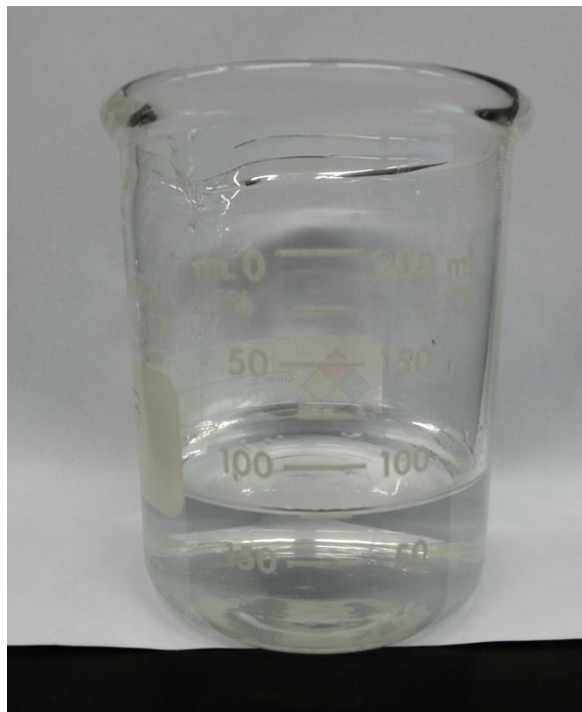
Appendix 15. 1000 ppm of polymer solution C with 10 000 ppm of salinity



Appendix 16. 1000 ppm of polymer solution C with 20 000 ppm of salinity



Appendix 17. 1000 ppm of polymer solution C with 35 000 ppm of salinity



Appendix 18. 1000 ppm of polymer solution C with 70000 ppm of salinity