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MATHEMATICAL MODELS FOR COMPATIBILITY OF AN EFFICIENT MATRIX ACIDIZING FLUID DESIGN

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ABSTRACT

In this study, mathematical models have been generated for the prediction of time of separation (compatibility) for four matrix acidizing fluids in contact with reservoir fluids. The treatment fluids formulated are used for the removal of wellbore damages due to organic and inorganic materials, fines, mudcake, *etc*. The study determined the viscosity and the behaviour of the acidizing fluids in contact with the formation fluids as well as the time it takes for separation. The treatment fluids are: clay stabilisation fluid, matrix stimulation, oil-based dispersant fluid and non-retarded mud acid systems. The rheological and the separation time analyses were conducted at temperatures of 80 °F, 150 °F and 190 °F. Generally, rheological values were affected by temperatures; increase in temperature decreased the values in most cases with the exception of oil-based dispersant fluid. Clay stabilisation and matrix stimulation fluids recorded low separation times at all test temperatures which proved compatibility. Again oil-based dispersant fluid could not separate out of the crude within the test time of 10 minutes at all test temperatures. Low viscosity values are desirable so that acid treatment fluid can easily be flowed out of the wellbore after stimulation operation and also to avoid the occurrence of adverse effects such as precipitating out. The model equations generated can be used to determine the fluid – crude compatibility when the viscosity of fluid and the working formation temperatures are known.

KEYWORDS: Matrix Acidizing, Compatibility, Rheology, Viscosity, Temperature, Productivity.

1.0 INTRODUCTION

The essence of determining the rheology of fluid system is to predict its pumpability in and out of the wellbore. The measurement of viscosity is the most sensitive or desirable means of ensuring that a particular fluid system can be pumped into and out of a wellbore within certain period of time after its interaction with other fluids. This means that viscosity measurements would show if a fluid system has changed in terms of density or weight. Matrix stimulation operations involve some form of flow characterisation into and out of the wellbore, therefore, viscosity measurement becomes necessary. Viscosity measurements are often the quickest, most accurate and most reliable way to analyse some of the most important factors affecting stimulation fluids performance. Rheological relationships help to understand the fluids being worked with so that their behaviour can be known or let them behave according to needs. Rheological measurements are also useful in following the course of a chemical reaction. Such measurements can be employed as a quality check during production operations or to monitor and control a process. Rheological measurements allow the study of the effects of additives, or the course of a curing reaction. They also help to predict and control the properties of fluid system, performance and behaviour (Anon, 2015 and Kelland, 2014). Rheology is the deformation and flow behaviour of all forms of matter. Rheological measurements such as viscosity helps to determine how the fluid will flow under a variety of different conditions (Anon, 2003).

One of the most obvious factors that can have an effect on the rheological behaviour of a material is temperature. Some materials are quite sensitive to temperature, and a relatively small variation will result in a significant change in viscosity. Others are relatively insensitive. Consideration of the effect of temperature on viscosity is essential in the evaluation of materials that will be subjected to temperature variations in use or processing. This analyses aims at determining the viscosity and the behaviour of the acid fluid in contact with the formation fluid at certain temperatures. As much as possible, low viscosity values are desirable so that acid treatment fluid can easily be flowed out of the wellbore after treatment (Cooley *et al.*, 2014) and also not to cause any further adverse effect such as precipitating out to block the wellbore or formation around the wellbore. If viscosity values are too high after mixing acid treatment fluid with crude, it indicates incompatibility. Joel

(2010) reported that, higher acid ratio in the mixture improves rheological properties and compatibility and points out, rheological values are said to be compatible if the rheological values of the mixtures fall between the values of the uncontaminated acid mix or crude (Scott, 2007). Rheological values are also affected by temperature, increase in temperature decreases the values and vice versa. Also, blend of treatment fluid with crude also modifies the rheological properties of the individual fluids. The effect of the two fluid mixture in this test revealed an increase in the rheological values notwithstanding the statement made by the authors. Joel (2010) stated that, the blend is acceptable if no separation of additives used in the acid formulation occurs on the top, bottom or sides of the container. Compatibility is defined by Joel (2010) as the capacity of forming a fluid mixture that does not undergo undesirable chemical or physical reactions, and not leading to sludge or separation. And from a similar study (Dankwa *et al*., 2016) carried out on emulsion break test of similar acid formulations fluids, it can be seen that most of the test at 150 °F and 190 °F did not form any sludge or sediments.

In this study, four different treatment fluids namely: clay stabilisation, matrix stimulation, oil-based dispersant and non-retarded mud acidizing fluids systems have been formulated to be tested with reservoir fluids (crude oil). This is to ascertain the mixture's behaviour in terms of viscosity for establishing compatibility.

