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MODELLING THE EFFECTS OF TEMPERATURE AND AGING TIME ON THE RHEOLOGICAL PROPERTIES OF DRILLING FLUIDS

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Abstract

The rheological properties of drilling fluid change owing to elevated temperature and aging time and these in effect, cause problems in drilling deep wells. A laboratory investigation of the effects of temperature and aging time on the properties of water-base drilling fluid is made with Fann Model 800 HighTemperature, High Pressure (HTHP) Viscometer. It is evident from the findings that effective viscosity, plastic viscosity and yield point decrease steadily with increase in temperature for all values of aging time. It is observed as well that viscosity at a given temperature decreases with increase in aging time and the aging effect are diminishing as the aging time increases especially for the effective viscosity and yield point. It is also observed from this study that viscosity, yield point, gel strength and shear stress at a given shear rate decrease with increase in temperature and aging time. Finally, this paper presents a predictive model equation good enough to analyse trends and predict future values for effective and plastic viscosities.

Keywords: Aging; Rheology; Model; Temperature; Drilling Fluids.

1. Introduction

There is no doubt that to successfully drill a well for the production of either crude oil or gas, the properties of the drilling fluid used has to be continuously monitored and controlled during the drilling operation. However, the determination of the mud properties requires the experimental examination of the mud system at both the standard API and the high temperature, high pressure conditions at intervals throughout the duration of the drilling process. It is quite easy to determine the mud properties at the surface conditions. These properties do not in any way represent the true bottom-hole conditions. In addition, maintaining bottom-hole conditions at the surface for experimental reasons is difficult and risky. In order to investigate the properties of a drilling fluid at bottom-hole conditions from the surface conditions, the concept of aging is used.

Most drilling fluid formulations contain a base liquid and additives which must be dissolved or mechanically dispersed into the liquid to form a homogenous fluid. The resulting fluid may contain one or more of the following: water-dispersible (soluble) polymers or resins, clays or other insoluble but dispersible fine solids and soluble salts. The fluids are mixed or sheared for the number of times appropriate to achieve a homogenous mixture and are then set aside to “age”. Aging of drilling fluid is the process in which a drilling fluid sample previously subjected to a period of shear is allowed to more fully develop its rheological and filtration properties. Aging takes place when mud is left inactive for example during tripping. Aging is done under conditions which vary from static to dynamic and from ambient to highly elevated temperatures.

Annis [1] investigated the changes in rheological property with time and temperature up to 300^0F by a concentric-cylinder, rotational viscometer of the Fann type. His experiments covered the effects of temperature and aging on shear rate – shear stress , gel strength and viscosity. The study concluded that high temperature causes flocculation of bentonite clays, resulting in high yield points, high viscosities at low shear rates, high gel strengths and a permanent thickening of the mud.He added that proper treatment of bentonite mud with NaOH and lignosulphate reduces the effect of dispersion and flocculation at high temperature.

Alderman *et al* [2], carried out experiments with water-base muds to study the rheology at temperatures up to 266^0F and pressures up to 145000psi. They concluded that high shear viscosity decreases with increasing temperature in a similar manner for all drilling fluids examined and increases with pressure to an extent which depend on mud density. Yield stress is essentially independent of pressure and weakly dependent on temperatures. Their study did not simulate the bottom-hole conditions and did not consider the aging effect.

Mohammed Shahjahan Ali [3], later wrote a thesis from a laboratory investigation on the effect of high temperature (490^0F) and aging time of 30days on water-base mud properties using the HTHP viscometer, baroid roller oven(dynamic aging) and distilled water as the continuous phase.

The result shows a decrease in viscosity, yield point and gel strength with the increase in temperature for all values of aging time. He concluded that shear stress for a particular temperature increases with increase in shear rate, but shear stress at a given shear rate decreases with increase in temperature. Viscosity, yield point and gel strength at a given temperature increase with aging time and aging effects are diminishing with the increase in aging time. Shear stress at a given shear rate increases with aging time and aging effects decrease with the increase in aging time.

Shokoya *et al* [4] conducted a study on the rheology and corrosivity of water-base drilling fluid under simulated downhole conditions. The rheological property and corrosion behavior relationship of mild steel type 1018 in a typical drilling fluid used in deep drilling and hot wells was studied. The tests were conducted under conditions that simulate flow, temperature, and pressure encountered during drilling operations. Physical properties that were considered are: shear stress-shear rate relationship, effective and plastic viscosities, yield strength and gel strength. The properties were determined under high temperature and pressure by using a flow loop, the Baroid roller oven and the FANN-70 viscometer. The corrosion measurements were carried out by weight loss and electrochemical techniques. The effective and plastic viscosities of the drilling fluid decrease with increase in temperature and increase in time of exposure to downhole conditions. The corrosion rate of 1018 mild steel increase with decrease in pH of the fluid. The corrosion rates are lower at the mildly alkaline pH and higher in the mildly acidic pH range. The drilling fluid generally attacks the grain boundaries of the steel samples. Diffusion was found to be the rate limiting step for the corrosion reactions.

S.Salimi *et al* [5] conducted a research on the rheological behavior of polymer-extended water-based drilling muds at high temperatures and high pressures simulating their true working conditions in a deep oil well. The performance of these polymers as a rheology modifier in drilling systems was then investigated using a Fann 50C commercial viscometer. By measuring shear stress vs. shear rate (i.e., the flow curve) at pressures up to 500 psi and temperatures up to 300°F , it was found that temperature had a detrimental effect on the rheological properties of the test fluids while the effect of pressure on these properties was realized to be less significant (specially at pressure above 300 psi).

Osman and Aggour [6] carried out an experiment to determine drilling mud density change with pressure and temperature using a newly developed Artificial Neural Networks (ANN) model. Available experimental measurements of water-base and oil-base drilling fluids at pressures ranging from 0 to 1400 psi and temperatures up to 400 °F were used to develop and test the ANN model. With the knowledge of the drilling mud type (water-base, or oil-base) and its density at standard conditions (0 psi and 70°F) the developed model provides predictions of the density at any temperature and pressure (within the ranges studied) with an average absolute percent error of 0.367, a root mean squared error of 0.0056 and a correlation coefficient of 0.9998.

Exner [7] carried out an investigation on the effects of temperature on the viscosity of some Gulf coast drilling muds. The purpose of this investigation was to determine the relative changes in the apparent viscosity of muds with changes in temperature and to discover other physical effects due to heat. Exner states: "Very little information has been published regarding the effects of temperature on the viscosity of drilling mud". He quoted Maustl who stated that "The viscosity of most muds is decreased on heating, but the interesting thing is that the degree of flocculation is also increased on heating. There will be a greater tendency to seal off formations at high temperatures than at low temperatures." With regard to the effect of temperature on viscosity and yield point, Exner states: "The variation of yield point and viscosity of mud with temperatureis not very clearly brought out by the data available. Both appear to decrease slightly with increasing temperature up to 200^0F." The experimental results presented in this paper further emphasize this point. Two types of viscosimeters are available for measuring the apparent viscosities of drilling muds: the efflux tube type as used by Herrick3 and Marsh, and the torsional type such as the McMichael or the Stormer viscosimeters.

Pavel [8] published an article titled "High-Pressure/High-Temperature Operations: Aqueous drilling fluid contends with HP/HT wells". In this article, he presented a new water-based drilling fluid developed specifically to contend with the unique challenges of onshore ultra-deep HP/HT wells in sensitive ecosystems. He stated that HT gelation is an overriding problem with water-based muds even in routine applications but is magnified considerably in deep HP/HT wells. Gelation is caused when clay or bentonite in the fluid flocculates. Aqueous systems require very tight control of the solids content along with selecting thermal-stable products for treatment. HT gelation and degradation of product and mud properties increase HP/HT fluid loss. With drilling fluid densities approaching 17 lb/gal, barite sag can impact the entire operation. Very high rheology was observed, with some samples appearing almost dry after aging. For this work, the final temperatures were 482°F (250°C), 446°F (230°C), and 410°F (210°C).

