Predictive Model for Compressive Strength of Epoxy Sand Consolidation System for Oil Wells

[1]S. A. Marfo, [2]D. Appah, [2]O. F. Joel and [1]G. Ofori-Sarpong
[1]University of Mines and Technology, P.O. Box 237, Tarkwa, Ghana
[2]University of Port Harcourt, PMB 5323 Choba, Rivers State, Nigeria

Marfo, S. A., Appah, D., Joel, O. F. and Ofori-Sarpong, G. (2017), "Predictive Model for Compressive Strength of Epoxy Sand Consolidation System for Oil Wells", *Ghana Journal of Technology*, Vol. 1, No. 2, pp. 73-79.

Abstract

Compressive strength is a critical parameter for the success of chemical sand consolidation operations in oil wells. Predicting the right compressive strength is affected by factors such as curing time, bottomhole temperature, pore volume treatment and active clay concentration of the formation. The ability to model and optimise these factors is therefore crucial in obtaining the desired compressive strength required to stop fines migration in hydrocarbon production without excessive reduction in permeability. This paper studied the individual and interactive effects of curing time and temperature on the compressive strength of an epoxy sand consolidation system. Based on the results obtained and with the aid of statistical analysis software, a predictive compressive strength model and software were developed for predicting the compressive strength for epoxy sand consolidation system. The results revealed significant impacts of the curing time and the temperature on the compressive strength of the epoxy system, though the interactive effects of these two factors did not have much significant effect on the compressive strength. The compressive strength model developed could be used as an aiding tool to explain about 97 % of the variability in the experiment conducted. The software developed could also be useful in laboratory and field applications for estimating compressive strength, while the predictive model could be employed as optimisation tool for designing epoxy sand consolidation operations in the oil and gas industry.

Keywords: Compressive Strength, Epoxy Sand Consolidation, Predictive Model, Curing Time, Temperature

1 Introduction

Chemical Sand Consolidation (SCON) operations have been employed in the oil and gas industry for close to six decades. Despite the numerous successes recorded in the industry over these years with the application of SCON, there are still some grey areas when it comes to its applications especially in problematic brown fields. The challenges encountered during chemical sand consolidation in the field raises some level of uncertainties in estimating the parameters that impact on the compressive strength, which needs to be addressed (Marfo *et al.*, 2015). The success of chemical sand consolidation operations is affected by a number of factors which could be formation or resin related (Bradley *et al.*, 1992; Carlson *et al.*, 1992). Among these factors, permeability reduction and formation strength or compressive strength attained are always critical in the treatment of chemical sand consolidation. Based on these; the application of resins is reserved for highly permeable reservoirs (Allen and Robert, 1989; Kuncoro *et al.*, 2001; Marfo *et al.*, 2015).

Studies conducted by Allen and Robert, (1989), Carlson *et al.* (1992) and Kuncoro *et al.* (2001) show there is always a compromise between reductions in the permeability and achievement of the right compressive strength. This compromise dictates the amount of resin injected into the formation of interest. There could be a decrease in permeability by 25% which could result in almost 10% reduction in productivity if unconsolidated formation having 8 000 mD is treated with a resin to give compressive strength of about 22.75 MPa. Due to this assertion, chemical sand consolidation operations is highly recommended for short intervals in the range of up to 3 to 5 m (Chaloupka *et al.*, 2010; Lahalih and Ghloum 2010; Renpu, 2011).

