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Modelling the Effect of Contamination on the Rheological Properties of Cement Slurry Using Oil-Based Mud as Contaminant, To Improve Cementing Job Design and Execution in the Oil & Gas Industry

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ABSTRACT: Cementing job failure often occurs due to cement slurry contamination with drilling mud during primary cementing and remedial cementing jobs in the oil & gas industry. The enormous consequences of cement slurry contamination with drilling mud include drastic reduction in the thickening time of cement slurry and increased rheological properties of the cement slurry due to the much more viscous resultant cement slurry/mud mixture often leading to incomplete cement job, poor mud removal, poor cement bond, gas channeling, gas kick, blow out, downtime, revenue loss and remedial cementing. The rheological properties of cement slurry and drilling mud are strongly dependent on temperature. There are also emergency situations in the oilfield where bottomhole temperature changes to a higher temperature requiring adjustments in the original cementing job design to include the new bottomhole temperature when Laboratory services are not immediately available. The aforesaid and the associated cost of remedial operations prompted this work to investigate the effect of temperature and contamination on the rheological properties of cement slurry using oil-based mud as contaminant to invent a process to better avoid cement slurry contamination and to improve cementing job designs and execution in the oil & gas industry. The methods applied include Laboratory testing and mathematical modeling. Mathematical models were developed using Microsoft Excel to predict the rheological properties of contaminated cement slurries as a function of temperature and contamination with oil-based mud as the contaminant. Results showed that the Plastic viscosity and yield stress of the contaminated cement slurries increased with temperature and extent of contamination with oil-based mud but the yield stress also decreased with extent of contamination at high temperatures. The very high regression coefficient obtained with each of the mathematical models showed that the mathematical models can be confidently applied to predict the rheological properties (Plastic viscosity and yield stress) of the contaminated cement slurries as a function of temperature and extent of contamination with the oil-based mud.

KEYWORDS: Cementing job failure; Oil & gas industry, Oil & gas well cementing; Job design, Investigation, Post job evaluation

1.0 INTRODUCTION

The contamination of cement slurry by drilling mud during oil & gas well cementing operations and the associated problems have been reported repeatedly in the oil and gas industry. It occurs in primary cementing and also in remedial cementing operations. The consequences of cement slurry contamination by drilling mud include drastic reduction in the thickening time of cement slurry and increased rheological properties of the cement slurry due to the much more viscous resultant cement slurry/mud mixture which often leading to incomplete cement job, poor mud removal, poor cement bond, gas channeling, gas kick, blow out, downtime, revenue loss. The contamination of cement slurry with drilling mud often results in the formation of a very viscous or non-flowing mixture especially at the cement slurry/drilling mud interface causing change in the design placement flow regime of the cement slurry, poor cement job or cement job failure. Wang et al (2023) stated that cement slurry contamination with drilling mud causes micro-cracks and pores on the cement/formation interface and decreases the tensile strength of the cement sheath. Santos et al., (2019) stated that contamination of cement slurry with drilling mud prevents it from developing strong bonding to the casing and the walls of the formation. Soares et al., (2017) reported that the contamination of cement slurry with oil-based mud changes its rheological properties which may cause incomplete cementing job and serious accidents on drilling Rigs leading to loss of life and damage to the environment. El Sayed (1995) stated that contamination of cement slurry with oil-based mud increases its rheological parameters. Nelson and Guillot (1990) stated that it is customary to circulate drilling mud through the well and around the drill bit during drilling operations. Nahm and Wyant (1993) reported that the interface between the cement and the borehole wall is the source of many cementing problems. Savery et al., (2007) wrote that oil & gas well cementing is to provide zonal isolation preventing wellbore fluids from contaminating fresh water aquifers. Teodoriu et al., (2008) stated that for an oil or gas well to maintain its integrity and produce effectively and economically, effective zonal isolation by the cement sheath is required. Nahm and Wyant (1993) reported that complete zonal isolation is required during the life of an oil & gas well but it depends on the integrity of the cement sheath.