Andreas *et al* [9] investigated the effects of Shear rejuvenation, aging and shear banding in yield stress fluids. The purpose of his work was to simulate shear rejuvenation and aging effects in shear thinning yield stress fluids in a typical rotational rheometer and to provide a common framework to describe the behavior of yield stress materials in general. The breakdown and buildup of structure were studied using a theory based on the Herschel–Bulkley flow model that is consistent with experimental data. The theory was implemented using a novel computational method. Interestingly, the simulations revealed the existence of time-dependent shear banding that occurs within the gap when the macroscopically imposed shear rate is below a certain critical value. Shear banding was analyzed in detail and results showing the effects of major parameters on the phenomenon were presented.

2. Experimental

2.1 Materials

The experimental apparatus used in this study consists of a Fann Model 800 HighTemperature, High Pressure (HTHP) Viscometer, the Hamilton beach mixer, the hot plate, stirrer and the mud balance.

2.2 Methods

The materials used for the mud sample of this study are as follows:

i. Fresh water: 350ml of fresh water was used as the continuous phase for all the experiments where the different components are blended with it to form the drilling fluid.
ii. Wyoming bentonite: This was used as the clay mineral to develop viscosity. 22.5g of bentonite was used in 350ml of fresh water.
iii. Barite: 5g of Barite was added to the bentonite suspension to serve as a weighting material.
iv. Sodium Chloride (NaCl): 5g of Sodium Chloride was added to the bentonite suspension to attain maximum gel strength of the drilling fluid.

v. CMC: 5g of CarbonMethylCelulose was added for modification of viscosity.
vi. Lignosulphate (Thinner): 5ml of Lignosuphate was used as an additive for thinning of mud sample.

The density of the freshly prepared mud was found to be 8.7ppg and its P^H was measured to be 9.3.

Procedures

The experimental procedures for some of the instruments are as follows:

Procedure for mud balance:

Calibration

- The cup was filled with fresh water, the lid was replaced and wiped dry.
- While the rider is set on 8.3 ppg or 1.0 s.g., lead shot was added or removed from the shotwell until instrument was balanced.

Procedure:

- The mud balance base (in a carrying case) was placed on a flat level surface.
- Then the cup was filled to the top with the test fluid.
- Covering the hole in the lid with a finger and washing all mud from the outside of the cup and arm, the entire balance was thoroughly dried.
- With the balance placed on the knife edge, the rider was moved along the outside of the arm until the cup and arm are balanced as indicated by the bubble.
- Then the mud weight was read at the edge of the rider towards the mud cup.

2.3 Aging

After the mud sample has been prepared, it was poured into a container, properly covered and allowed to age for a desired period of time after which the test was run on the aged sample at varying temperatures. This process is called static aging as opposed to dynamic aging where the mud sample is placed in high-pressured aging cells and rolled in an oven for a specified period.

The Baroid roller oven is used for dynamic aging of the mud samples for more accurate results but could not be used because of its unavailability as a result of its ill-working condition as at the time this research work was done hence the employment of static aging as an alternative.

3. Results and discussions

3.1 Results of the experiment

Values of effective viscosity, plastic viscosity, yield point and gel strengths are presented respectively as functions of temperature in figures 1 through 4 for the different aging periods. Each curve of these figures represents the result for a different aging time.Values of shear stress (recorded dial readings) as a function of shear rate (revolutions per minute) at a fixed aging time while varying temperature are presented in figures5 through 12 and values of shear stress as functions of shear rate for different aging time at fixed temperature are also presented in figures13 through 18.

3.2 Analysis of results

3.2.1 Effect of temperature

The effect of temperature on drilling mud can be attributed to the complicated interplay of several causes, some of which are more dominant than others. Factors such as reduction in the degree of hydration of the counterions, reduction of the viscosity of the suspending medium, increased dispersion of associated clay micelles, changes in the electrical double layer thickness and increased thermal energy of the clay micelles. Since all these processes take place in the drilling fluid simultaneously as temperature is varied, an interpretation of the observed results will only be possible in cases whereby some of the effects are predominant and as such be easily identified.

As shown in figures1 through 3, effective viscosity, plastic viscosity and yield point decrease steadily with increase in temperature for all values of aging time with a slight increase in viscosity at 80°C. These changes in rheological properties can be explained according to the investigation carried out by Annis [1]. He found out that high temperature causes flocculation of bentonite clays resulting in high viscosities at low shear rates and high gel strengths but proper treatment of bentonite mud with lignosulphate reduces the effect of flocculation at high temperature. Also, Exner J.D. [7] quoted an author to have stated: "The viscosity of most muds is decreased on heating, but the interesting thing is that the degree of flocculation is also increased on heating. The effect of temperature on gel strength could not be considered because of laboratory constraints but the aging effect is presented as shown in figure 4.4.

Also, figures5 through 12 show that:

1. For a particular temperature, shear stress increases with shear rate
2. For the same shear rate, shear stress decreases with increasing temperature (a slight deviation from this trend was observed at 80°C but no specific conclusion can be made on this, since tests were not taken at higher temperatures than 80°C) and temperature effects are diminishing with increase in temperature.

This observed result can be explained according to the research conducted by Mohammed Sahjan Ali [3]. He discovered that the above stated effects are as a result of severe degradation of copolymers (CMC) and bentonite clay due to the application of heat as well as mechanical shearing. As the polymer degrades*,* the clay platelets start to dehydrate, the platelets approach each other so closely that the attractive forces dominate, resulting in a state of dispersion with edge to face contacts of the platelets. Increase in temperature causes the platelets to aggregate, and ultimately leads to a state of aggregation and flocculation resulting in low rheological properties.Another reason is that in HTHP viscometer, the mud sample is subjected to continuous shear rate. The high shear rate prevents the bentonite platelets from building structures like house of cards and thus there is gradual change in rheological properties. The results of the effect of temperature on shear stress-shear rate relationship are similar to that found by Mohammed Sahjan Ali [3]; who collected data at 77, 122, 212, 302, 392 and 490°F. However, in this research work, data were collected at 86, 104, 122, 140, 158 and 176°F and no further because of the constraint imposed by the equipment limitation (maximum operation temperature of the viscometer is 190.4°F) but similar results were observed. The results of the effect of temperature on shear streess-shear rate relationship follows the same trend as found by Hiller [10]. He used 4 percent pure sodium montmorillonite to which 5 liters of NaOH was added and measured the shear stress- shear rate values for 78 and 350°F at constant pressure of 8000psi. He observed that shear stress for a particular temperature increases with shear rate, but shear stress at a given shear rate decreases with the increase in temperature although no specific conclusion was drawn on temperature effect as data was collected only at two temperatures.

3.2.2 Aging effect

The effect of aging on mud rheology was also studied. The results are presented in figures1 through 4 and also in figures 13 through 18. From figures 1 through 3, it was observed that viscosity at a given temperature decreases with increase in aging time and the aging effect are diminishing as the aging time increases especially for the effective viscosity and yield point. This result is in good agreement with that obtained from the study conducted on the rheology and corrosivity of water-base drilling fluid under simulated downhole conditions by Shokoya *et al* [4]. The tests were conducted under conditions that simulate flow, temperature, and pressure encountered during drilling operations and they found out that effective and plastic viscosities of the drilling fluid decrease with increase in temperature and increase in time of exposure to downhole conditions (i.e. aging).

The explanation for decrease in viscosity may be gotten from an analysis of the composition of the drilling fluid formulated for this study. Salt (NaCl) was added to maximize gel strength and also for compatibility against salt formations.Moreover, salt from its chemical properties is known to have a high water holding capacity which increases with exposure time (i.e.aging). This can even be physically observed when a sample of sodium chloride salt is exposed to the air; the salt becomes moist-hygroscopy-after some time (especially with use) having absorbed moisture from the atmosphere. From the foregoing, it can be deduced that there is an increase in moisture content as a result of the absorption of water molecules from the surrounding by the salt molecules as aging time increased which therefore results in a decrease in viscosity.