The consolidation strength obtained in SCON operations is dependent on the pore volume treatment, temperature, curing time and the formation's permeability among others (Sumit *et al.*, 2014; Marfo *et al.*, 2015). The minimum consolidation strength reported as safe for oil producing well formation is 1.01 MPa irrespective of the curing time used, but some polymers have recorded values in the range of 0.24 to 0.69 MPa (Lahalih and Ghloum, 2010). Lahalih and Ghloum (2010) established correlations between the compressive strength and a number of factors such as resin concentration, sand particle size, clay content among others. The effect of these factors on the compressive strength was studied using one-factor-at-a-time, thus strategy ruling out the impact of the interactive effect of these factors on compressive strength. The major disadvantage of

*Manuscript received December 10, 2016
Revised version accepted March 12, 2017

this approach or strategy is that it fails to consider any possible interaction between the factors under study (Montgomery, 2001). However, employing factorial design, the individual and interactive effect of the factors on the compressive strength could be ascertained. Marfo *et al*. (2016) employed factorial design to ascertain the individual and interactive effect of temperature, polymer and cross linker concentration on gelation time of an organically cross-linked water-shutoff system. Factorial design allows an experimenter to handle different factors, vary these factors together and determine both the individual and interactive effect of these factors on the response variable (Montgomery, 2001).

The compressive or consolidation strength attained is important for the success of chemical sand consolidation operations. This paper presents the impacts the individual and interactive effect of curing time and temperature have on compressive strength of epoxy sand consolidation system, a system extensively used in the petroleum industry. These impacts on the compressive strength were modelled and a compressive strength software developed for laboratory and field applications and for optimisation of chemical sand consolidation operations.

2 Resources and Methods Used

2.1 Resources

Epoxy systems comprising of a resin and hardener in aqueous form were used in this experiment. The chemicals used are American Chemical Standard (ACS) grade to ensure the purity of these resins. Syringes of 60 ml capacity were used for the consolidation and development of the core samples. The compressive strengths of core samples were determined using the Carver Hydraulic Press and Vernier callipers. 20/40 US mesh size sand samples with dimensions in the range of 0.084 to 0.043 cm were used to simulate downhole formation sand.

2.2 Methods

American Petroleum Institute (API) 10A and 10B were adopted for the compressive strength determination through the following steps: The epoxy resin and hardener were mixed in ratio 1:1, using a spatula. The sieved sand was filled to the 40 ml mark of the 60 ml syringe. This was followed with pouring SCON fluid from the top into the syringe and allowed to drain through the sand by gravity. The suction/discharge end of the syringe was plugged once the sand in the syringe was totally saturated with the SCON fluid. To consolidate the sand material, the syringe with the SCON fluid-sand mixture was placed in a large glass beaker filled with water and placed in water bath pre-set to the required Bottom Hole Temperature (BHT) that is 150 ^{o}F (65.6 ^{o}C) and 190 ^{o}F (87.8 ^{o}C) for curing. The diameter and the height of the cured samples were measured using Vernier callipers before determining the compressive strength. The compressive strength of the cured samples was determined after 2 days, 4 days, 7 days, 10 days and 14 days by crush method using Carver Hydraulic Press.

3 Results and Discussion

The results on compressive strength of cured core samples at 150 ^{o}F (65.6 ^{o}C) and 190 ^{o}F (87.8 ^{o}C) using epoxy sand consolidation system for up to 14 days of curing are presented and discussed in the ensuing sections. JMP statistical analysis software was used in the factorial design and analysis of the results. The characters assigned to the parameters used in the experiment are presented in Table 1. The pattern followed is that 1 to 5 represent the curing times of 2 days to 14 days and (-) for 150 ^{o}F (65.6 ^{o}C) and (+) for 190 ^{o}F (87.8 ^{o}C).

Table 1 Factorial Design for Compressive Strength

Test Run	Pattern	Temp (^{o}F)	Curing Time (day)	Compressive Strength psi (MPa)
1	+ 5	190	14	1291 (8.90)
2	− 2	150	4	460 (3.17)
3	+ 2	190	4	590 (4.07)
4	− 5	150	14	1090 (7.52)
5	+ 3	190	7	919 (6.34)
6	+ 4	190	10	1131 (7.80)
7	− 3	150	7	702 (4.84)
8	− 1	150	2	251 (1.73)
9	− 4	150	10	890 (6.14)
10	+ 1	190	2	347 (2.39)

3.1 Effect of Curing Time on Compressive Strength

Compressive strength attained is important as this indicates the success of sand consolidation operations. The compressive strength is influenced greatly by the formation temperature and the curing time. To study the effect of curing time on the compressive strength, the samples were cured at five different curing conditions at the two test temperatures of 150 ^{o}F (65.6 ^{o}C) and 190 ^{o}F (87.8 ^{o}C), and these are shown in Figs. 1 and 2 respectively.

