International Journal of
Science and Engineering Investigations vol. 8, issue 89, June 2019
Received on June 20, 2019 ISSN: 2251-8843

Synergistic Effect of Temperature and Pressure on Cement Compressive Strength

Samuel S. Mofunlewi[1], Ogbonna Joel[2], Dulu Appah[3], Chikwendu Ubani[4]
[1,2]World Bank African Centre of Excellence, Centre for Oilfield Chemicals Research, University of Port Harcourt, Nigeria
[3]Institute of Petroleum Studies, University of Port Harcourt, Port Harcourt, Nigeria
[4]Department of Petroleum Engineering, University of Port Harcourt, Port Harcourt, Nigeria
([1]samuel.mofunlewi@aceuniport.org, [2]ogbonna.joel@uniport.edu.ng, [3]chikwendu.ubani@uniport.edu.ng)

Abstract- One of the challenges during oil well cementing operation is the ability to predict the compressive strength of cement. Database reports are sometimes recommended when there is insufficient time for testing prior to the execution of cementing jobs. Previous studies on the compressive strength of cement have been carried out to show the effect of temperature at a single point of pressure without considering the effect of changes on the pressure profile. At the moment, no comprehensive study has been done to demonstrate the combined effect of temperature and pressure on compressive strength of cement. Compressive strength tests are conducted in the cementing laboratory using the bottom hole static temperature (BHST) and the cumulative hydrostatic pressure of the fluids in the well at the well depth. However, since temperature and pressure increases with increasing depth of the well, it is important to understand the combined effect of these varying parameters on the compressive strength of cement in the annular space between the casing and the formation.

Compressive strength tests were conducted at 80^{o}F and 120^{o}F while varying bottom hole pressures between 0psi and 20,000psi using neat cement slurry. A model was developed using the multiple regression method. The model was developed to show the relationship between compressive strength and temperature and pressure. The model can also be used to predict the compressive strength of cement with changes in temperature and pressure. Results also show that compressive strength of cement slurry increases as temperature and pressure increases. Test results indicate that changes in temperature and pressure significantly affect the compressive strength.

Keywords*-Temperature, Pressure, Compressive Strength, Cement*

I. INTRODUCTION

Generally, cement when used in the oil industry has a primary purpose to hold the casing in place and to prevent fluid migration between subsurface formations creating a zonal isolation [1]. Oil well cementing is the process of mixing water, additives and cement to form a slurry and pumping down the slurry through casing to critical points in the annulus around the casing or in the open hole below the casing string.

Additives are chemicals that are added to cement systems in order to achieve certain desired qualities depending on down hole conditions. Compressive strength development and thickening time are functions of well temperature. To partially tackle cementing problems associated with well temperature accelerators or retarders can be used to adjust the pumpable time and likewise affect the strength development [2].

The knowledge of the actual temperature that cement slurry encounters in not as easy to obtain as it seems. The well under static conditions will have a temperature gradient. Upon pumping initiation and when circulating the slurry, the local temperature around the wellbore will decrease. Consequently, there are two temperatures at every well depth, circulating (BHCT) and static (BHST). BHCT is used for pumpable time estimations while BHST is relevant to strength buildup.

If pressure is not accurately anticipated, the casing and cement sheath may not be able to withstand the pressure from the rock formation and this can lead to a total collapse of the wellbore [3].

II. COMPRESSIVE STRENGTH

Compressive strength is defined as the maximum compressive stress that, under a gradually applied load, a given solid material can sustain without fracture [4].

The Ultrasonic Cement Analyzer (UCA) is the equipment used in measuring the compressive strength of a cement slurry. The UCA is an equipment that correlates compressive strength to sound wave transit time. Compressive strength can also be measured with the crushing cube molds with a press but UCA is more widely used. This property is the key for "Waiting-on-cement" time determination. The drilling team will need to wait until the slurry develops some strength before they can resume well operations. Traditional rules of thumb include the following:

i. 5 to 200psi required to support casing

ii. 500psi required to continue drilling

iii. 1000psi required to perforate

iv. At least 2000psi required to stimulate and isolate zones

Joel and Ademiluyi reported that compressive strength increased with temperature and weight of cement slurry. They went further to state that this is in line with the previous established findings that the hydration rate for cement is dependent on the cement particle size and temperature experienced by the slurry during setting [5].