Another factor to consider is the presence of carboxymethyl cellulose (CMC) that was added in the drilling fluid formulation. As the drilling fluid ages, the CMC component becomes degraded leading to the weakening of its viscosity modification effect moreso as temperature is increased. The result observed agrees with that gotten by S. A. Williams [11] who studied viscometric and filtration properties at 80°F and at elevated temperature for a saturated gypsum mud and a 20,000 ppm sodium chloride mud, treated with sodium carboxymethyl cellulose (CMC) and then with another polymer. In the muds containing CMC, the observed plastic viscosity decreases (at 175°F.) and the API filter loss increase (at 200°F). Data was presented to illustrate the extent of degradation of CMC in a gypsum mud when heated for 16 hours (aging) at 350°F under a nitrogen atmosphere. These results show that, from an operational point of view, CMC was completely degraded.

Furthermore, it is found from the chemistry of lignosulfonate that all prepared lignosulfonates have between 30% and 70% high dispersion efficiency. The efficiency can be explained in two ways:

1) The high molecular weight of lignosulfonates has a large steric repulsive force, and
2) Some lignosulfonates contain a higher sulfur content than others (such may be the case for the lignosulfonate used in preparing the mud for this study) and therefore have a larger electrostatic repulsive force thus making mud become less viscous.

As shown in figure 4.4, the initial and 10minutes gel strengths increase with aging time and aging effects become diminished as aging time increases. This is so because as the particle numbers increase, the attractive and large interparticle forces become greater and thus, the gel strength is also increased.

Furthermore, figures 13 through 18 show that shear stresss at a given shear rate decreases with the aging time. This is expected as viscosity is directly proportional to shear stress. As observed earlier that viscosity decreases with aging time, consequently, shear stress also increases with aging time. This again agrees with the results obtained by Shokoya *et al* [4] as explained earlier.

It is a known fact that temperature and aging have effects on the drilling fluid properties. It is also observed from this study that viscosity, yield point, gel strength and shear stress at a given shear rate decrease with increase in temperature and aging time. A lot of drilling problems can be avoided if the optimum values of these properties are maintained.

Mud rheology is of utmost importance in drilling as viscosity practically influences penetration rate. Cutting slip velocity for instance correlates better with yield point than any other parameters. Proper gel strength is needed to keep the cuttings in suspension, and relatively low gel strength is better for high penetration rate.This causes less pressure drop in the hole.

It also worth noting that the addition of lignosulfonate into drilling fluid system can reduce the viscosity of the mud and therefore will reduce the amount of energy needed to rotate the drill stem and the drill bit. As an example of their effectiveness as a thinner, lignosulfonate with sodium hydroxide are the best treatments for salt contamination, which come from formation and cementing.

3.3 Model development

A predictive model equation was also developed using regression tool in Excel to analyse trends and predict future values for effective and plastic viscosities. From the regression, the following model was developed:

$$1\ \mu_e = 16.0996738 - 0.1053571\Theta - 0.5350361t$$

$$2\ \mu_p = 7.339696 - 0.04911\ \Theta - 0.21749t$$

where μ_e, μ_p are respectively the effective and plastic viscosities, Θ stands for temperature and t denotes the aging time.

Figures show that 19 through 22 show the Regression for Effective and Plastic Viscosities and their Coefficients of Regression, R^2. It can be observed in figures 20 and 22 that there is a good correlation between the experimental and the predicted values thus making the developed model reliable to a good extent.

4.Conclusions

Based on the foregoing laboratory investigation, the conclusions drawn are as follows:

1. The effective and plastic viscosities, yield point and gel strengths of water-based drilling fluids decrease with increase in temperature and with increase in aging time.
2. For the same shear rate, shear stress decreases with increasing temperature and temperature effects are diminishing with increase in temperature and for a particular temperature, shear stress increases with shear rate.
3. As aging time increases, its effect on effective viscosity, yield point and gel strengths become diminished.
4. For every temperature that was considered, the shear stress at a given shear rate decreased with increase in aging time and this effect also reduces as aging tme increases.
5. The developed models can be used to predict future values for Effective and Plastic Viscosities since there is a good correlation as shown provided the mud composition is not too different from what is used in this study.

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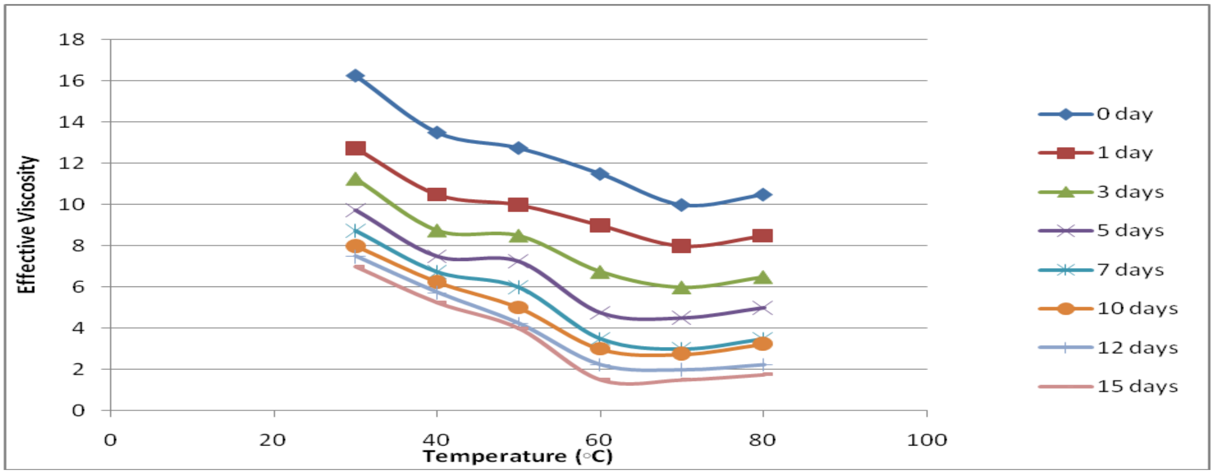

Figure 1 Effective viscosity as a function of temperature for different aging times.

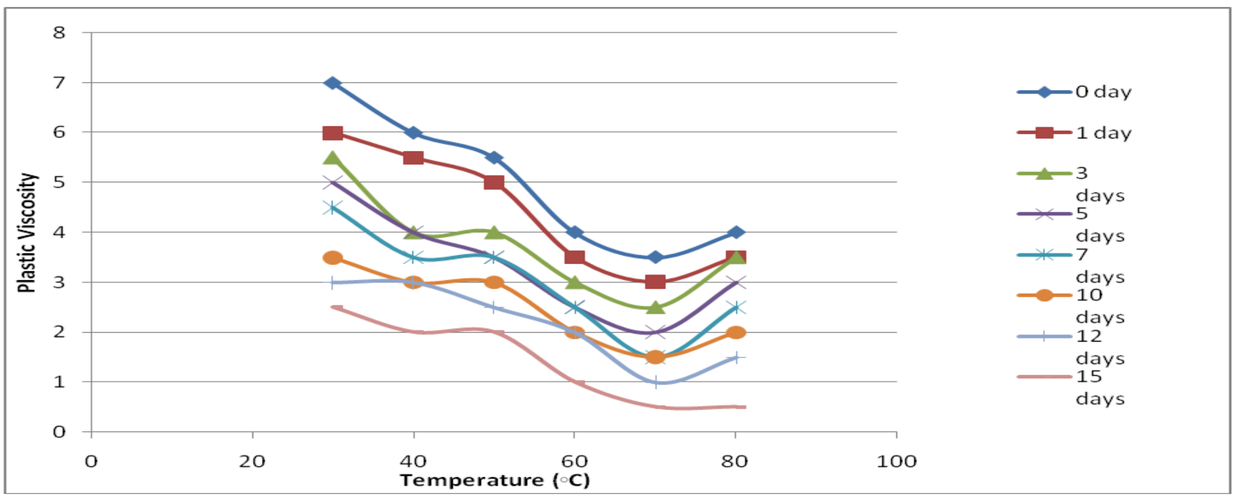

Figure 2 Plastic viscosity as a function of temperature for different aging times.