Irrespective of the test temperature, increasing the curing time increased the compressive strength. The minimum curing time of 2 days resulted in a compressive strength of 251 psi (1.73 MPa) and 347 psi (2.39 MPa) at curing temperatures of 150 °F (65.6 °C) and 190 °F (87.8 °C) respectively. These minimum values exceeded the safe consolidation strength of 1.01 MPa for oil producing well formations as reported by Lahalih and Ghloum, (2010) and Zhiyong *et al.* (2012). It is observed that increasing the curing time condition increased the compressive strength regardless of the test temperature, and this is in conformity with previous research conducted (El-Sayed *et al*, 2001; Zhiyong *et al.*, 2012). This affirms the importance of identifying and testing the reservoir conditions and shut-in time to attain the required and safe compressive strength before conducting chemical sand consolidation operations on the field (Lahalih and Ghloum, 2010; Marfo *et al.*, 2015).

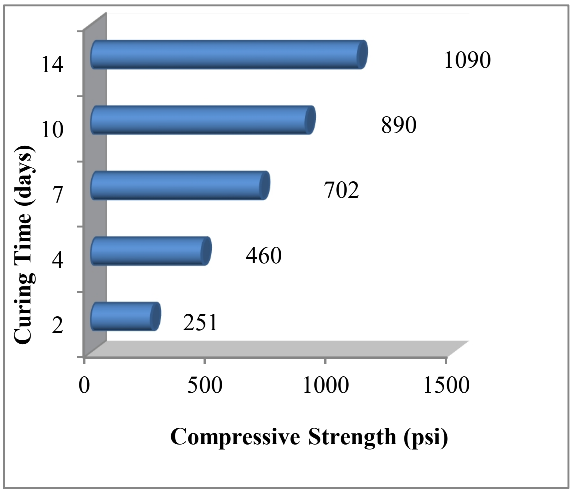

Fig. 1 Effect of Curing Time on Compressive Strength at 150 °F (65.6 °C)

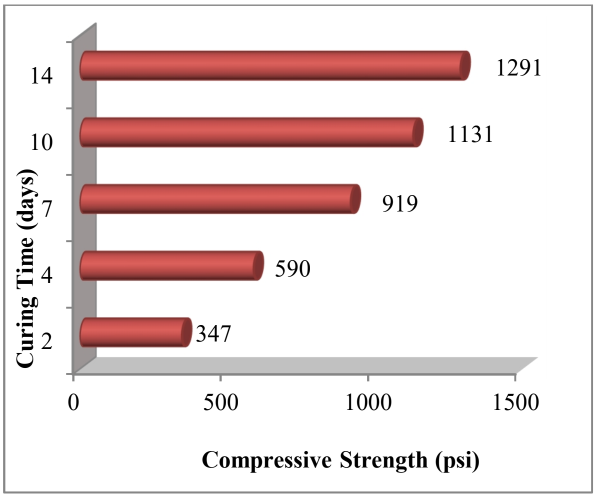

Fig. 2 Effect of Curing Time on Compressive Strength at 190 °F (87.8 °C)