The ultimate compressive strengths of the cements under an effective confining pressure of 15000psi range from about 30,000psi to 50,000psi [6]. The figure below shows the equipment used in determining the compressive strength of cement slurry.

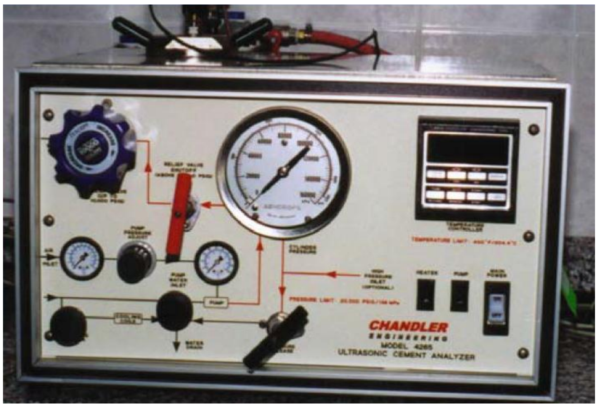

Figure 1. Ultra-Sonic Cement Analyzer for determining compressive strength of cement slurry

III. BOTTOM HOLE STATIC TEMPERATURE

This is the temperature measure in the well when the well is in an undisturbed state. That is when the fluids in the well are not mobile. The formation cools during drilling and most of the cooling dissipates after about 24 hours of static conditions, although it is theoretically impossible for the temperature to return to undisturbed conditions [7]. This temperature is measured under static conditions when all mobile effects have been eliminated. There are several calculators, Tables, charts and computer simulators that can be used to predict BHST as functions of depth, geographic area and various time functions.

Typically, the temperature approaches the BHST after about 24 to 36 hours (depending on the well conditions) after circulation and after the well is shut in. This is the temperature under which the cement slurry finally set after placement. This is because the cement slurry remains in static state after it has been spotted in the well for the period of the thickening time. Drilling operations typically will not proceed until the cement has attained the required compressive strength.

IV. BOTTOM HOLE PRESSURE

There is need to design cement slurry to be able to withstand pressure from the rock formation. If pressure is not accurately evaluated, the casing and cement sheath may not be able to withstand the pressure and this can lead to a total collapse of the wellbore [3]. According to Smith [8], pressure imposed on a cement slurry by the hydrostatic load of well fluids also reduces the pumpability of cement. In some deep wells, the combination of hydrostatic pressure and surface pressure during cement slurry placement may exceed 20,000psi.

The cement slurry physical state progresses from liquid immediately after its placement in the annular space between casing and formation, transmitting its hydrostatic pressure to a gel after a certain period (known as transition time) under static conditions.

V. SELECTION OF CEMENT SLURRY SYSTEMS

Cement slurry systems are selected based on well objectives and requirements. Cementing systems vary in their capability to provide good zonal isolation in changing environments. The traditional approach to cement slurry design has been on the basis that higher compressive strengths result in higher cement sheath quality [9]. However, studies have shown that the ability of cement to provide good zonal isolation is better defined by other mechanical properties. Good isolation does not necessarily require high compressive strength. According to Crook [9], the real competence test is whether the cement system in place can provide zonal isolation for the life of the well.

VI. METHODOLOGY

The following sub-sections highlight the different steps that were taken in conducting the compressive strength tests using the ultrasonic cement analyzer. The tests were conducted at varying BHST between 80^{o}F – 120^{o}F and varying pressure between 0psi - 20,0000psi. Care was taken not to exceed the design temperature and pressure while testing. The strength is determined by measuring the change in velocity of an ultrasonic signal transmitted through a cement specimen [10]. This change in velocity is referred to as the transit time.

The choice of additives and testing criteria is dictated primarily by the specific parameters of the well to be cemented. During the compressive strength test, the UCA test cell is subjected to controlled temperature and pressure for curing of the cement slurry. The cell includes a temperature measuring system (thermocouple) and sonic signal measuring system (transducers).