The magnitude of the aforesaid problems and the cost of remedial operations associated with cement slurry contamination by drilling mud during well cementing operation prompted this work to investigate the effect of contamination on the rheological parameters of cement slurry at different temperatures using oil-based mud as contaminant. This work also aims to establish a method for developing mathematical models to predict rheological parameters of cement slurries contaminated with drilling mud at different temperatures as there is no present standard worldwide. The ability to predict the effect of contamination on the rheological parameters of cement slurries at different temperatures and various levels of contamination with drilling mud will aid cementing design engineers in the oil & gas industry to better understand the implications of cement slurry contamination with drilling mud and prompt them to always take into account the rheological parameters of likely contamination of cement slurry during cementing job design both at the design temperature and higher temperatures, especially for production casing and liner cementing. Furthermore, in emergency situations where there is change in bottom-hole temperature of an oil & gas well and laboratory services are not immediately available, the mathematical models will help cementing design engineers to predict the rheological parameters of the contaminated cement slurry at the new bottom-hole temperature. The broader understanding of the effect of contamination on the rheology of cement slurries at different temperatures; provided by the mathematical models will also prompt cementing job design engineers to better justify the need to include larger volumes of spacer fluids to be pumped ahead of cement slurries during primary cementing or remedial cementing operations. Isehunwa and Mumuni (2010) stated that contamination of cement slurry with drilling mud can cause cement job failure.

Mathematical models are mathematical relationships between process or system variables that describe the behavior of the process or the physical system. Mathematical models can be used as surrogates for the physical system to investigate the response of the physical system under various conditions without necessarily using the actual physical system. Therefore, if during the job design stage, mathematical models representing different extents of contamination of the original cement slurry were proactively developed at different temperatures by simulating the cement slurry contamination with drilling mud at various proportions of the cement slurry and drilling mud, those mathematical models can be used to save time and effort when there is a change in bottomhole temperature in emergency situations or when Laboratory services are not immediately available. Nelson and Guillot, (1990) reported that temperature has a drastic effect on cement slurry rheology and the extent of this effect is highly dependent on the cement brand and the additives in the cement slurry. Furthermore, the mathematical models can also be applied during post job evaluations where design displacement rate could not be achieved during the job execution. The mathematical models can also be included in the training programmes for Cementing Laboratory engineers and Field cementing engineers to train them on the effect of contamination and temperature on cement slurry rheology with drilling mud as contaminant and to predict the rheological parameters of contaminated cement slurries at different temperatures and extent of contamination of the cement slurry.

Oil-based mud was chosen for this study because it is used more often than water based mud in the drilling of oil and gas wells. Taugbol et al. (2005) stated that oil-based mud exhibit better temperature stability when drilling at high temperatures compared to water-based mud providing better drilling performance, better lubricity, lower coefficient of friction and better hole-stability than water-based mud. Wang et al (2023) stated that cement slurry contamination with drilling mud causes micro-cracks and pores on the cement/formation interface and decreases the tensile strength of the cement sheath.

2.0 BODY TEXT

Methods applied include laboratory testing and mathematical modeling using Microsoft Excel. The experimental materials include Class G cement, freshwater, antifoam additive and oil-based mud. The cement slurry was prepared according to API Spec 10B and heated for 20 minutes in an Atmospheric Consistometer that has been pre-heated to each test temperature. The rheology of the cement slurry was measured using Chan-35 Rheometer. Same procedure was applied to measure the theology of the cement slurry at the different test temperatures of 27C, 38C, 49C, 60C and 71C. Fresh cement slurry was prepared for the rheology measurement at each test temperature. Rheology of the oil-based mud was also measured using the Chan-35 Rheometer after conditioning in the Atmospheric Consistometer for 20 minutes at each test temperature.

The contamination of the cement slurry with oil-based mud was simulated in the Laboratory by mixing them at the ratios of 90/10, 80/20, 70/30, 60/40 and 50/50 % by volume respectively. The mixtures of the cement slurry and the oil-based mud were separately conditioned for 20 minutes in the Atmospheric Consistoometer that has been preheated to each test temperature. The rheology of each of the contaminated cement slurries was measured using the Chan-35 Rheometer. This procedure was repeated separately for each contaminated cement slurry at each of the different test temperatures of 27C, 38C, 49C, 60Cand 71C. A stepwise procedure applied in this work is hereby stated as follows:

Step 1: Prepare the cement slurry (1.90 SG) with the cement and antifoam additive according to API Spec 10B.

Step 2: Condition the cement slurry for 20 minutes in the atmospheric consistometer that has been pre-heated to each test temperature and run the rheology at the different test temperatures. Prepare fresh cement slurry for each test temperature. Calculate the Plastic viscosity and the yield stress of the cement slurry at each test temperature.