3.2 Effect of Temperature on Compressive Strength

Temperature has significant effect on the compressive strength attained, and this is confirmed by comparing the test temperatures of 150 °F (65.6 °C) and 190 °F (87.8 °C) for the different curing times (Fig. 3). Increasing temperature increases the consolidation strength attained for each of the curing times. The compressive strength attained for each of the curing times exceeded the minimum consolidation strength reported as safe for oil producing well formation of 1.01 MPa by Lahalih and Ghloum, (2010) and Zhiyong *et al.* (2012). The compressive strength was affected by the curing temperature, and this is confirmed by previous research findings by Dewprashad *et al.* (1997), Parlar *et al.* (1998) and Sumit *et al.* (2014). Work done by Osman *et al.* (2000); El-Sayed *et al.* (2001) and Villesca *et al.* (2010) showed that increasing temperature up to 200 °C increased the compressive strength but any increment above 200 °C resulted in the decline of compressive strength. This is an indication that, epoxy sand consolidation systems can be used in formations with temperatures in the range of 37.8 °C and 107.2 °C and attain the desired and safe compressive strength. For this research, it must be stated that samples cured at 26.7 °C and below failed to achieve any meaningful compressive strength using the epoxy sand consolidation system with resin-hardener ratio of 1:1. Additionally, this also confirms the abysmal performance of resins when the formation temperature is outside the range conducive for cross-linking. When epoxy resins are used outside the temperature range of 37.8 °C and 107.2 °C, they fail to crosslink and react to bind the sand matrix during sand consolidation operations.

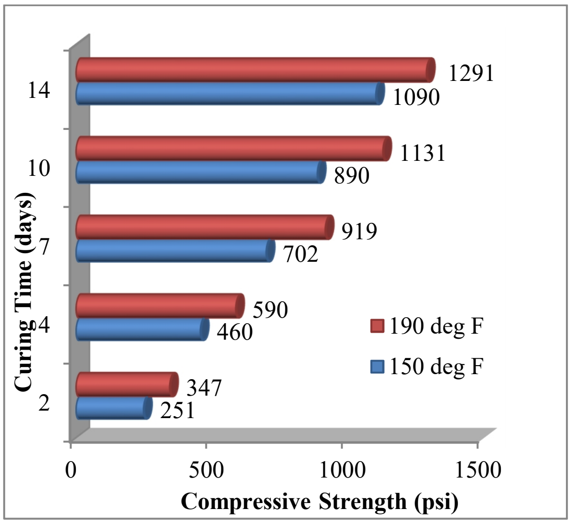

Fig. 3 Effect of Temperature on Compressive Strength

3.3 Characteristics of the Compressive Strength Model

The factorial design characters assigned for the compressive strength of consolidation system is shown in Table 1. The compressive strength of consolidated formation or sand matrix is influenced by a number of factors. However, for this model, the effect of two of these important factors (that is temperature and curing time) on compressive strength were considered.

The summary of fit and Analysis of Variance (ANOVA) generated for modelling the compressive strength are shown in Tables 2 and 3 respectively. The R^2 value obtained for the compressive model is 0.9685. This is an indication that the model can be used to explain about 96.85% of the variability or inconsistency of the compressive strength of the chemical sand consolidation system in a new data, confirming the model developed is a good predictor. However, this was tested for a minimum and maximum curing times of 2 days and 14 days respectively at 150 ^oF and 190 ^oF.

Table 2 Summary of Fit for Compressive Strength Model

Parameter	Value
R-Square	0.9685
R-Square Adj	0.9528
Root Mean Square Error	77.0487
Mean of Response	768.6
Observations (or Sum Weights)	10

Table 3 Analysis of Variance for Compressive Strength Model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1096369.8	365457	61.572
Error	6	35612.6	5935	Prob > F
C. Total	9	1131982.4	_	< 0.0001*

The correspondent R-Square adjusted (R^2 adj) obtained is about 95.28%. Statistically, F-ratio probability value of or less than 0.05 ($\leq$ 0.05) is considered good for a model. The probability value assigned to the F-ratio is far below this value (< 0.0001), a confirmation that the model has better statistical data fit, and is effective.