2.0 MATERIALS AND METHODS

2.1 Materials used in this study include

- Crude oil from the Niger Delta region
- Acids (HCl, HF, *etc*), KCl, Diesel, Xylene, Mix water
- Special additives comprising of Corrosion inhibitors, Surfactants, Mutual solvents, Iron Control agent, pH Control, Emulsifier, Non-Emulsifier, Penetration Aid and *etc*.
- Fan Viscometer, Hot water bath for temperatures, measuring cylinder, mixer, pipettes, beakers, *etc*.

2.2 METHOD

In this study, a Fann Viscometer was used to take the RPM readings of the different formulated fluid systems and the sample crude at different test temperatures (80 °F, 150 °F, 190 °F). A ratio proportion of 1:1 fluid system versus crude was also mixed together and

RPM dial readings were recorded with the same instruments at the test temperatures. All these results were recorded at the various temperatures with the aid of a regulated water bath.

The purpose of this section was to run rheology of the acidizing fluids mixed with crude to determine their viscosities. Viscosity is important in matrix acidizing operation in order to achieve easy pumpability of the fluid to surface after the operation. A highly viscous fluid will increase the pump pressure needed to pump back the acid fluid to surface. More so, there is the tendency for fluid to become too viscous and form precipitates which can fill the existing pores, hence hindering flow.

Non-retarded Mud Acid

Non-retarded mud acidizing fluid was formulated to be a fast reacting fluid and the major constituents are HCl and Ammonium Bi-Fluoride which undergo reactions to generate HF in-situ to form the required mud acid. Ammonium Bi-Fluoride produces HF acid when mixed with HCl acid (Cooly *et al*., 2014). Rheological analysis was performed with this fluid and sample crude to determine the fluid mixture’s viscosity and establish compatibility.

Clay Stabilisation Fluid

The purpose of formulating clay stabilisation treatment fluid is for the stabilisation of clay content in the formation around the wellbore during matrix acidizing operation. This is to prevent any adverse reactions and effects such as clay swellings and fines migration which can eventually block the formation pores and perforations. This fluid is used for carrying out rheological analysis for the determination of viscosity.

Matrix Stimulation Fluid

Matrix stimulation fluid was also designed to depict acidizing fluid capable of removing damages which block pore spaces in the formation matrix near wellbore. Rheological analysis was performed with this fluid system mixed with crude oil for the determination of viscosity.

Oil-Based Dispersant

This fluid system is intended to act as a dispersant for an oil-based, perforating/breakdown fluid for cleaning up invert oil based mud before stimulation treatments. It has been designed to be used on oil based muds such as invert emulsion mud which are usually used in drilling through shales and other water sensitive formations. This prevents the adverse effects of gummy, viscous emulsion created when common aqueous perforating and breakdown fluids contact invert muds. In fact it can be used as a clean-out fluid by circulating it at high pumping rate (Halliburton, 2008). The treatment fluid was used with sample crude for carrying out rheological analysis.

3.0 RESULTS AND DISCUSSION

The dial readings from the viscometer during the experiments have been used to compute the fluids viscosities in Table 3.1 for all the designed fluid + crude mixtures. Equation (1) was used for calculating the apparent viscosities for all the acidizing fluid to crude mixtures.

$$\text{Apparent Viscosity (cP)}=\frac{\theta_{600}}{2} \qquad (1)$$

where, θ_{600} = Dial reading at 600 rpm

Table 1: Computed Viscosity for Specific Wellbore Fluids.

Composition	Temp (°F)	Clay stab	Matrix Stim	Dispersant	Non-retarded
Crude	80	5	5	6	5
Fluid only	80	3	3	4	4
(1:1)	80	10	20	4	14
Crude	150	4	4	4	4
Fluid only	150	3	3	4	2
(1:1)	150	7	6	5	6
Crude	190	4	4	6	4
Fluid only	190	1	1	4	2
(1:1)	190	4	3	5	5