Step 3: Condition the oil-based mud for 20 minutes in the atmospheric consistometer that has been pre-heated to each test temperature and run the rheology at the different test temperatures. Use fresh sample of mud for each test temperature. Calculate the Plastic viscosity and the yield stress of the mud at each test temperature.

Step 4: Using Microsoft Excel, plot the graphs of the Plastic viscosity versus temperature and yield stress versus temperature for the cement slurry

Step 5: Using Microsoft Excel, plot the graphs of the plastic viscosity versus temperature and yield stress versus temperature for the oil-based mud

Step 6: Run the contamination tests by mixing the oil-based mud and the cement slurry in the following proportions (10/90, 20/80. 30/70. 40/60 and 50/50 % by volume) respectively and run the rheology of each mixture at each of the test temperatures of 27°C, 38°C, 49°C, 60° and 71°C by conditioning each mixture separately for 20 minutes in the atmospheric consistometer that has been pre-heated to each respective test temperature.

Step 7: Using Microsoft Excel plot the graphs of Plastic viscosity versus temperature for each mixture.

Step 8: Using Microsoft Excel plot the graphs of Yield stress versus temperature for each mixture.

Step 9: Use the "Add trend-line" option in Microsoft Excel and click "display Equation on chart" and the "R-squared value on chart" on the graphs of each of the cement slurry/mud mixtures in steps 7 & 8. Choose the linear or polynomial option whichever, gives the higher R-squared value.

3.0 RESULTS AND DISCUSSION

Results showed that the plastic viscosity and yield stress of the cement slurry increased with rise in temperature as evidenced by Figures 1 and Figure 2. This is supportive of the fact that the rate of the hydration reaction of cement slurry or the rate of formation of the hydration products responsible for the rheological parameters (plastic viscosity and yield stress) of the cement slurry increases with rise in temperature. Nelson and Guillot (1990) stated that the hydration rate of cement and the nature, stability and morphology of the hydration products are strongly dependent on temperature.

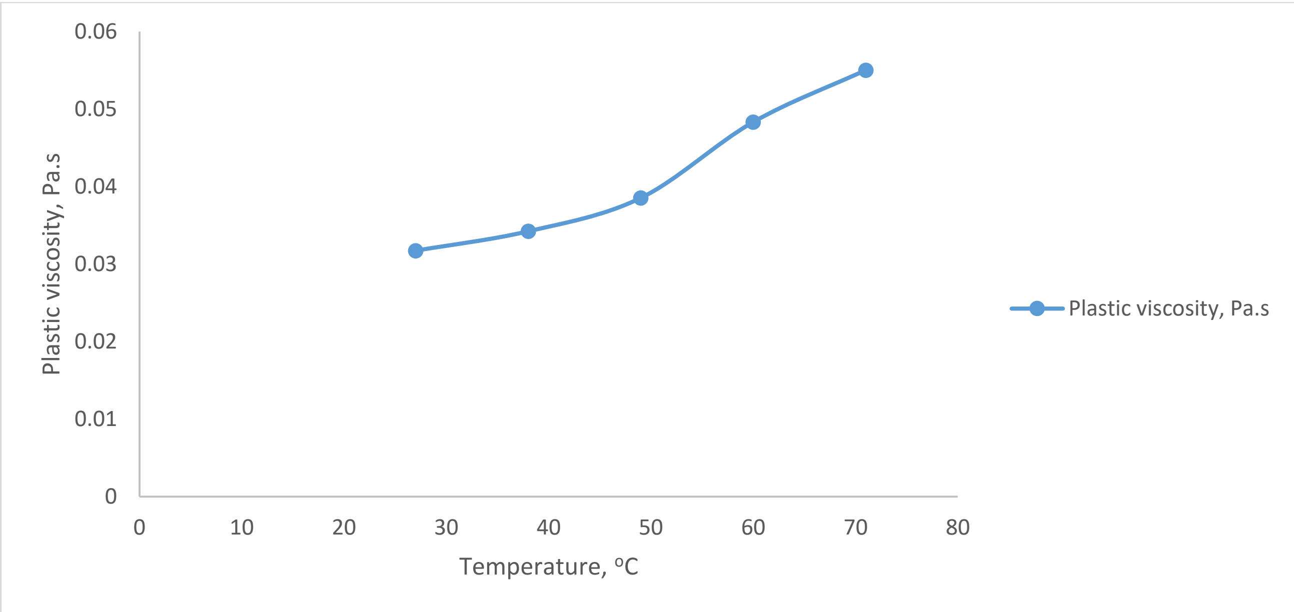

Figure 1: Variation of the Plastic viscosity of cement slurry with temperature

The variation of the Yield stress of the cement slurry with temperature is presented in Figure 2.