The sorted parameter and expanded parameter estimates for the compressive strength model are shown in Table 4. The highest impact on the model is from the temperature parameter (87) followed by the curing time (74.7) and the interaction between temperature and curing time reported the least impact (4.4). The individual effects of curing time and temperature are significant having t-ratio probability values of less than 0.05 (<0.05). However, the interactive effect of these factors is insignificant to the model, having Prob>|t| value greater than 0.05 (that is 0.4674). All the parameters recorded positive values indicating direct and proportional relationship between the parameters studied and the response variable that is the compressive strength. This is an indication that increasing temperature and keeping the curing time constant and the vice versa or increasing both temperature and curing time would results in improved compressive strength.

Table 4 Sorted Parameter Estimates for Compressive Strength Model

Term	Estimate	Standard Error	t Ratio	Prob>|t|
Curing Time (day)	74.6743	5.7044	13.09	<0.0001
Temp (deg F)(150,190)	87.0000	24.363	3.57	0.0118
Temp (deg F)*(Curing Time (day) -7.4)	4.4243	5.7045	0.78	0.4674

The residuals for the compressive strength model are confirmed by the residual by predicted plot shown in Fig. 4 and the R-square value of about 97 %.

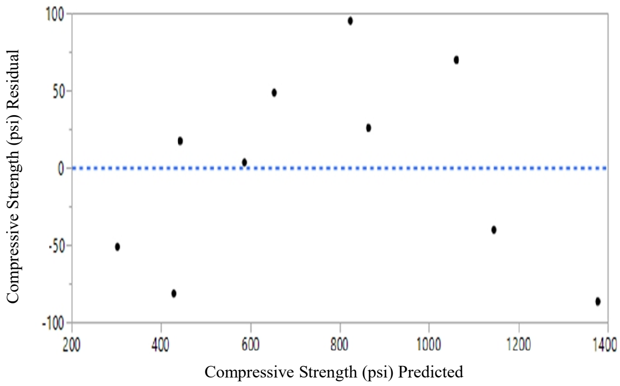

Fig. 4 Residual by Predicted Plot for Compressive Strength Model

The interaction between the design parameters that is the temperature and the curing time and the effect on the compressive strength model is presented in a cube plot (Fig. 5). The cube plot can serve as a tool for determining the desired compressive strength during sand consolidation operations. This is done by controlling the appropriate design factor that is temperature and curing time. In addition, the cube plot can be used in optimising the compressive strength for chemical sand consolidation operations. The values in the four corners of the box are the predicted compressive strength for the model using the extreme values for the design factors (that is temperature and curing time).

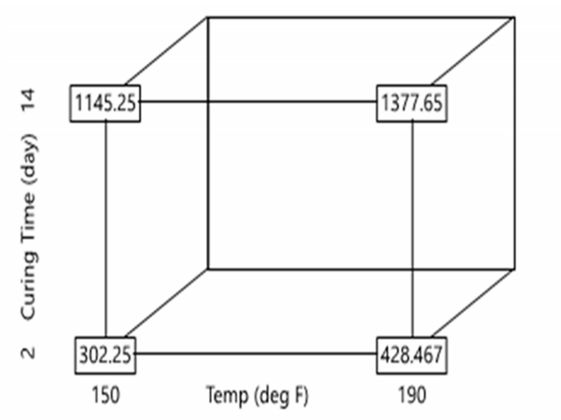

Fig. 5 Cube Plot for Compressive Strength Model

The highest compressive strength predicted by the model, 1377.65 psi (9.50 MPa) occurred when the temperature and curing time parameters were at the highest levels of 190 ^{o}F (87.8 ^{o}C) and 14 days respectively. The lowest predictable compressive strength, 302.25 psi (2.08 MPa) happened at the lowest level of temperature and curing time that is 150 ^{o}F (65.6 ^{o}C) and 2 days respectively.