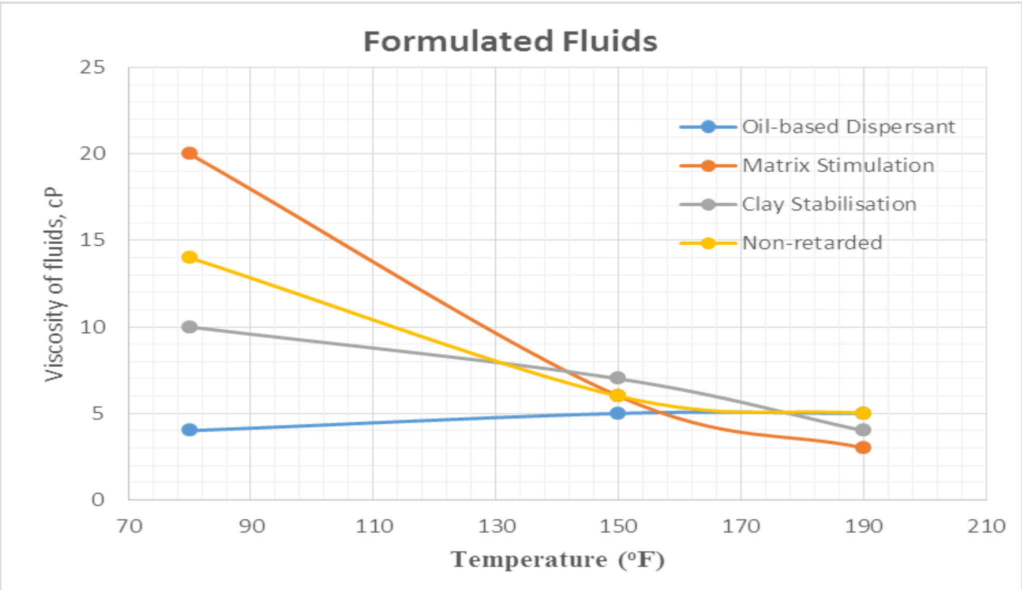

Figure 1: The trend of temperature effect on viscosity of fluid+crude.

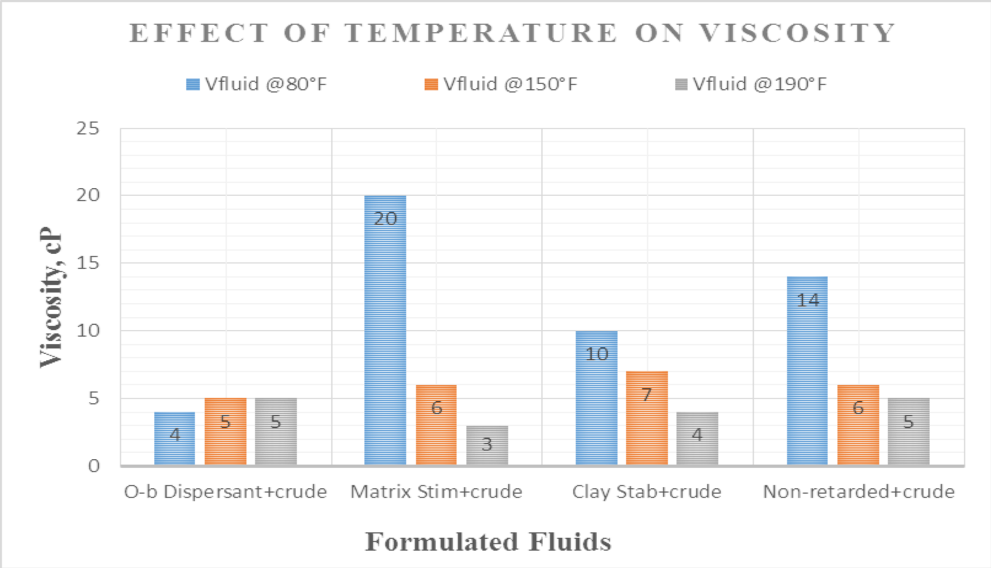

Figure 2: Graphical representation of the viscosity of fluid system+crude under each test temperature.

Clay Stabilisation

Table 1 shows the computed viscosity values in centipois and they reveal the behaviour of the fluids and fluid mixture encountering varying formation temperatures in the wellbore. Rheology was run for 80 °F, 150 °F and 190 °F respectively. The viscosity values in Table 1 show a very good trend (Figure 1) with respect to increasing temperature, in that, the values decrease with increasing temperature. Though the treatment fluid – sample crude mixture (1:1) gave higher rheological values, this is actually expected because of the effect of the two fluids mixing together. The values are acceptable and would not cause any difficulty when flowing out the fluid from the wellbore after stimulation operation. The mixing of the sample crude with the formulated treatment fluid did not produce any sludge, there was compatibility and increase in temperature only reduced the viscosity values which is good for wellbore stimulation.