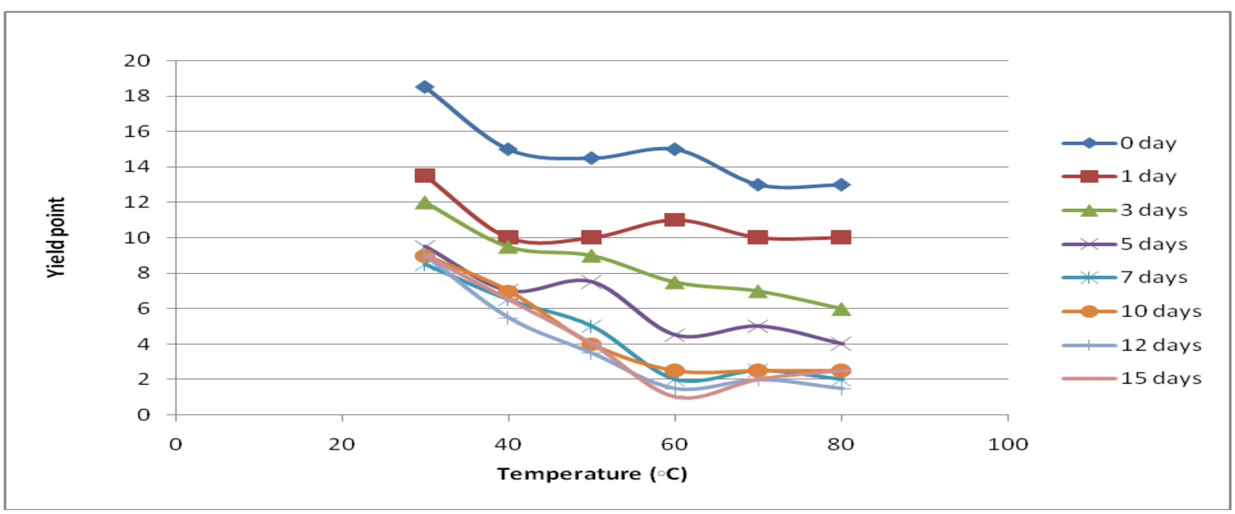

Figure 3 Yield point as a funtion of temperature for different aging times.

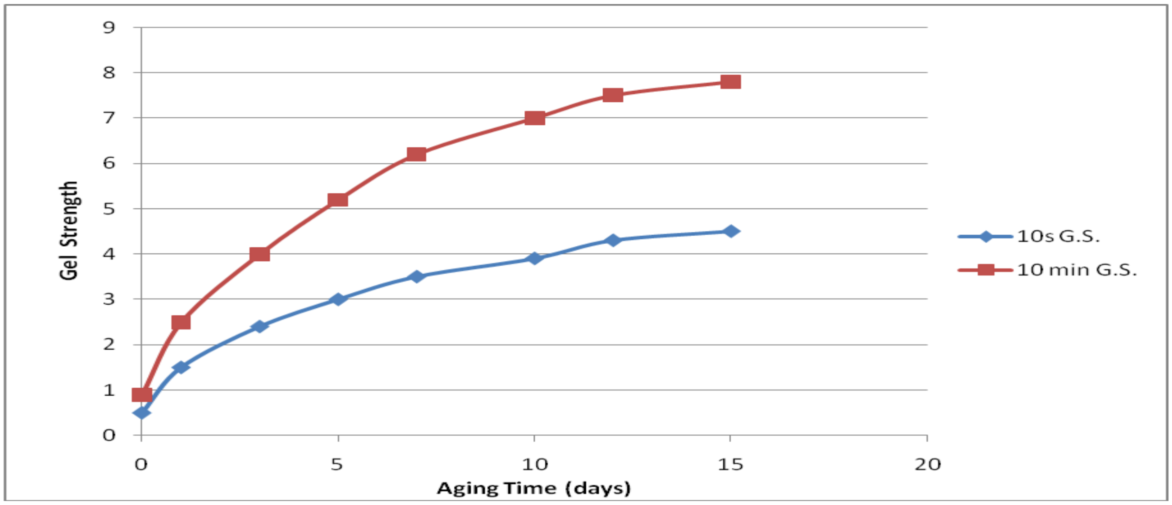

Figure 4 Gel strength as a function of aging

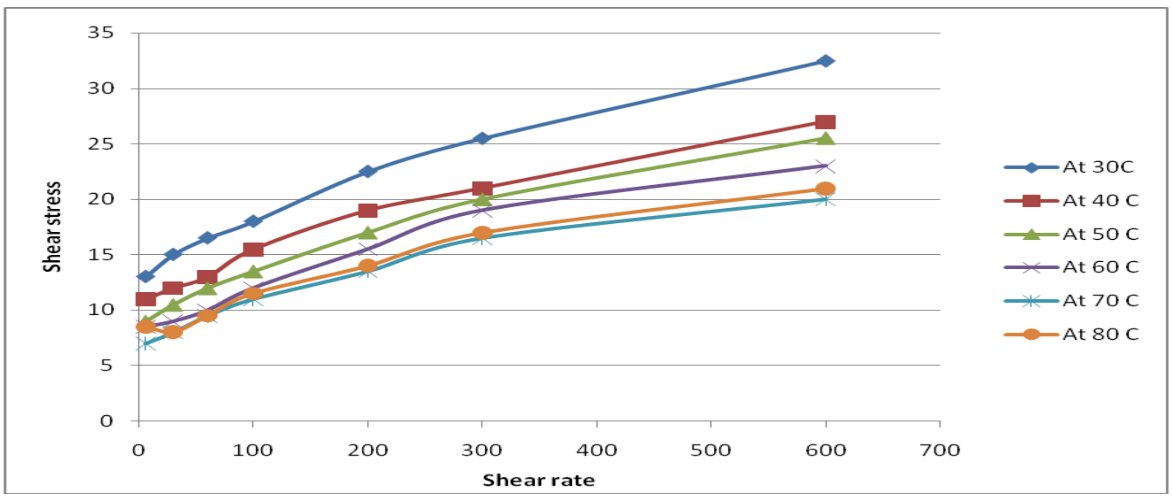

Figure 5 Shear stress as a function shear rate for different temperature at 0 day aging time

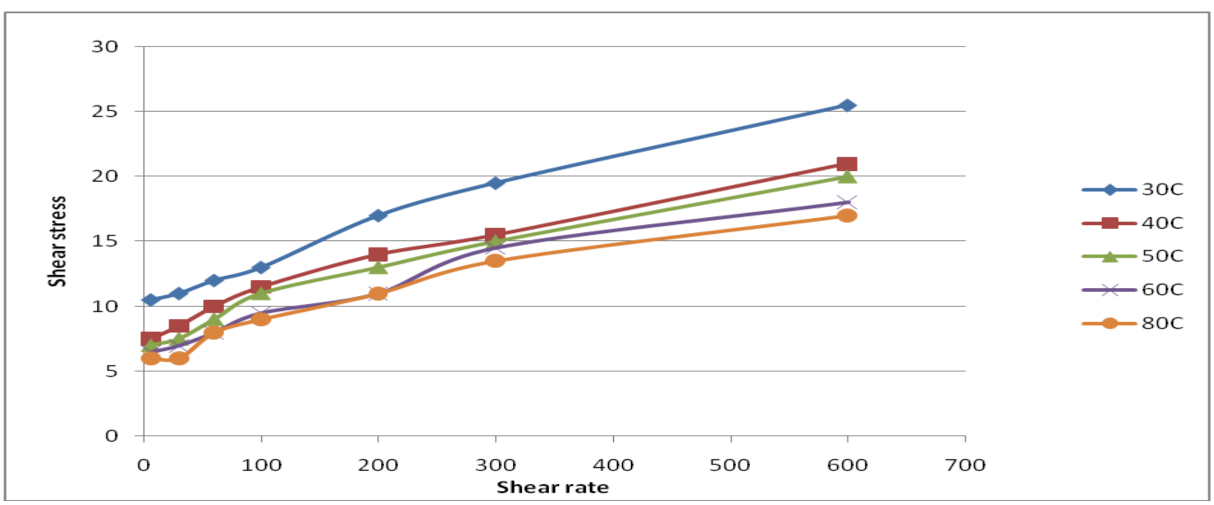

Figure 6 Shear stress as a function shear rate for different temperature at 1 day aging time