The cement slurries used for the test in this study are mainly neat cement slurries containing only water, defoamer and cement at the concentrations presented below:

Slurry Design Data : 15.8ppg Cement Slurry						
Yield:	1.148	ft3/sk	Fresh Water:	4.960	gps	Total Fluid:
Product Code	Function		SG	Concentration / Units		
Fresh Water	Mixing Water		1.000	4.960	gps	
Defoamer	Foam Preventer		0.880	0.040	gps	
Dyckerhoff	Cement "G"		3.140	1.00	sk	

Figure 2. cement slurries used for the test

The compressive strength tests were conducted separately at 80°F and 120°F while varying pressures between 0psi and 20,000psi respectively.

VII. RESULTS AND DISCUSSION

The results of the experiments conducted are presented in the Table below. The Table shows the results of the tests conducted at 80°F and 120°F respectively. These tests were conducted by pressures varying between 0psi to 20,000psi. Results of the tests at 80°F show that the compressive strength of cement slurry increases as pressure increases. A similar trend was observed for the test conducted at 120°F. In addition to this, comparing the compressive strength at specific pressures for temperatures at 80°F and 120°F show that the strength of the cement is more at 120°F than at 80°F. For example, the compressive strength at 80°F and 10,000psi was 1946psi while the compressive strength compressive strength at 120°F and 10,000psi is 2649psi. These results demonstrate the effect of temperature and pressure on the thickening time of cement slurry.

TABLE I. COMPRESSIVE STRENGTH TESTS RESULTS

Pressure (psi)	compressive strength (psi)	
	at 80oF	at 120oF
0	1224	2194
2000	1405	2214
4000	1644	2340
6000	1756	2396
8000	1874	2431
10000	1946	2649
12000	2136	2835
14000	2214	3100
16000	2265	3650
18000	2412	3694
20000	2542	3721

The above results are presented in the charts in Figure 3 and 4. From Figure 3, it can be observed that as the pressure increases, the compressive strength also increases when temperature was constant at 80°F and 120°F. Similar Trend can also be observed with Temperature, as the temperature increase the compressive strength also increases. This show that both temperature and pressure have a positive relationship with compressive strength. A similar trend is also observed in the 3-dimensional view of the data presented in Figure 4.

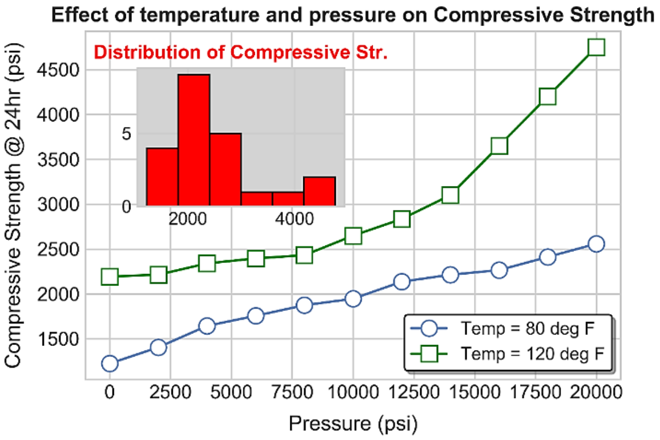

Figure 3. The effect of temperature and pressure on Compressive strength at 24hrs

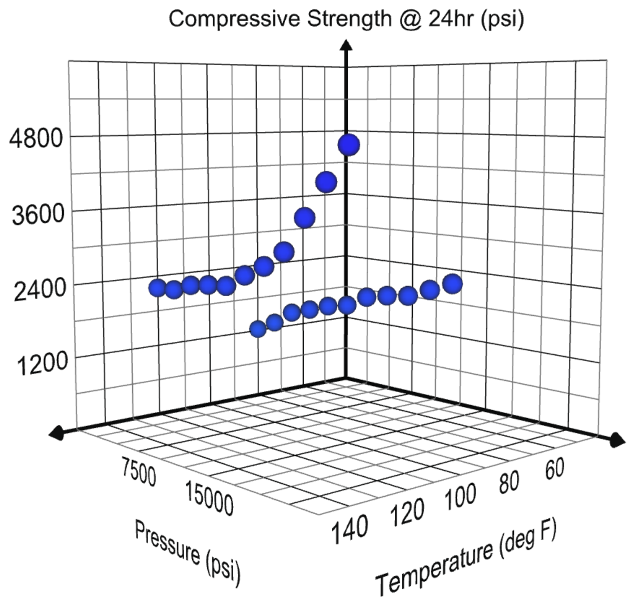

Figure 4. 3-D View of the effect of temperature and pressure on Compressive strength