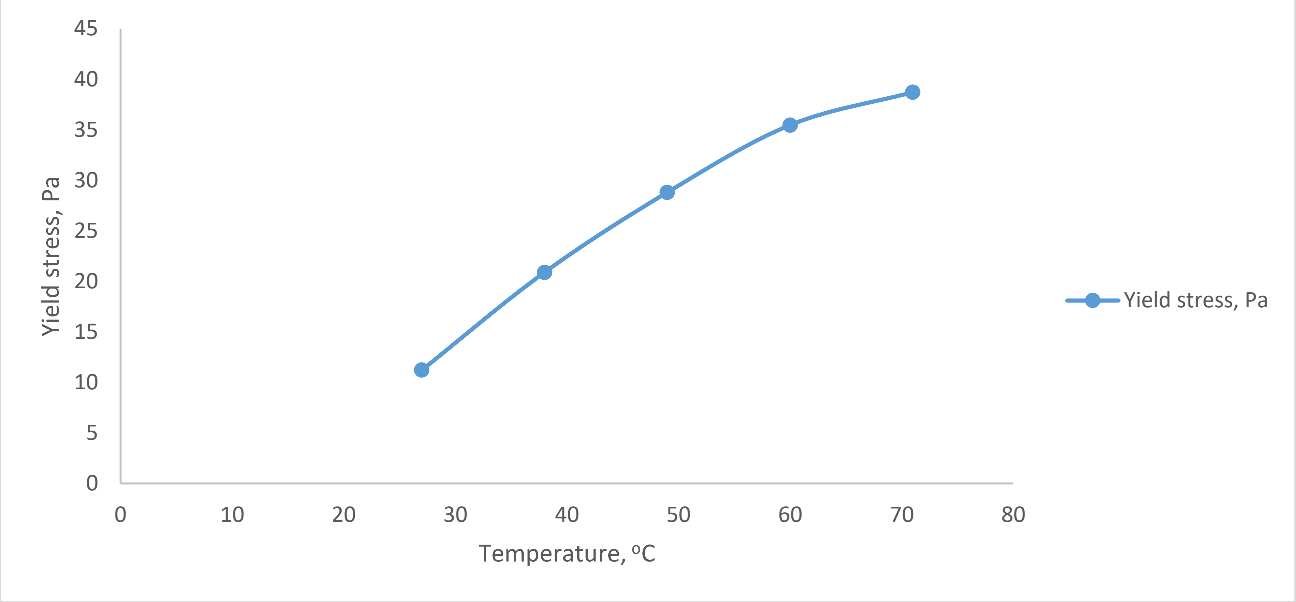

Figure 2: Variation of the Yield stress of cement slurry with temperature

The results revealed that the Plastic viscosity and Yield stress of the oil-based mud decreased with rise in temperature as evidenced by Figure 3 and Figure 4. This trend is normal with oil-based mud.