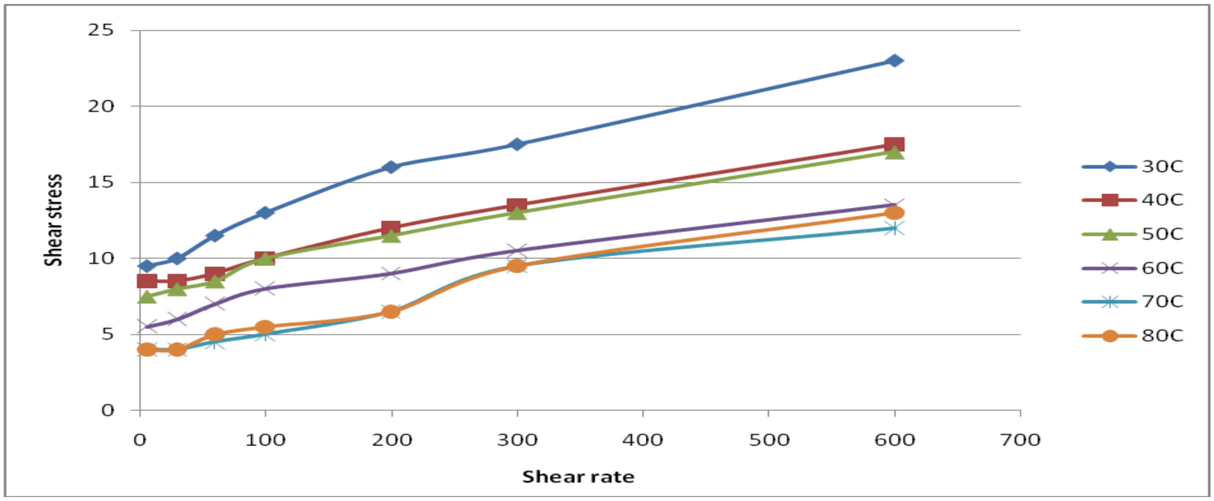

Figure 7 Shear stress as a function shear rate for different temperature at 3 days aging time

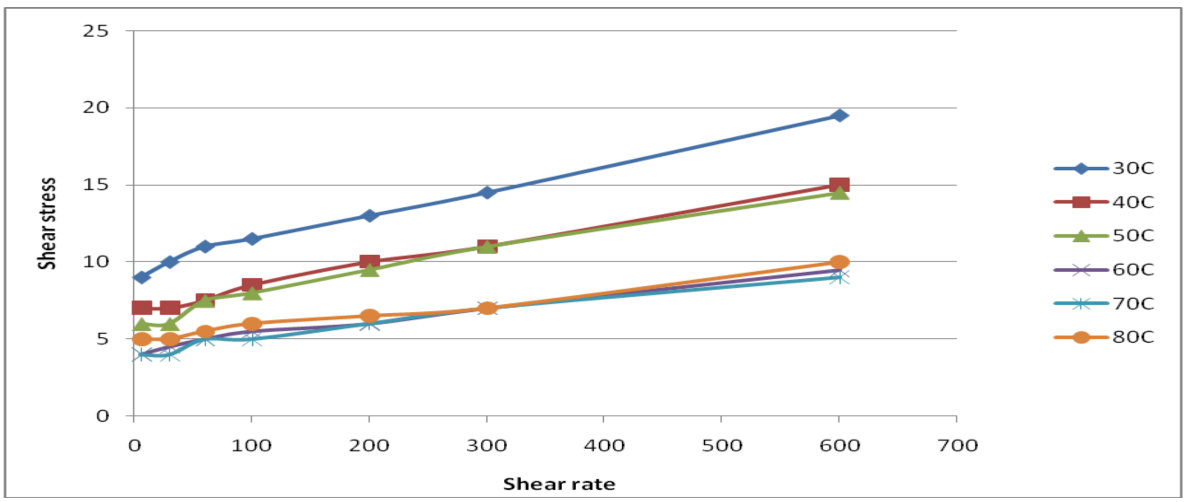

Figure 8 Shear stress as a function shear rate for different temperature at 5 days aging time

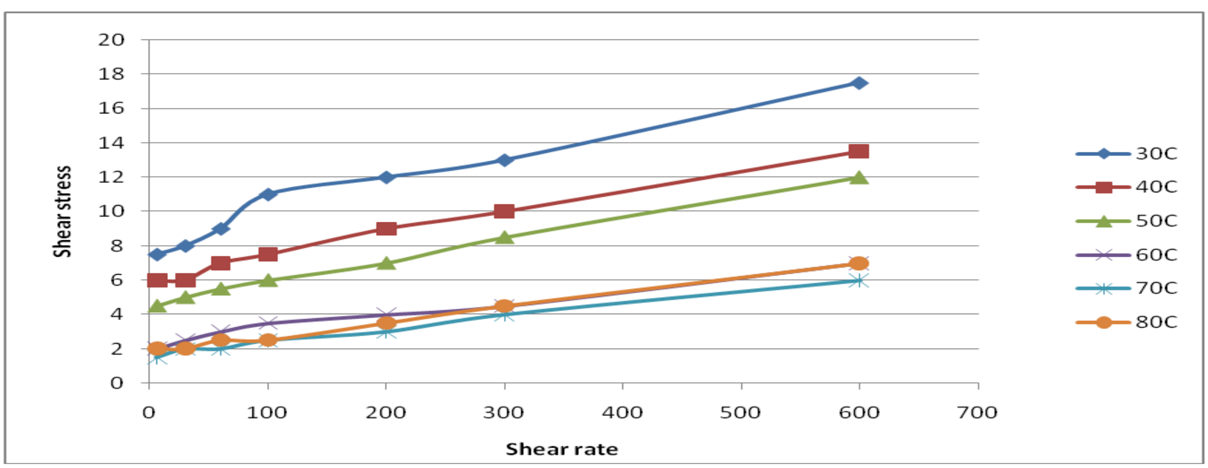

Figure 9 Shear stress as a function shear rate for different temperature at 7 days aging time

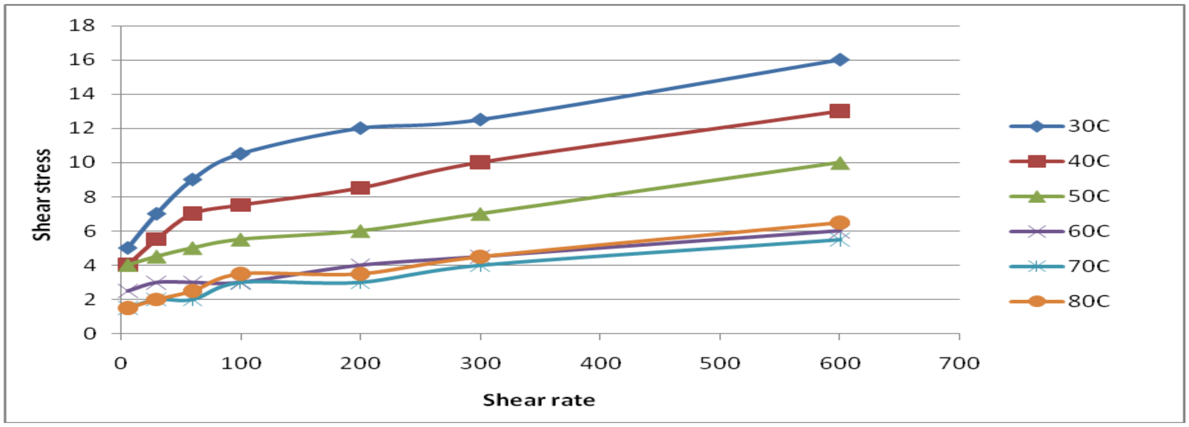

Figure 10 Shear stress as a function shear rate for different temperature at 10 days aging time