The interaction profile for the compressive strength model is presented in Fig. 6. The interaction profile shows how compressive strength behaves with regards to regulating the temperature and curing time (the design parameters). The absolute change in compressive strength at 150 ^{o}F (65.6 ^{o}C) and 190 ^{o}F (87.8 ^{o}C) when the curing time increased from 2 days to 14 days are 854 psi (5.89 MPa) and 944 psi (6.51 MPa) respectively.

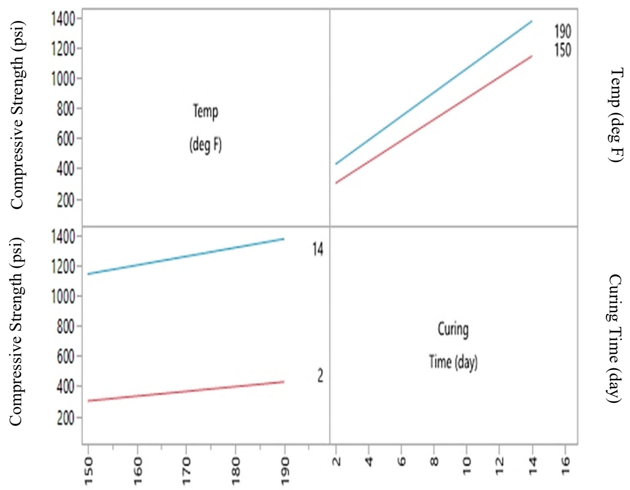

Fig. 6 Interaction Profile for Compressive Strength Model

The surface response plot for the compressive strength model is presented in Fig. 7. This plot shows how the compressive strength behaves in the low and high level regions of the curing time and temperature design parameters. The maximum compressive strength occurred at 190 ^{o}F (87.8 ^{o}C) and 14 days region whereas the minimum compressive strength occurred at 150 ^{o}F (65.6 ^{o}C) and 2 days region.

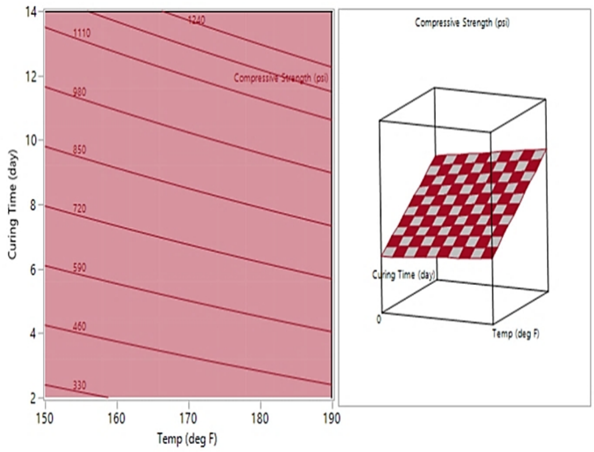

Fig. 7 Surface Response Plot for Compressive Strength Model

The predictive equation developed for predicting the Compressive Strength *CS* (psi) of epoxy chemical sand consolidation is given in Equation 1.

$$CS = -245.22 + 2.71 * T + 37.07 * CT + 0.2212 * T * CT \cdots (1)$$

This equation applies to epoxy resin systems with resin-hardener ratio of 1:1, Temperature *T* (^{o}F) and Curing Time *CT* (days). The equation is a good predictor as it can explain about 97% of the inconsistencies or variability of the model for curing time in the range of 2 days to 14 days at 140 ^{o}F and 190 ^{o}F.

For field and laboratory applications, a new software package has been developed for the compressive strength model. The software package indicates the input parameters required for the model using field units, and a snapshot is presented in Fig. 8.