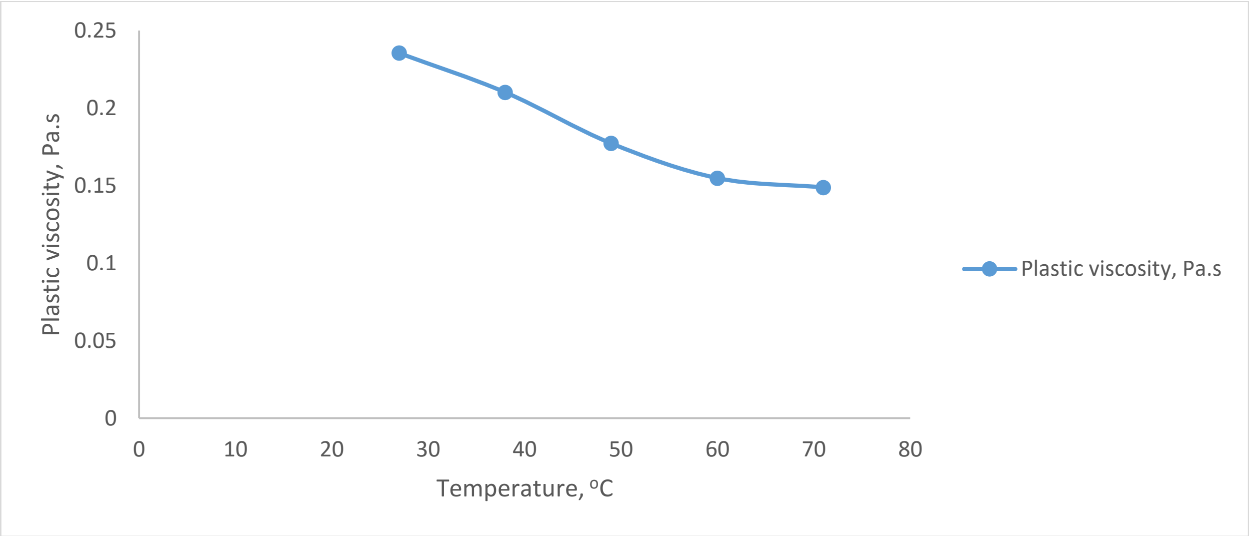

Figure 3: Variation of the Plastic viscosity of oil-based mud with temperature

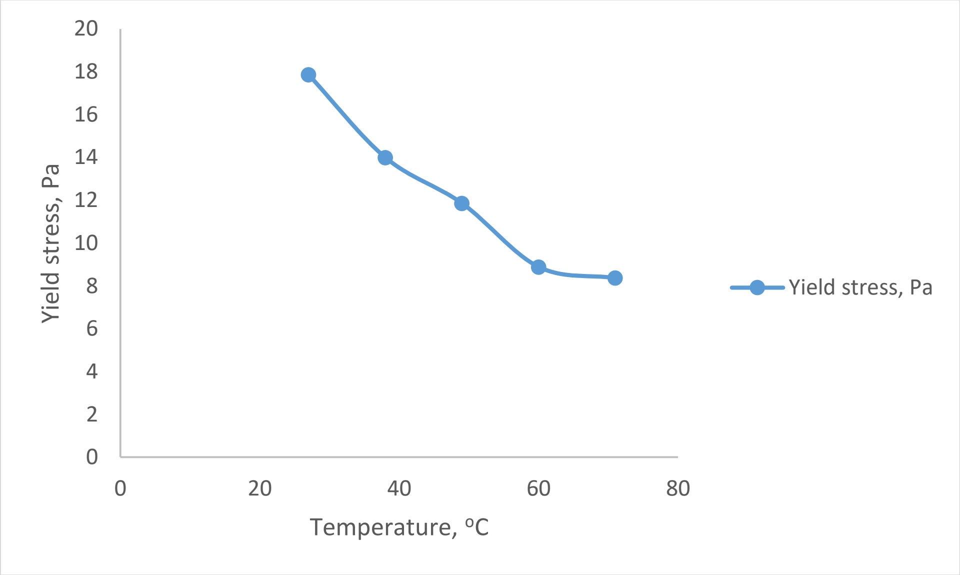

Figure 4: Variation of the Yield Stress of oil-based mud with temperature

The variation of the Plastic viscosity of the contaminated cement slurries (cement slurry & oil-based mud mixtures) with temperature at different percentage of contamination with oil-based mud are as presented by Figure 5 and Figure 6.