Matrix Stimulation

From Table 1, it can be seen that, this fluid system also exhibited good rheological property desirable for wellbore stimulation operation as compared to clay stabilisation. From Figure 1, it can be seen that viscosity decreases with increasing temperature. It was also observed from the fluid – crude mixture that, no sludge formation occurred and the additive did not separate out of the mixture. This proves to be good characteristics for any treatment fluid for stimulation purposes.

Oil-Based Dispersant Fluid

The rheological measurements of the fluid and fluid mixed with sample crude are presented in Table 1 for oil-based dispersant fluid. The rheological values obtained for this fluid and its mixture with crude were generally low however, increasing temperature did not cause the viscosity to reduce as was observed for clay stabilisation and matrix fluid systems. The low rheological values are good for stimulation operations, however, it can be said of this fluid and crude mixture that, its response to temperature is not favourable even though the mixture was devoid of any sludge formation. Oil-based dispersant fluid is not compatible with the reservoir fluid because as viscosity was expected to decrease with increasing temperature, it rather increased. Such fluid system will have difficulty flowing out of the wellbore after stimulation operation should it encounter high formation temperatures.

Non Retarded Mud Acid Fluid System

From Figure 1, it can be seen that temperature has effects on the viscosity of non-retarded fluid mixed with crude; and as temperature increased, the viscosity of fluid also decreased. No sludge was observed to have been formed in the crude – fluid mixture at all the temperatures and the additives did not separate out from the fluid mixture or fluid – crude mixture which shows compatibility.

Modelling of Results

In this session, JMP software, version 12, has been used to model the results through factorial design by combining the viscosity, temperature and the time of separation (ToS) (Dankwa *et al*., 2016). Regression analysis carried out on each of the fluid system has been tabulated under Table 2.

Table 2: Regression Analysis of Mathematical Models of the Specific Wellbore Fluid Systems.

Dependent Variable: Time				
	Matrix Fluid	**Non-retarded mud acid**	**Clay Stabilisation fluid**	**Oil-based Dispersant**
Temperature	0.010**	-0.100***	-0.059**	-0.125
Viscosity	0.144***	1.167***	-0.034	3.75
Interaction	0.0000123	-0.018***	-0.021***	0
Constant	-1.975**	14.616***	10.283	20
NB *** signifies significance at 1%				
** signifies significance at 5%				
* signifies significance at 10%				

Regression Analysis for Combined Variables of the Non-Retarded Mud Acid Systems

The model equations obtained for the combined temperature and viscosity variables is presented in equation 2 for the prediction of the time of separation (ToS) which depicts compatibility of the fluid mixture. The regression analysis is shown in Table 2.

$$Comp_{non-R} = 14.6162 + (-0.1005 * \mathrm{T}) + 1.1672 * V_{non-R} + (\mathrm{T} - 140) * [(V_{non-R} - 7.7222) * -0.0177] \quad (2)$$

From Table 2 it can be seen that, temperature has a negative relationship on the time of separation (ToS) for non-retarded mud acidizing, 9%HCl - 1.5%HF and fines control acidizing system. This means that a unit increase in temperature can reduce the time of separation. These fluid systems also have 1% significance at their respective p-values. This is good because it is expected that, an increase in temperature should cause the fluids mixture to separate faster and hence proving compatible.

Viscosity has a positive relationship with ToS on non-retarded mud acidizing and shows a 1% significance level at its p-value of 0.0001. This means that a unit increase in the viscosity will cause time of separation to increase which does not agree with theory

The interactive parameters of temperature, viscosity on ToS, have a negative relationship and there is 1% level of significance at its p-value of 0.0001.

The prediction profiler and the actual versus predicted ToS plots of all acidizing mix fluids of their respective models are given in Figures 1 and 2 respectively.

In terms of the model diagnostics, non-retarded fluid system recorded an adjusted R^2 value of 0.999 which boost the confidence level of the model.

Thus we can say that the regression line which is shown in Figures 4 fit the data extremely well; as it can be seen from the figure that the actual data points are almost all lying on the estimated regression line.