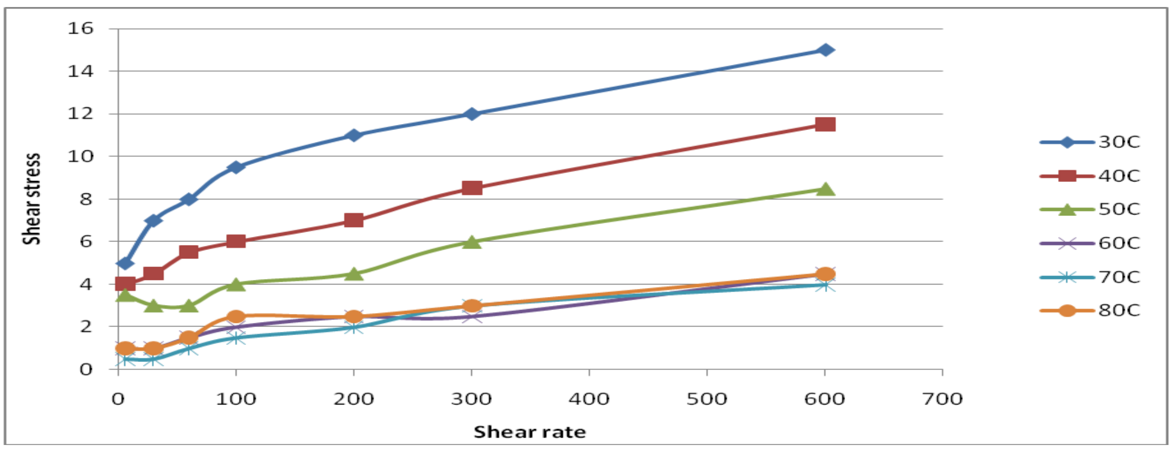

Figure 11 Shear stress as a function shear rate for different temperature at 12 days aging time

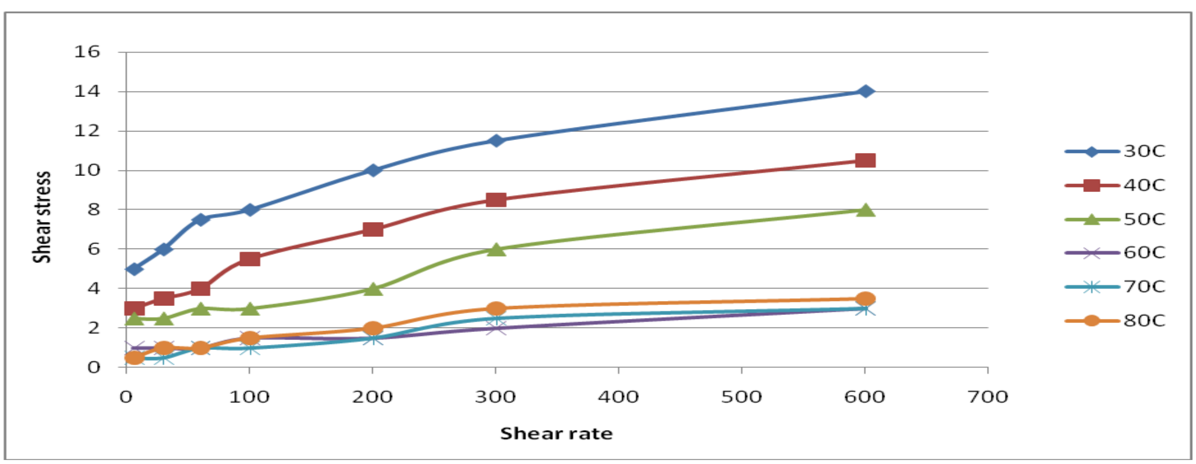

Figure 12 Shear stress as a function shear rate for different temperature at 15 days aging time

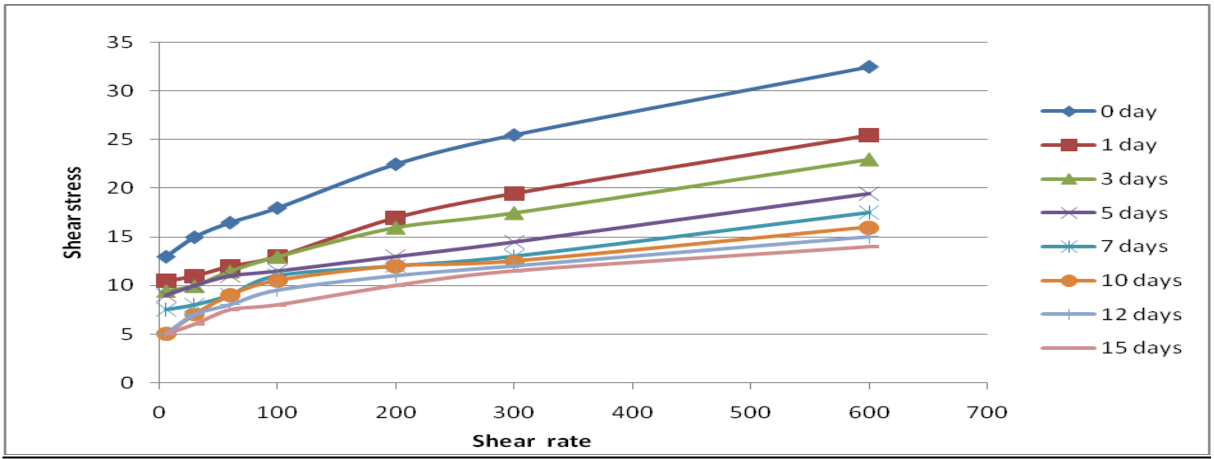

Figure 13 Shear stress as a funtion of shear rate for different aging time at 30°C

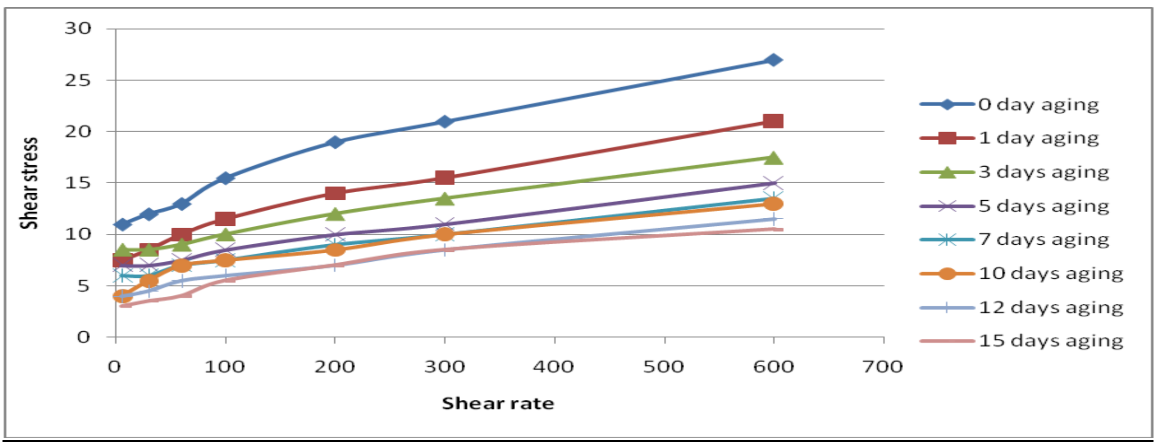

Figure 14 Shear stress as a funtion of shear rate for different aging time at 40°C

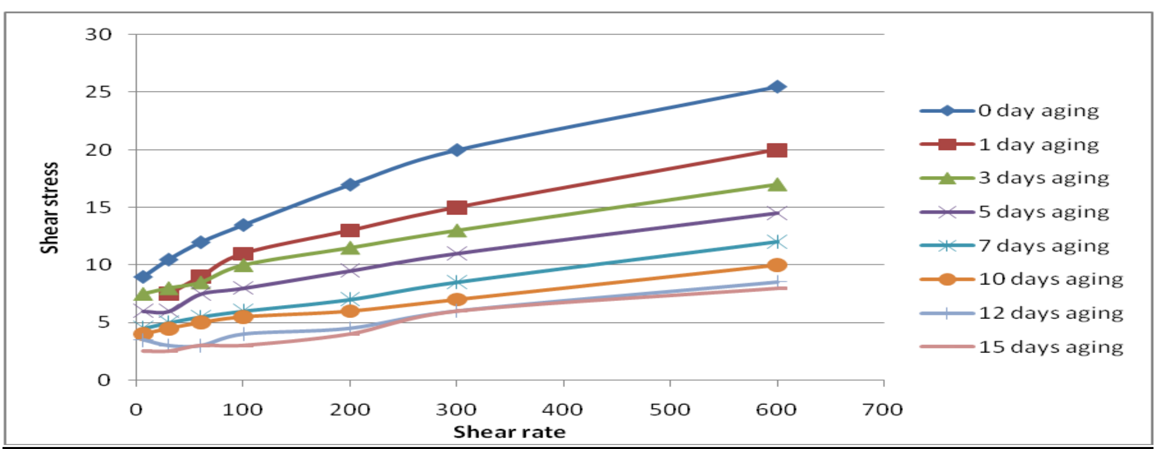

Figure 15 Shear stress as a funtion of shear rate for different aging time at 50°C