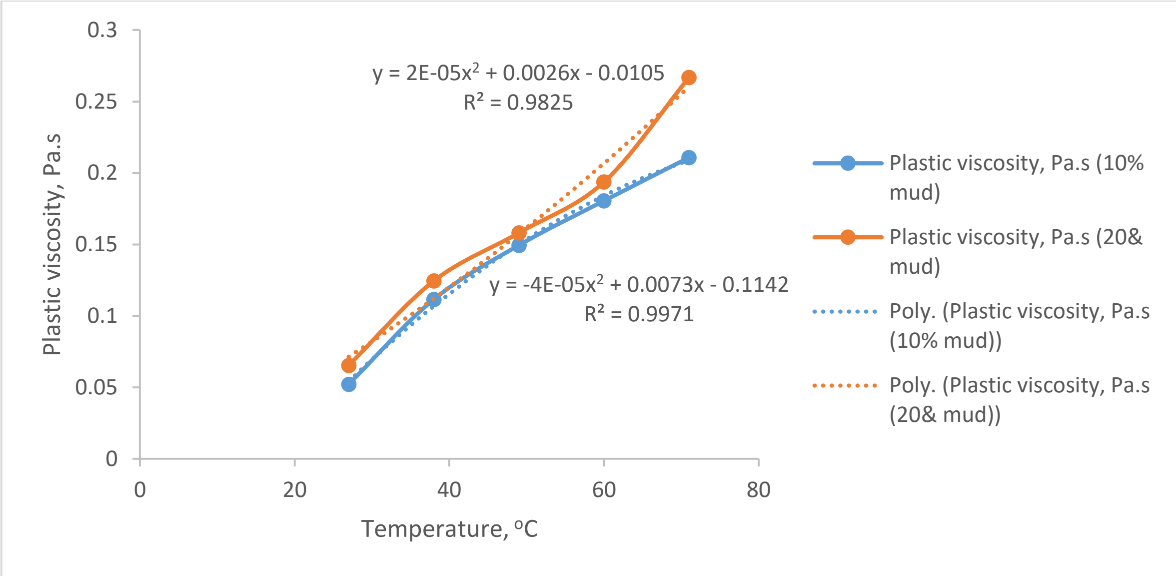

Figure 5: Variation of Plastic viscosity of contaminated cement slurry with temperature at different percentage of contamination with oil-based mud (10% & 20% contamination)

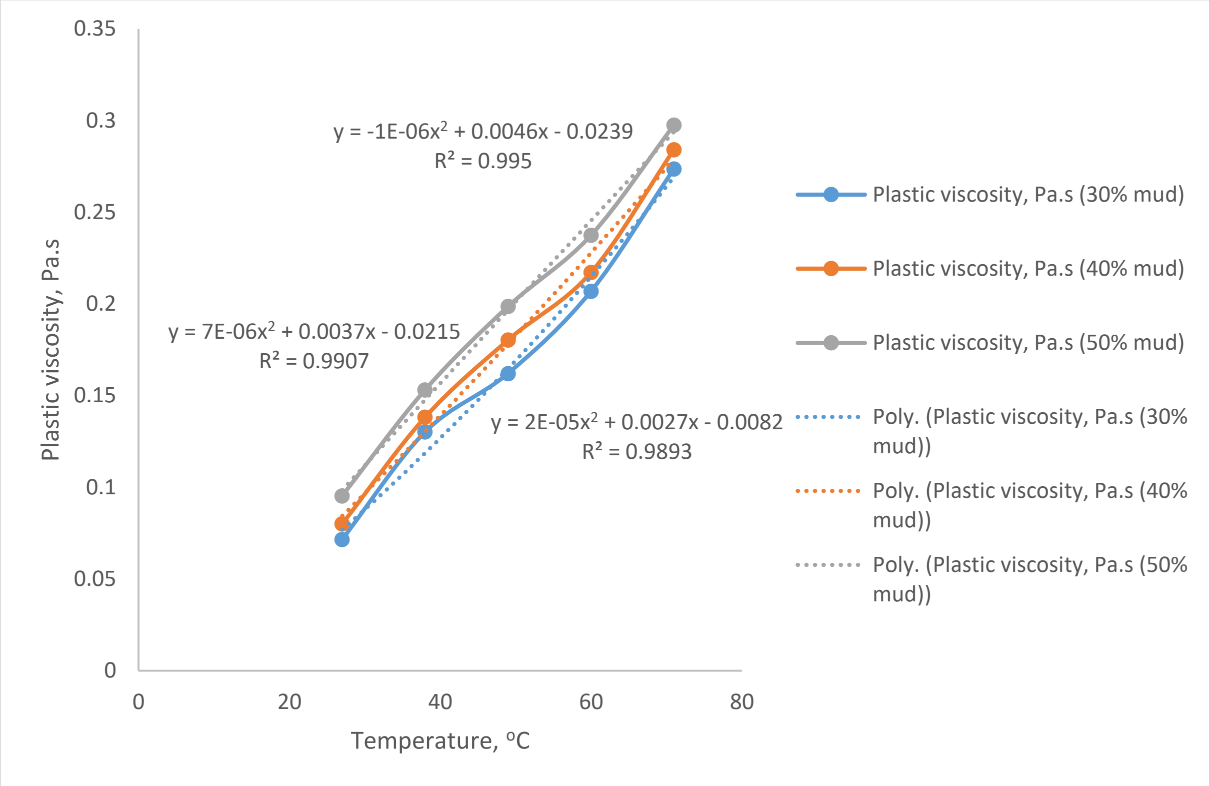

Figure 6: Variation of the Plastic viscosity of cement slurry with temperature at different percentage of contamination with oil-based mud (30%, 40% & 50% contamination)

