J Petrol Explor Prod Technol (2013) 3:297–302
DOI 10.1007/s13202-013-0071-0

ORIGINAL PAPER - EXPLORATION ENGINEERING

Prediction of compressive strength of oil field class G cement slurry using factorial design

O. A. Falode · K. K. Salam · A. O. Arinkoola · B. M. Ajagbe

Received: 8 November 2012 / Accepted: 29 July 2013 / Published online: 13 August 2013

Abstract Proper slurry design is critical to the success of a cementing job. The best method to obtain a good slurry design with desired compressive strength is by laboratory experiments which involve experimenting different formulations and selecting the best composition for the specific cementing operation. This exercise is not only time consuming considering the amount of time required, but also expensive. Sixteen sets of experiments were conducted in the laboratory, and factorial design was used to design the experiments for the sensitivity analysis of four different factors impacting on the compressive strength of cement slurry. The responses from the 16 experimental runs were used to develop a model which can be used for optimization purposes. The model developed was simple, in agreement with the experimental data used and can be implemented using an ordinary simple calculator.

Keywords Compressive strength · Class G cement · Factorial design

Abbreviations

Y	Response of the model
β_0	Intercept of the model
$\beta_1, \beta_2, \beta_3$ and β_4	Coefficients of main effects of X_1, X_2, X_3, and X_4
$\beta_{12}, \beta_{13}, \beta_{14}, \beta_{23}, \beta_{24}$ and β_{34}	Coefficients of two-interaction effects of X_{12}, X_{13}, X_{14}, X_{23}, X_{24}, and X_{34}
$\beta_{123}, \beta_{124}, \beta_{134}$ and β_{234}	Coefficients of three-interaction effects of X_{123}, X_{124}, X_{134}, and X_{234}
β_{1234}	Coefficients of four-interaction effect of X_{1234}
R	Compressive strength

O. A. Falode
Department of Petroleum Engineering, University of Ibadan, Ibadan, Nigeria

K. K. Salam (✉) · A. O. Arinkoola · B. M. Ajagbe
Petroleum Engineering Unit, Department of Chemical Engineering, P.M.B. 4000, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria
e-mail: kaykaysalam@yahoo.co.uk

Introduction

Cementing is the most important and the most expensive exercise during drilling operation. In cementing operation, the annulus between the casing and the adjacent rock formation is filled with a certain compound of cement grout and allowed to set, usually after a few hours or a few days, and solidify strongly to join the casing to the formation. This compound could be made from different ingredients with different percentage of weight with respect to the weight of cement in the grout mixture (Labibzadeh et al. 2010). Compressive strength is one of the properties used to test the reliability of cementing and is the ability of a material to withstand deformation when load is applied. Compressive strength of a cement concrete depends on the type of raw materials including additives used, mixture proportions, concrete structure, method and time of curing, and exposure conditions (Herianto and Fathaddin 2005).

Cement with a good compressive strength should be able to withstand hard and corrosive formations, lost circulation zone, carbon (IV) oxide and other toxic gas intrusion, and extremely high temperature (Benjamin et al. 2010). Problems of poor cementing have led to myriad research in this field using different approaches. Sauki and Irawan (2010) investigated the effect of pressure and temperature on well cement degradation by super-critical CO_2 and concluded that compressive strength loss was greater at elevated temperature and pressure due to the formation of alpha-calcium silicate, and in CO_2 environment due to formation of carbonation which gives temporary strength to the cement. Labibzadeh et al. (2010) considered the effect of contemporary pressure and temperature changes in the early compressive strength of oil well class G cement and concluded that faster early-age compressive strength could lead to reduction in transition phase time (thickening time). They also observed that cement strength could also experience strength retrogression if crystalline silica was added to the cement slurry (Benjamin et al. (2010)).

Zhou and Jia (2010) developed a low-density and high-compressive strength cement slurry based on the theory of particle grading over numerous experimentations. The performance of the compressive strength of the cement slurry developed has been improved over the existing one. Ordinarily, class G cement is one of the types used for sealing off of formations because of its ability to withstand high resistance of pressure, temperature, and sulphate. Despite these qualities, additives are required to improve the properties of the cement (Xi et al. 2010). Bayu et al. (2010) concluded in their work that the addition of 0.2 % of lignosulfonate to a cement slurry increased compressive strength. Above this value, compressive strength was noticed to have reduced. Performance of other additives to enhance cement operations to optimally increase compressive strength during cement operation depends on the correct proportion of each of the additives. The best way is to subject these additives to a series of experimental runs, which is usually time consuming, tedious, and expensive (Isehunwa and Orji 1995).

Factorial design (FD) is a method that monitors the interactions of multiple factors which accommodate the effect of both main and interaction effects (Cheong and Gupta (2005)). FD has been successfully used in solving engineering problems, some of which are analysis of rheological properties of treated Nigerian clay (Adeleye et al. (2009), indentifying and estimating significant geological parameters White et al. (2001), uncertainty assessment Peake et al. (2005), and much more. Arising from advantages of FD and the importance of additives in the performance of cement, this research aims at development of mathematical model to predict compressive strength using four different additives for improving compressive strength during cementing operation using factorial design.