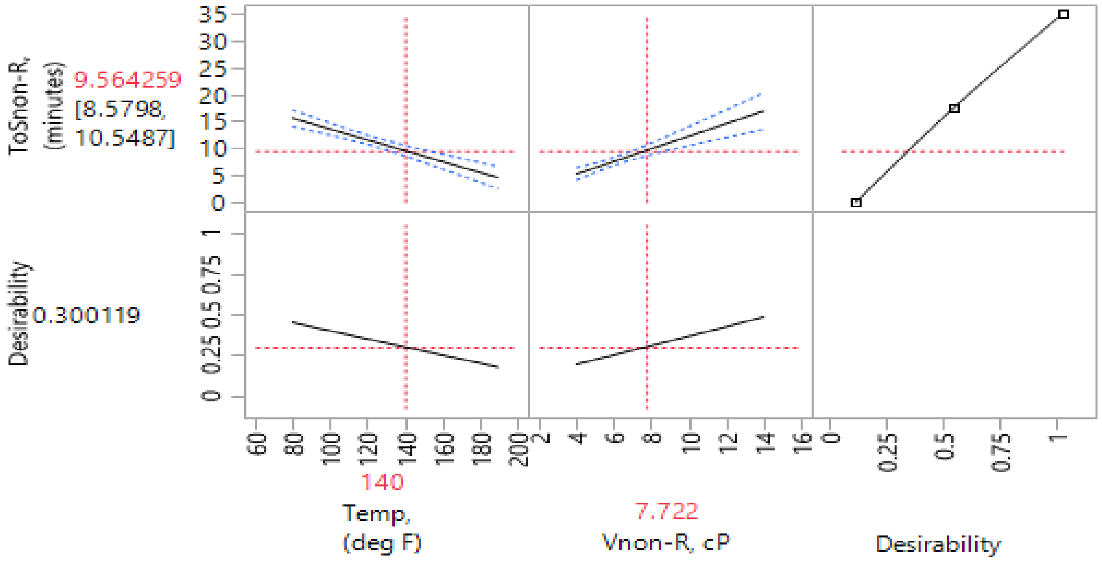

Figure 3: Prediction profile for non-retarded mud acid mix design model.

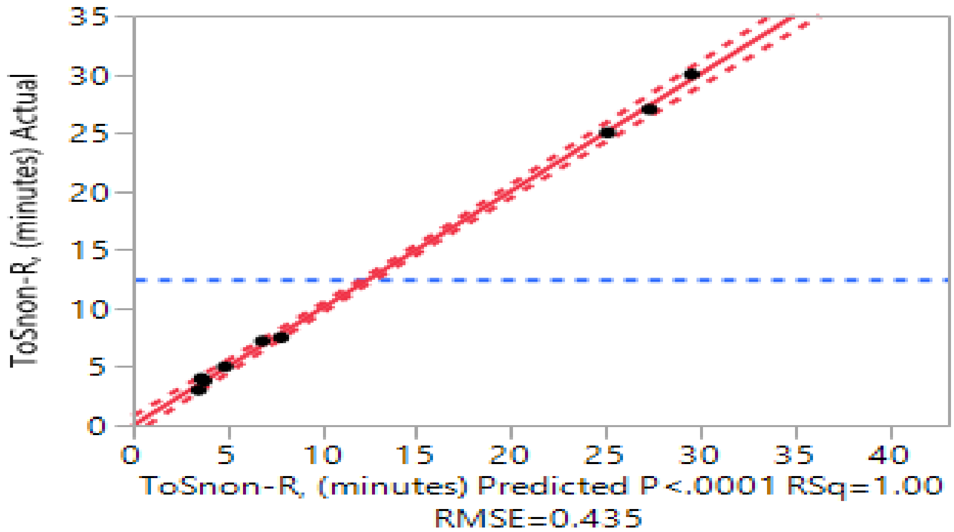

Figure 4: Actual ToS against predicted ToS of non-retarded mud acid mix design.

Regression Analysis for Combined Variables of the Clay Stabilisation, Matrix and Oil-based Dispersant Fluid Systems

The model equations obtained for the combined temperature and viscosity variables is presented in equations 3 to 5 for the prediction of compatibility.

$$Comp_{clay\,stab} = 10.2829 + (-0.0582 * \mathrm{T}) + \left(-0.0344 * V_{clay\,stab}\right) + (\mathrm{T} - 140) * \left[\left(V_{clay\,stab} - 7.0556\right) * -0.0207\right] \quad (3)$$

$$Comp_{mat\,stim} = -1.9755 + 0.0099 * T + 0.1438 * V_{mat} + (\mathrm{T} - 140) * [(V_{mat} - 9.3333) * -0.0001] \quad (4)$$

$$Comp_{Dis} = 20 + (-0.125 * \mathrm{T}) + 3.75 * V_{dis} + (\mathrm{T} - 140) * [(V_{dis} - 4.6667) * 0] \quad (5)$$

From Table 2 it can be seen that, temperature has a negative relationship on the compatibility, i.e. time of separation (ToS) for two of the fluid system thus, clay stabilisation and oil-based dispersant fluids whiles there is a positive relationship between temperature and ToS of matrix fluid system.