The variation of the yield stress of the contaminated cement slurries (cement slurry & oil-based mud mixtures) with temperature at different percentage of contamination with oil-based mud are as presented by Figures 7 & 8.

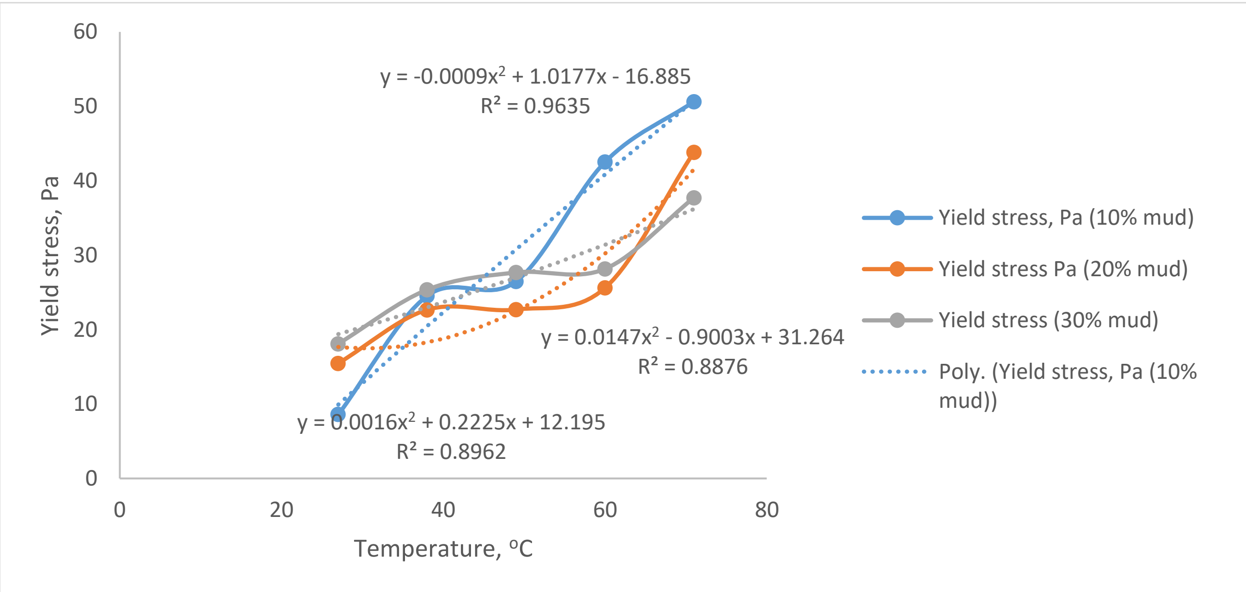

Figure 7: Variation of Yield stress of contaminated cement slurry with temperature at different percentage of contamination with oil-based mud (10%, 20% & 30% contamination)