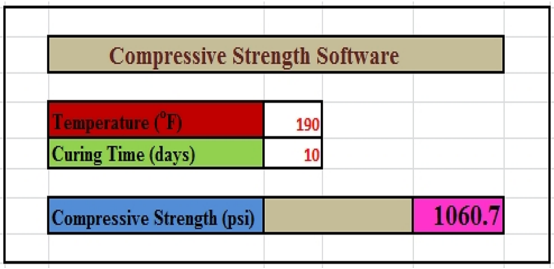

Fig. 8 Snapshot of Software for Compressive Strength Model

4 Conclusions

An efficient predictive model has been developed for predicting compressive strength. The model could also be used as optimisation tool for effectively executing sand consolidation operations. The model developed took into consideration two important parameters (curing time and temperature). These parameters on individual basis had significant effects on the compressive strength of the epoxy system, though their interactive effects did not have significant impact on the compressive strength. The greatest effects of curing time and temperature on compressive strength were 74.7 and 87.0 respectively. The compressive strength values obtained for the test temperatures at 150 ^oF (65.6 ^oC) and 190 ^oF (87.8 ^oC) at all curing times exceeded the minimum safe consolidation strength of 147 psi (1.01 MPa).

The compressive strength model developed could be used as a tool to explain about 97% of the inconsistencies or variability in the model which is affirmative of an effective model with minimal errors. However, at temperatures below 37.8 ^oC, no values were obtained due to poor consolidation attained using the epoxy sand consolidation system. The efficiency of this model has not been tested in high temperatures above 93.3 ^oC because the performance of the chemicals (epoxy systems) used in developing the model at temperatures above 104.4 ^oC are unpredictable.

Acknowledgements

The authors wish to thank the World Bank for the offer of PhD scholarship at the World Bank Africa Centre of Excellence - Centre for Oilfield Chemicals Research (ACE-CEFOR), University of Port Harcourt, Nigeria and University of Mines and Technology, Tarkwa, Ghana for financially supporting this research work.

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Author

Solomon Adjei Marfo is a Lecturer at the Petroleum Engineering Department of University of Mines and Technology, Tarkwa, Ghana. He holds PhD in Petroleum Engineering from the University of Port Harcourt, Nigeria, MEng Degree in Mining (Petroleum Engineering) from the University of Belgrade, Serbia and BSc in Chemical Engineering from the Kwame Nkrumah University of Science and Technology, KNUST, Kumasi, Ghana. He is a member of the Society of Petroleum Engineers (SPE), a Registered Environmental Specialist (RES) with the National Registry of Environmental Professionals (NREP) of USA. His research interests include sand and water control in oilfields using chemicals, agro-waste and local materials evaluation for oilfields application.

Dulu Appah is a Professor of Petroleum & Gas Engineering at the University of Port Harcourt. He holds PhD in Petroleum Engineering from the University of Port Harcourt Nigeria, and MSc (with distinction) in Petroleum Engineering from the Azizbekov Institute of Oil and Gas (now Petroleum Academy), Baku, Azerbaijan. He is a member of the Society of Petroleum Engineers (SPE). His research includes aerated wellbore sand cleanout, cement slurry design for HPHT wells, fines migration, produced water management, hydrate/emulsion control, and artificial lift optimization.

Ogbonna F. Joel is a Professor of Petroleum Engineering at University of Port Harcourt, Nigeria. He holds a PhD from the River State University of Science and Technology, Nigeria and MSc from the University of Benin, Nigeria. He is a member of Nigerian Society of Chemical Engineers (NSChE) and Nigerian Society of Engineers (NSE). His research interests include design and field applications of drilling, cementing and stimulation fluids.

Grace Ofori-Sarpong is an Associate Professor of Minerals Engineering at the University of Mines and Technology, Tarkwa, Ghana. She holds PhD in Energy and Minerals Engineering from the Pennsylvania State University, USA, MSc in Environmental Resources Management and BSc in Metallurgical Engineering, both from Kwame Nkrumah University of Science and Technology, KNUST, Kumasi, Ghana. She is a member of the Society for Mining, Metallurgy and Exploration (SME), USA, Society of Petroleum Engineers (SPE), USA, International Women in Mining Community (WIM), UK. Her areas of research interests include bio-mineral interaction, microbial treatment of oil waste, recovery of precious metals, water quality monitoring and mine waste management.