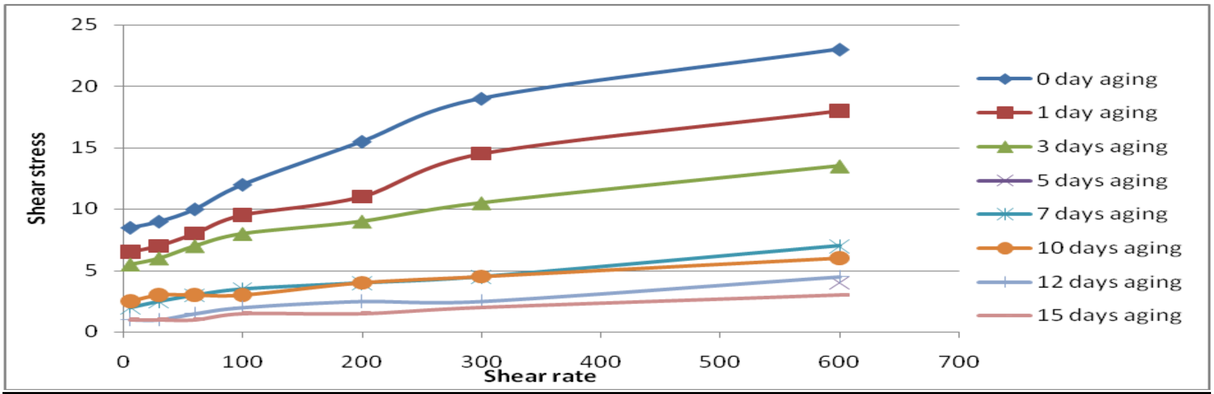

Figure 16 Shear stress as a funtion of shear rate for different aging time at 60°C

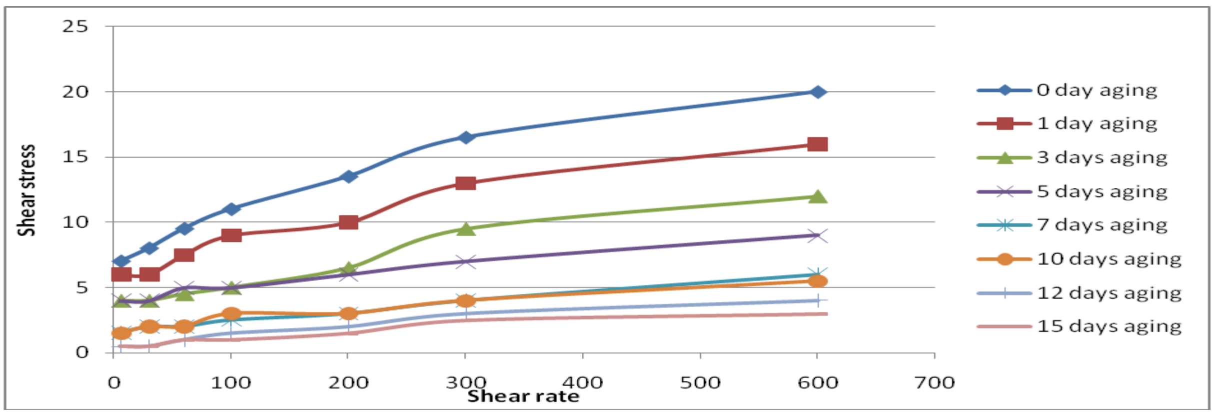

Figure 17 Shear stress as a funtion of shear rate for different aging time at 70°C

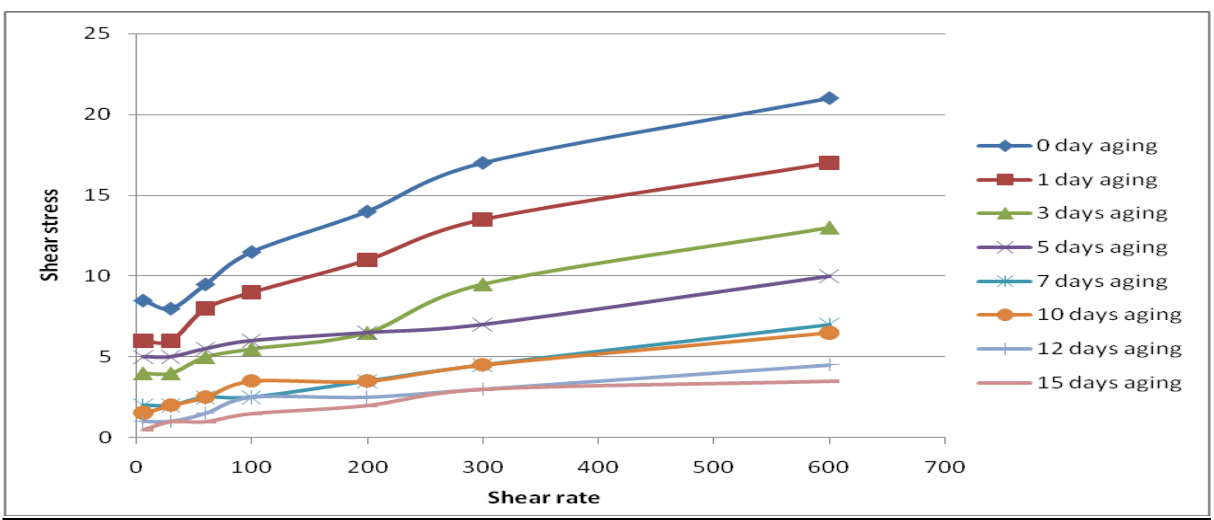

Figure 18 Shear stress as a funtion of shear rate for different aging time at 80°C

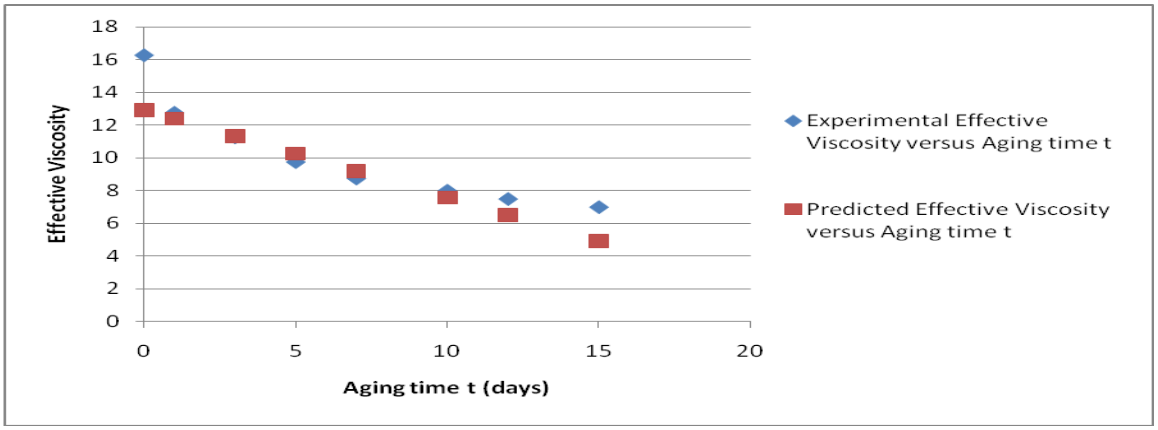

Figure 19 Effective viscosity (Experimental and Predicted) as a function of Aging