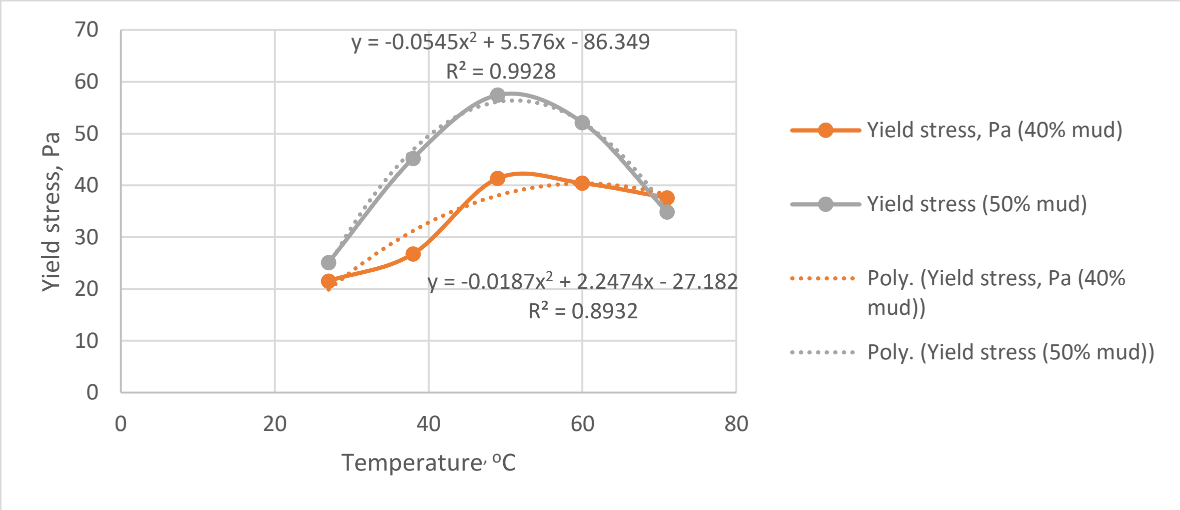

Figure 8: Variation of Yield stress of contaminated cement slurry with temperature at different percentage of contamination with oil-based mud (40% & 50% contamination).

The extent of contamination is a measure of the relative quantity of oil-based mud in the contaminated cement slurries (cement slurry/oil-based mud mixtures). Results showed that at a particular percentage or extent of contamination, the plastic viscosity of cement slurry increased with rise in temperature. The results also depict that at a particular temperature, the plastic viscosity of cement slurry increases with extent of contamination. In other words, the plastic viscosity of the contaminated cement slurry increases with the amount of oil-based mud contained in it. Bannister and Benge (1981) reported that the characterization of the flow properties of a fluid can be determined by relating the shear rate to the shear stress. Rajput (1998) stated that viscosity is a measure of the resistance of a fluid to shearing stresses and it results from the cohesion and interaction between molecules or particles of the fluid. Iyagba (1997) wrote that viscosity is a measure of the resistance of a fluid to shearing force and that cement slurry and drilling mud are Bingham Plastic fluids characterized by plastic viscosity and yield stress.

Similarly, at a given percentage or extent of contamination, the yield stress of the contaminated cement slurry increased with increase in temperature but it decreased with increase in the extent of contamination (e.g. at 40% to 50% contamination) at high temperatures (e.g. 60ºC and 71ºC) as depicted by Figure 8. The results also showed that at a particular temperature, the yield stress of cement slurry increases with the extent of contamination. In other words, the yield stress of the contaminated cement slurry increases with the amount of the oil-based mud contained in it but decreases with increase in the amount oil-based mud contained it at high temperatures.

Mathematical models representing the variation of the plastic viscosity and yield stress of the contaminated cement slurries with temperature were generated using regression analysis via Microsoft Excel. The polynomial equation option gave the best regression coefficient. The mathematical models obtained at different percentage of contamination of the cement slurries are displayed on Figure 5, Figure 6, Figure7 and Figure 8. The values of the regression coefficient (R^2) obtained are very high as they are all above 88% as evidenced on the aforesaid plots. Nachiket and Teodoriu (2020) stated that contamination of cement slurry with oil-based mud has negative effects on its rheological and mechanical properties and also the long term integrity of the oil & gas well.

Limitations encountered in this work are funding and equipment.

5.0 CONCLUSION

The significance of this work to the oil & gas industry cannot be over-emphasized.

The very high regression coefficient obtained for the rheological parameters of the contaminated cement slurries establish that the corresponding mathematical models can be confidently applied to predict effect of temperature on the rheological parameters of the contaminated cement slurries during primary cementing and remedial cementing design in emergency situations where Laboratory services are not immediately available.

Modelling the rheological parameters of contaminated cement slurry with temperature and extent of contamination will enable easier and better cementing job design and the investigation of cementing job failures in the oil & gas industry. Therefore, it is hereby recommended that mathematical models should be proactively developed to predict the contamination on the rheological parameters of cement slurry at different temperatures during the job design stage especially for production casing and liner cementing.

The application of the mathematical models will provide better understanding of cement slurry contamination with drilling mud and prompt design engineers to recommend the pumping of adequate spacer fluids ahead of cement slurry during primary cementing and remedial cementing job designs in order to better avoid cementing job failures.

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