In the case of the negative relationship, it means that a unit increase in temperature can reduce the time of separation, this shows compatibility though oil-based dispersant fluid did not show any significant influence of temperature on its time of separation. It can be seen from Table 2 that, only the clay stabilisation fluid has 5% level of significance at its p-value of 0.0001, oil-based dispersant is not significant. Matrix fluid system which shows a positive relationship between its temperatures and time of separation records a 5% level of significance at its p-value of 0.0001. The positive relationship is not good because it is expected that, an increase in temperature should cause the fluids mixture to separate faster and hence proving compatible but in this case, any unit increase in temperature, from the result, will make time of separation to be prolonged.

Viscosity also has a positive relationship with ToS on all the two fluid system except clay stabilisation fluid system however, clay stabilisation fluid recorded 1% level of significance on its p-value of 0.0001. Matrix stimulation fluid also recorded 1% level of significance based on its p-value of 0.0001. Viscosity is rather expected to relate to ToS positively and this should be the case for all the fluid systems so that, for instance a reduction in viscosity can reduce the time it takes for the fluid to separate in order to prove compatible. Fluids with reduced viscosities are able to achieve faster separation.

The interactive parameters of temperature, viscosity on ToS, have negative relationships on both matrix and clay stabilisation fluid systems while there is no relationship shown in the interacting parameters for oil-based dispersant fluid system. Clay stabilisation fluid system recorded 1% level of significance at its p-value of 0.0001 while there was no level significance for matrix fluid. Oil-based dispersant fluid on the other hand, did not show any response with its temperature and viscosity parameters on the time of separation. This may be attributed to other chemical reaction and the composition of the fluid system.

The prediction profiler and the actual versus predicted ToS plots of all acidizing mix fluids of the respective models are given in Figures 5 to 10 respectively.

In terms of the model diagnostics, matrix fluid and clay stabilisation systems recorded an adjusted R^2 values of 0.998 and 0.969 which make their models more reliable. Oil-based dispersant fluid though recorded an adjusted R^2 of 1 did not have temperature responding favourably with either viscosity or time of separation.

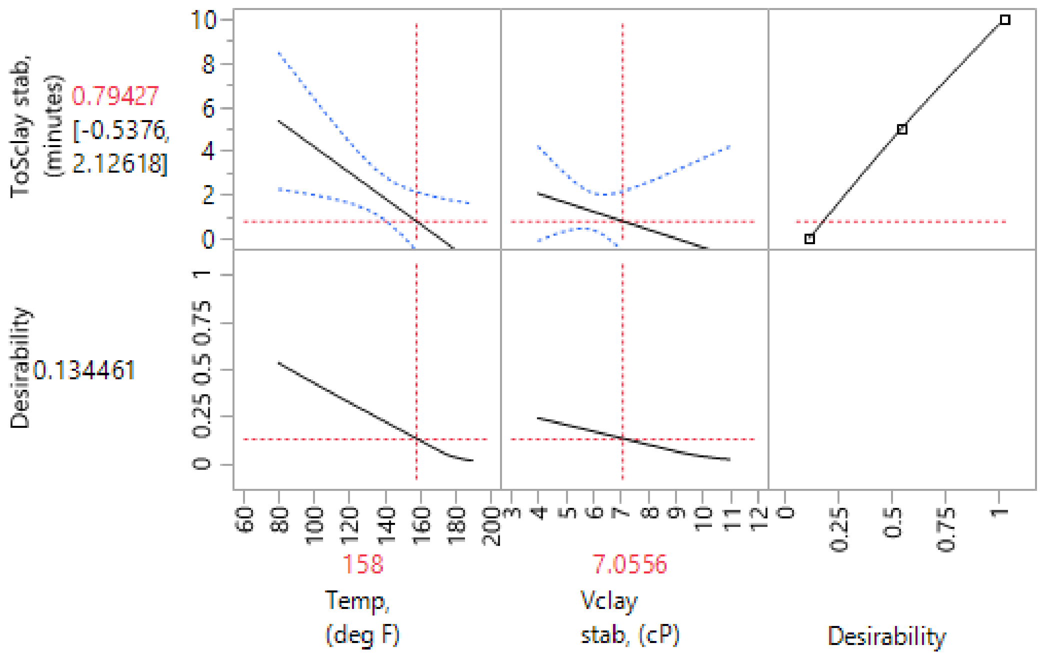

Figure 5: Prediction profile for clay stabilisation model equation.