VIII. STATISTICAL ANALYSIS

The results above were further analyzed using the multiple regression model. Multiple linear regression is a model for demonstrating the relationship between a dependent variable and a collection of independent variables (predictors). Linear regression is used to model a dependent scale variable based on its linear relationship or straight-line relationship to one or more predictors. It is used when one wants to predict one variable from a combination of several variables. For the purpose of this paper, the predictors are temperature and pressure while the dependent variable is compressive strength. Hence, the regression equation is presented below:

$$\hat{Y} = \beta_o + \beta_1 X_1 + \beta_2 X_2 \quad (1)$$

Where:

$\hat{Y}$ = the predicted value of an observation (thickening time)

β_o = the Y-intercept (the value of when all X's = 0)

β_1, β_2 = the unstandardized regression coefficients for the predictors

X_1, X_2 = values of the predictors

The results above were analyzed and the following output results were obtained. These results will be discussed one after the other.

IX. REGRESSION RESULTS

The value of the coefficient of determination, R-square (R^2) is presented in Table 2 below. The R^2 value will always lie between 0 and 1, where a higher R^2 indicates a better model fit. Here we can see from the model that R^2=0.925 (92.5%). This means the two variables, temperature and pressure, have a strong relationship with compressive strength. The adjusted R^2 show that the model accounts for 91.8% of variance in the predictors (temperature and pressure) in the model.

TABLE II. GOODNESS OF FIT

Observations	22.0000
Sum of weights	22.0000
DF	19.0000
R^2	0.9253
Adjusted R^2	0.9175
MSE	46417.1100
RMSE	215.4463
DW	0.4524

The ANOVA table presents the result of the F-test and p-value. This table assesses the overall significance of the model. The F-test helps to determine if the model is a good fit for the data. From the above, the f-test is 117.7 while the p-value is 0. Since the value of p is less than 0.0005, it can be concluded that the model is statistically significant. A large f value and a small p value suggests that a predictor variable (temperature or pressure) is having a large impact on the compressive strength. The mean square column shows that very much more of the variance is explained by the regression line than by the Residual 5,464,982.64 compare to 46,417.11). This reinforces the conclusion that the model is good.

TABLE III. ANALYSIS OF VARIANCE

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	2	10929965.272	5464982.6364	117.7364	< 0.0001
Error	19	881925.090	46417.1100		
Corrected Total	21	11811890.363			

Table 4 below contains the values for the construction of the regression equation. The standard error gives a measure of the contribution of each variable to the model (measured in standard deviation units of the target variable). The t value for pressure is 11.3156 with a corresponding p value <0.0001 (which is < 0.0005). This shows that the regression is statistically significant. A similar trend was observed for temperature with a t value of 10.36 and corresponding p value <0.0001.

The parameters under value are required for an equation that includes the two predictors - temperature and pressure. For this case, the equation for the regression line will be:

TABLE IV. MODEL PARAMETERS

Source	Value	Standard error	t	Pr > |t|
Intercept	-777.5455	245.2168	-3.1708	0.0050
Temp	23.8045	2.2967	10.3648	< 0.0001
Pressure	0.0822	0.0073	11.3156	< 0.0001

The model for this set of data therefore is:

Compressive Strength = -777.5455 + 23.8045 Temperature + 0.0822 Pressure (2)

X. CHECK FOR LACK OF FIT

From Figure 5, it can be seen that there was no systematic error in the residual plot. At no point in the graph were the error was consistently high or low, this shows that the model fit the data points.

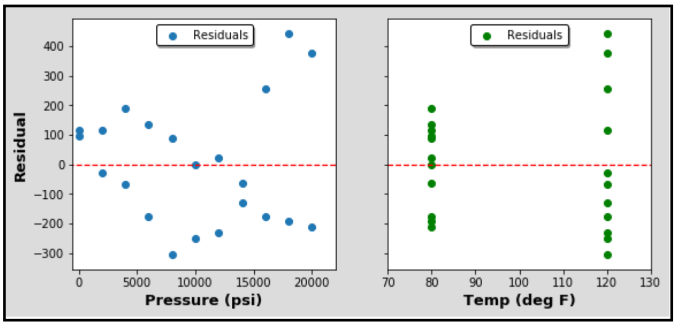

Figure 5. Lack of Fit plot for Compressive Strength

XI. CONCLUSION AND RECOMMENDATION

Cement systems require special design attention, modified testing procedures and special systems. Accurate data collection is key to a successful job design. Cement tests are done in the cementing laboratory using the pressure and temperature at well total depth. It is also recommended to utilize the maximum temperature in the annular space where the cement slurry is going to be placed during the temperature simulation. Whatever the case might be, it is imperative to understand the combined effect of temperature and pressure on cement slurry during and after placement. This study has been able to demonstrate that compressive strength of cement increases as temperature and pressure increases.