Methodology

Several experiments were run with the selected slurry systems aiming at the evaluation of the compressive strength of oil well class G cement using factorial design. The experiment was conducted based on the American Petroleum Institute (API) specification (American Petroleum Institute 1997).

Experimental design

The number of experimental runs performed for the model development is full factorial design which is governed by Eq. (1):

$$N = L^k \tag{1}$$

where L denotes factors which are four in this case, k is the number of levels, which is two, and N is the total number of experimental runs, which is 16. X_1 is extender, X_2 is accelerator, X_3 is antifoam, and X_4 is dispersant. The design of the experiment is tabulated in Table 1.

Response variable

The response variable for this experiment is the compressive strength. Sixteen (16) experimental runs were performed according to a full factorial design of four (4) factors using Table 1 as the guide to different formulations of slurry preparations and combination of factors. We use '−' to indicate low level and ' + ' for high level. The quantity of each of the variables under low and high is presented in Table 2. The response variable for the experiment is the compressive strength.

Table 1 Full factorial design for four variables at two levels

Run	X_1	X_2	X_3	X_4	Run	X_1	X_2	X_3	X_4
1	+1	−1	−1	−1	9	+1	−1	−1	+1
2	+1	−1	+1	+1	10	−1	+1	+1	−1
3	−1	+1	−1	−1	11	−1	−1	+1	+1
4	−1	−1	−1	+1	12	+1	+1	−1	−1
5	−1	+1	+1	+1	13	+1	−1	+1	−1
6	−1	−1	+1	−1	14	+1	+1	+1	+1
7	+1	+1	−1	+1	15	−1	−1	−1	−1
8	+1	+1	+1	−1	16	−1	+1	−1	+1

Table 2 Factor level settings

Factors	Levels (%)		
	Low (−1)	Standard (0)	High (+1)
Extender	5	10	15
Accelerator	0	5	10
Antifoam	0	5.9	7.9
Dispersant	0	2.9	4.2

Cement slurry preparation, curing time, and compressive strength measurement

For the preparation of cement slurry used for this study, 297 g of class G oil well cement was added to 447 ml of fresh water and blended using Waring Blender set at high speed for 35 s. The four additives identified in this study are: extender, accelerator, antifoam and dispersant. The additives which also serve as the variables are added to the blended cement slurry using Table 1, which gave different combinations of different slurry designs with different compressive strengths. The mixture of the based cement slurry and additives was mixed using a Constant Speed Mixer "Model 30-60" of Chandler Engineering Company at 12,000 rpm ± 500 to achieve the pre-calculated slurry density of 11.5 ppg.

The cement slurry formed from the 16 different experimental runs was poured under ambient pressure and temperature conditions into the curing chamber. In the curing chamber, the cement slurry was moulded into different shapes. The cement slurry was moulded to cubic moulds with diameter of 5.08 cm; thereafter the moulded samples underwent curing for 24 h.

After 24 h, the compressive strengths of the 16 formulations were measured using the Ultrasonic Cement Analyzer (UCA). Ultrasonic Cement Analyzer (UCA) provides a continuous non-destructive method of determining compressive strength as a function of time through the measurement of change in velocity of an acoustic signal according to API 8A (American Petroleum Institute (API) 1997). The UCA measures the delay time of an ultrasonic wave pulse that passed through the moulded cubic cement sample using set equations which converted velocity to uniaxial compressive strength and the values of all the compressive strengths were recorded. The response-dependent variable is the compressive strength which is determined for all the 16 samples. Each experimental run was conducted twice and the result of the response variable was recorded in Table 3.

Model development

Running the full complement of all possible factor combinations means that we can estimate all the main and interaction effects. In this experiment, there are four main effects, six two-factor interactions, three three-factor interactions and one four-factor interaction, all of which appear in the full model as follows:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{12} X_1 X_2 \\ & + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 - \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 \\ & + \beta_{34} X_3 X_4 - \beta_{123} X_1 X_2 X_3 - \beta_{124} X_1 X_2 X_4 \\ & - \beta_{134} X_1 X_3 X_4 + \beta_{234} X_2 X_3 X_4 - \beta_{1234} X_1 X_2 X_3 X_4 + e \end{aligned} \quad (2)$$

A Yates algorithm is used to calculate the main and interaction effect. These values are recorded in Table 4. These values are substituted for a corresponding value in Eq. (3) and fully expressed in equation 4 which is as follows:

Table 3 Experimental results

Run	X_1-extender	X_2-accelerator	X_3-antifoam	X_4-dispersant	Response		Average CS $_{(AV)}$
					CS I	CS II	
1	−1	−1	−1	−1	600	600	600
2	1	−1	−1	−1	450	450	450
3	−1	1	−1	−1	580	585	582.5
4	−1	−1	1	−1	580	580	580
5	−1	−1	−1	1	620	620	620
6	1	1	−1	−1	650	650	620
7	1	−1	1	−1	450	455	452.5
8	1	−1	−1	1	600	600	600
9	1	1	1	−1	550	560	555
10	1	1	−1	1	600	600	600
11	−1	1	1	1	500	500	500
12	1	1	1	−1	580	585	582.5
13	1	1	−1	1	440	435	437.7
14	1	−1	1	1	750	750	750
15	−1	1	1	1	630	630	630
16	1	1	1	1	750	750	750