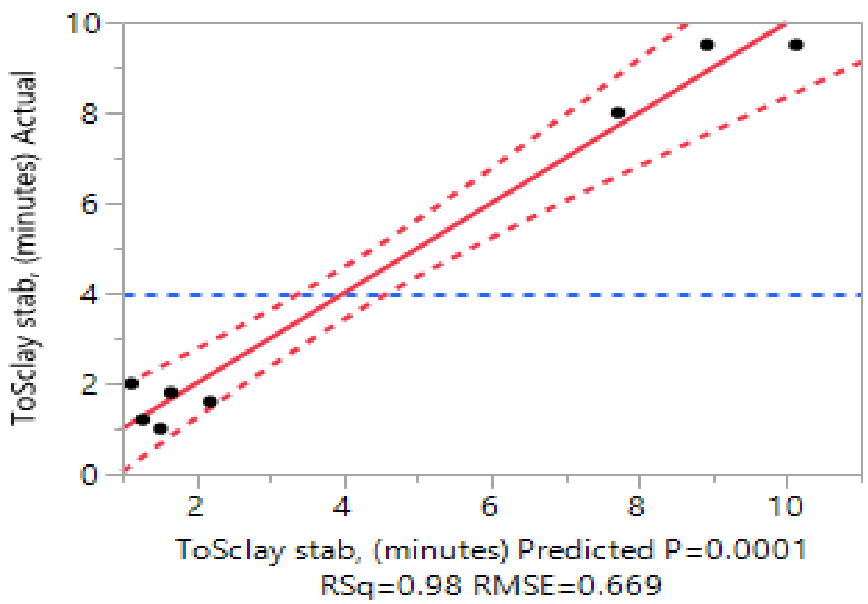

Figure 6: Actual versus predicted ToS plot of clay stabilisation model equation.

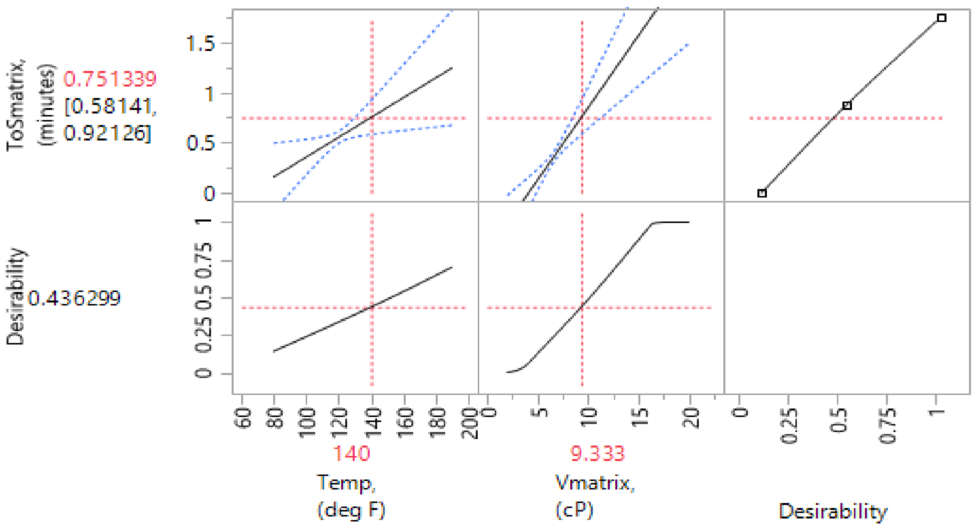

Figure 7: Prediction profiler for matrix stimulation model equation.

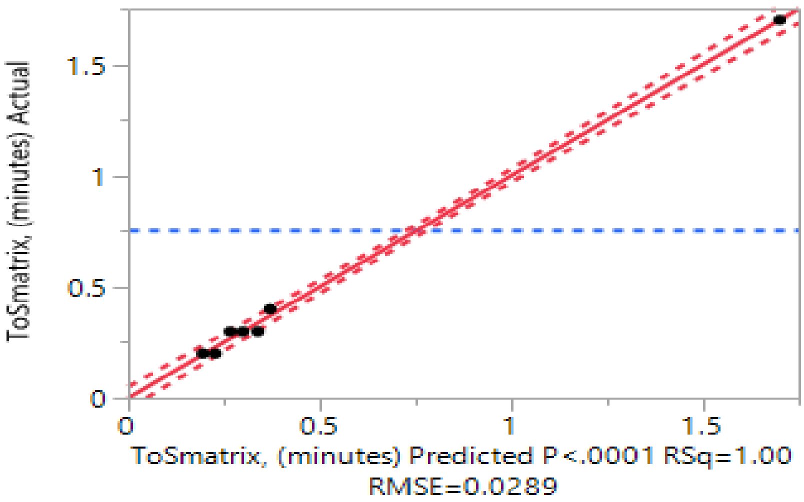

Figure 8: Actual versus predicted ToS plot for matrix stimulation model equation.