It is recommended that further studies be carried out at a wider temperature range in order to effectively model the combined effect of temperature and pressure on the compressive strength of cement.

ACKNOWLEDGMENT

This research work was supported by the World Bank Africa Centre of Excellence in Oilfield Chemicals Research (ACE-CEFOR), University of Port Harcourt, Nigeria. The authors wish to express their sincere thanks to World Bank for the support.

REFERENCES

[1] Kyrilis, E. (2016): "Fly Ash-Based Geopolymer Cement as Alternative to Ordinary Portland Cement in Oil Well Cementing Operations", Thesis, Department of Chemistry and Biotechnology, Aslborg University, Pp. 9.

[2] Devereux, S (1998): "Practical Well Planning and Drilling Manual", Pennwell.

[3] Wilcox B., Oyeneyin O. and Islam S. (2016): "HPHT Well Integrity and Cement Failure", Society of Petroleum Engineers (SPE), NAICE 2016 Conference, Lagos, P. 5.

[4] Rageh, S. M., Nezami, M. Z., Dhanalashmi, K. and Basha, S. L. (2017). Compressive Strength and Thickening Time of Cement in Oil Well. International Journal of Engineering Science Invention (ISSN Online). Vol. 6, Issue 12, pp. 1.

[5] Joel, O. F. and Ademiluyi, F. T. (2011): "Modelling of Compressive Strength of Cement Slurry at different Slurry Weights and Temperatures", Research Journal of Chemical Sciences, Vol. 1 (2), pp. 129.

[6] Handin, J. (1968). Strength of Oil Well Cement at Downhole Pressure-Temperature Conditions. Society of Petroleum Engineers, SPE 1300, pp. 347.

[7] Schlumberger (2018): "HPHT", http://www.glossary.oilfield.slb.com/Terms/h/hpht.aspx.

[8] Smith, T.R. and Crook, R.J. (1982): "Investigation of Cement Preflushes for a KCl-Polymer Mud", presented at the 33rd Annual Technical Meeting of the Petroleum Society of CIM, Calgary.

[9] Crook, R. J., Benge, G., Faul, R. and Jones, R. R. (2001): "Eight Steps to Ensure Successful Cement Jobs", Oil & Gas Journal, Pp. 16-17.

[10] Baker Hughes (2013): Determination of Compressive Strength Using UCA (Non-Destructive), CMT-LAB-SOP-011, Rev. A.

Samuel Mofunlewi was born in the Badagry area of Lagos State, Nigeria. Samuel holds a Bachelor's degree in Chemical Engineering from the Rivers State University of Science and Technology and a Master's degree in Petroleum and Gas Engineering from the University of Port Harcourt. He is currently a doctoral student at the World Bank African Centre of Excellence, Centre for Oilfield Chemicals Research, University of Port Harcourt, Nigeria

He is working with Baker Hughes as a technical support staff. He had previously worked with BJ Services, University of Port Harcourt and Integrated Petroleum Resources prior to joining Baker Hughes. He has experience in oil well cementing, coiled tubing design and production enhancement practices and his research interests are also in these areas.

Mr. Mofunlewi is a member of the Society of Petroleum Engineers (SPE), Nigerian Gas Association (NGA) and the National Registry of Environmental Professional (NREP). Samuel was awarded the best paper presenter award during the SPE 2011 Nigeria Annual International Conference and Exhibition in Abuja, Nigeria.

How to Cite this Article:

Mofunlewi, S. S., Joel, O., Appah, D. & Ubani, C. (2019) Synergistics Effect of Temperature and Pressure on Cement Compressive Strength. International Journal of Science and Engineering Investigations (IJSEI), 8(89), 154-158. http://www.ijsei.com/papers/ijsei-88919-24.pdf