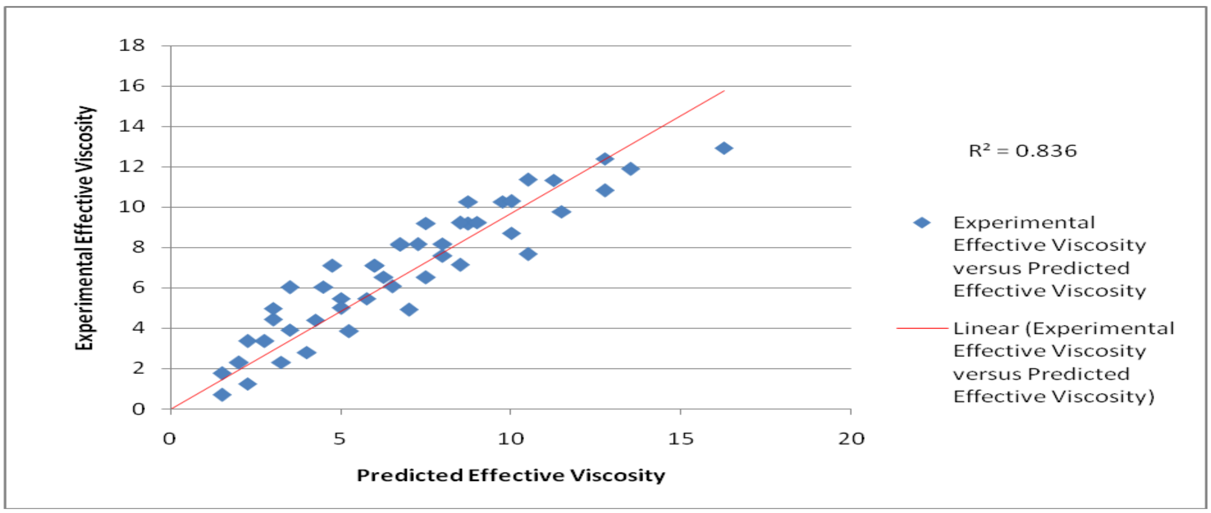

Figure .20 Experimental effective viscosity-predicted effective viscosity regression

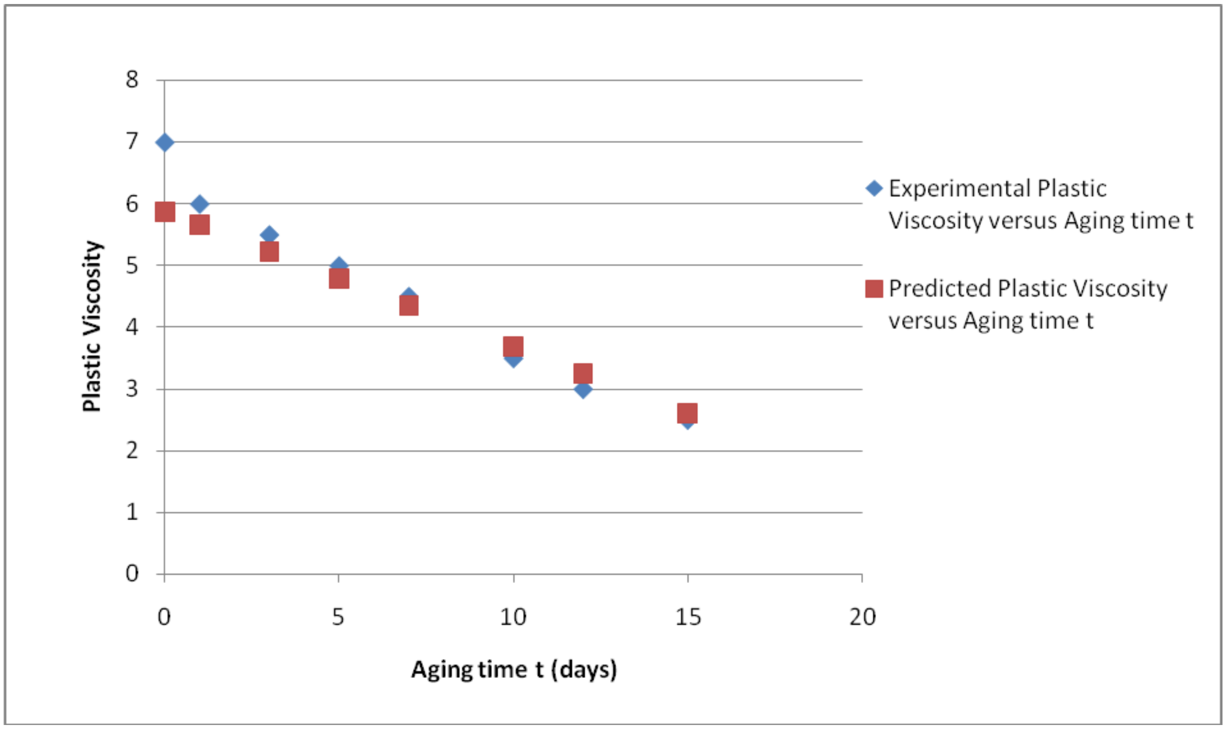

Figure 21 Plastic viscosity (experimental and predicted) as a function of aging

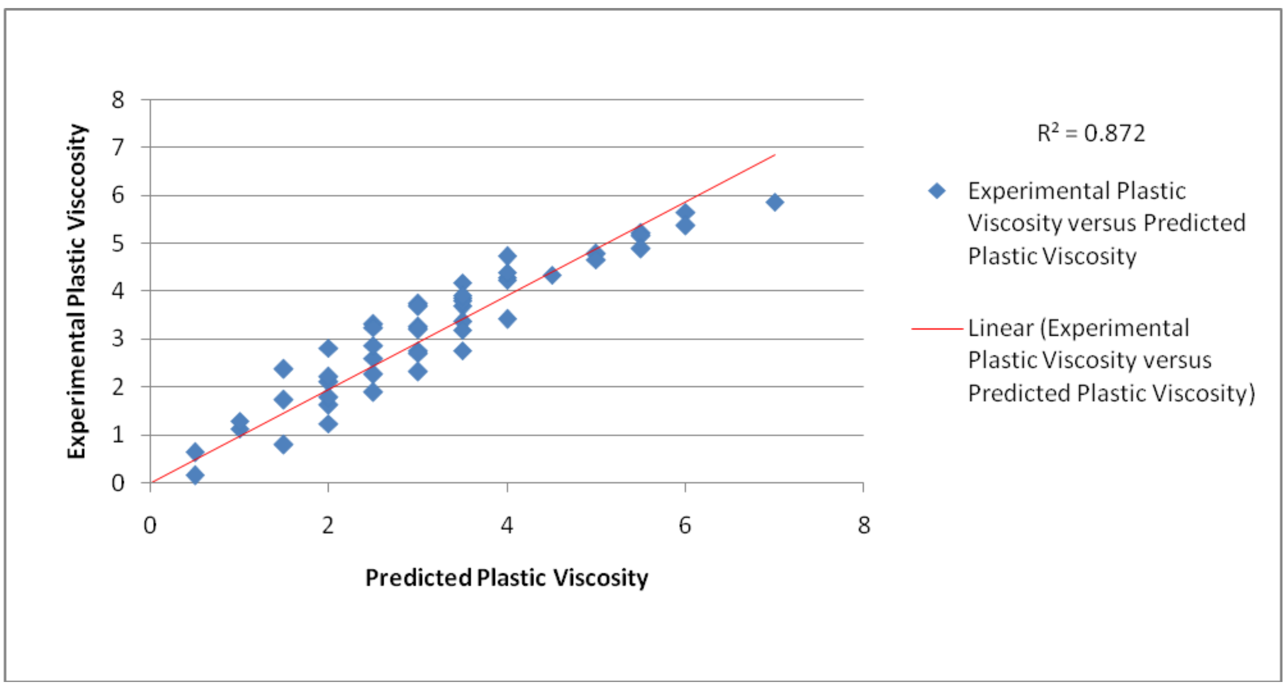

Figure 22 Experimental plastic viscosity-predicted plastic viscosity regression