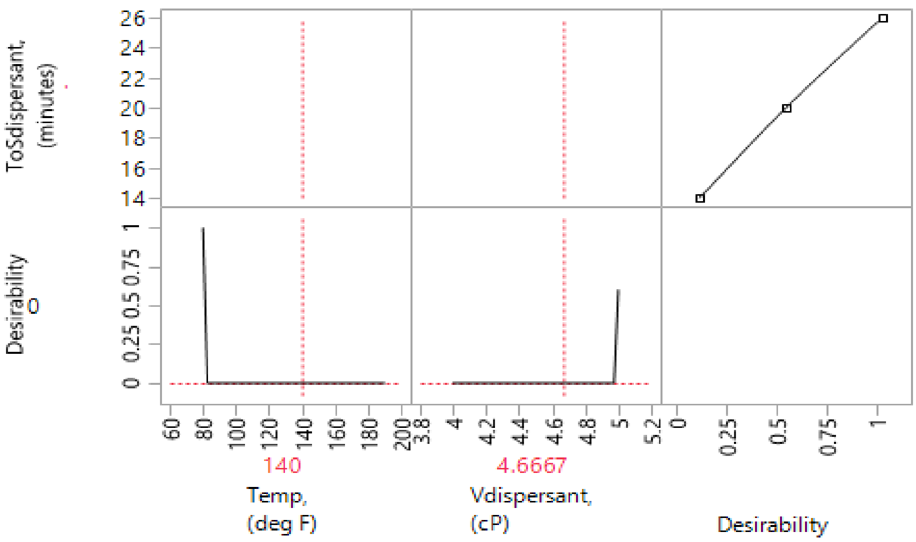

Figure 9: Prediction profiler for dispersant fluid mix model equation.

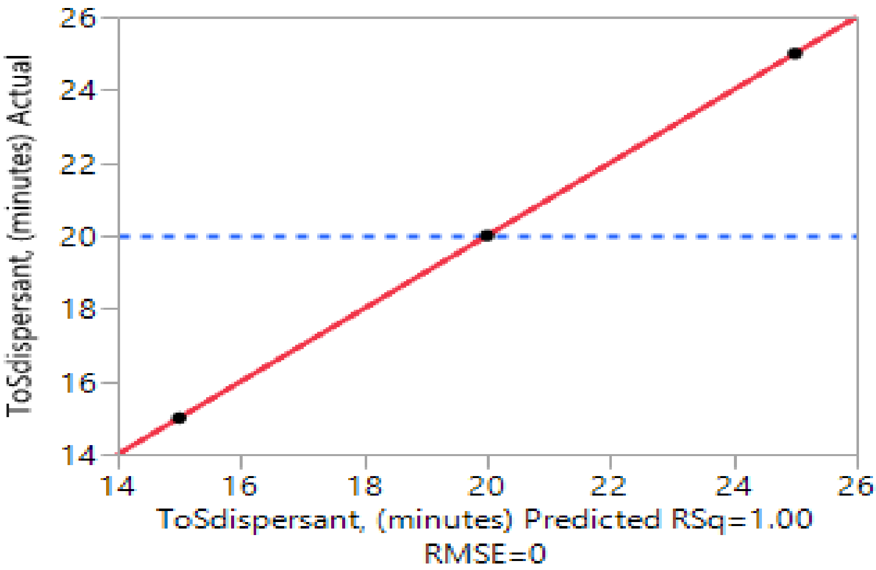

Figure 10: Actual versus predicted ToS plot for dispersant fluid mix model.

CONCLUSION

1. Non-retarded mud acid, clay stabilisation and matrix stimulation fluid systems had their viscosities decreasing with increasing temperatures and their model equations recorded an adjusted R^2 of not less than 90 % with 1% level of significance. Since the formulated fluids mixed with sample crude did not form any sludge and sediments, it is concluded that, these fluid systems are compatible.
2. Generally, temperature affected the viscosity of the fluid system and hence the time it takes for the formulated fluid to separate from the crude to make it easy for pumping out of the wellbore after the well stimulation operation. Higher temperatures gave low viscosities which is a good indication of compatibility between the two fluids.
3. Oil-based dispersant fluid did not show compatibility with the crude; instead of viscosity decreasing with increasing temperature, it was vice versa and hence difficulty to achieve separation between the formulated fluid and the sample crude.
4. From the analyses, it can be seen that different treatment fluid systems react differently with crude hence the need to test for compatibility.

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