Table 4 Level of variables used for the prediction

Run	X_1-extender (%)	X_2-accelerator (%)	X_3-antifoam (%)	X_4-dispersant (%)	Response		Average CS $_{(AV)}$
					CS I (psi)	CS II (psi)	
1	5	0	0	0	600	600	600
2	15	0	0	0	450	450	450
3	5	5	0	0	580	585	582.5
4	5	0	5.9	0	580	580	580
5	5	0	0	4.2	620	620	620
6	15	10	0	0	650	650	620
7	15	0	7.9	0	450	455	452.5
8	15	0	0	4.2	600	600	600
9	15	10	7.9	0	550	560	555
10	15	10	0	4.2	600	600	600
11	5	10	7.9	4.2	500	500	500
12	15	10	7.9	0	580	585	582.5
13	15	10	0	4.2	440	435	437.7
14	15	0	7.9	4.2	750	750	750
15	5	10	7.9	4.2	630	630	630
16	15	10	7.9	4.2	750	750	750

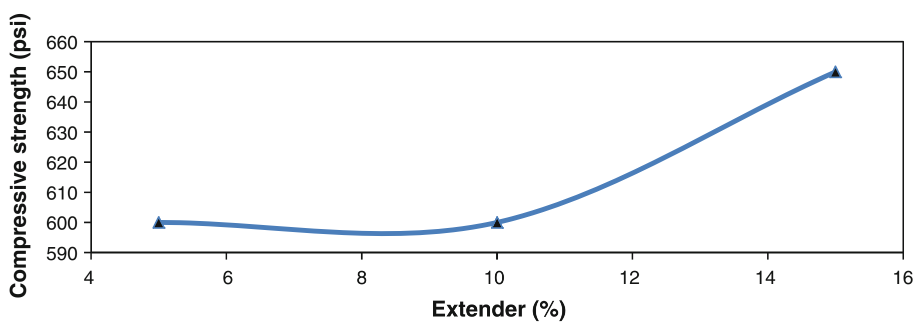

Fig. 1 Effect of extender on the compressive strength

$$R = 584.453125 + 36.171875X_1 + 1.32815X_2 + 26.859375X_3 + 16.984375X_4 + 6.859375X_1X_2 + 40.015625X_1X_3 + 33.765625X_1X_4 - 3.765625X_2X_3 + 13.734375X_2X_4 + 13.140625X_3X_4 - 16.796875X_1X_2X_3 - 25.671875X_1X_2X_4 - 1.140625X_1X_3X_4 + 37.390625X_2X_3X_4 - 13.078124X_1X_2X_3X_4 + 0.13258 \quad (3)$$

Results and discussion

Effect of the variables on compressive strength

The experiment conducted in this research showed that the compressive strength varies according to the proportion of the additives included during the design and formulation of the cement slurries for carrying out specific drilling operations. The influence of the various additives on the compressive strength of the cement has been studied in this work and the results of their sensitivities are as clearly displayed in Figs. 1 and 2 the accuracy of the model in Fig. 3.

It was evident from Figs. 1 and 2 that both the extender and antifoam impacted the compressive strength of the cement under investigation differently, at varying proportion and time. This behaviour is in agreement with literature. At different proportions, the additives change the velocity of the acoustic signal with time, thereby controlling the magnitude of the response measurable by the Ultrasonic Cement Analyzer. For example, the value of the cement compressive strength remains fairly constant with the extender concentration increase from an initial amount of 5 %. This trend continues up to 10 % of extender being included in the slurry; between the intervals, the value of compressive strength approximately remains at 600 psi. However, an additional 50 psi in compressive strength was observed when the extender increased from 10 to 15 % and this is attributable to increasing delay in the acoustic signal. The effect of the antifoam on the compressive strength of the cement is presented in Fig. 2. Antifoam inclusion in the cement

Fig. 2 Effect of extender on the compressive strength of cement slurry

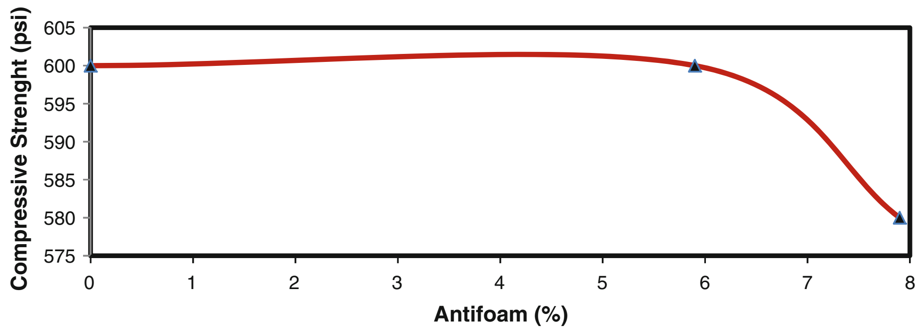

Fig. 3 Cross plot of experimental against predicted values

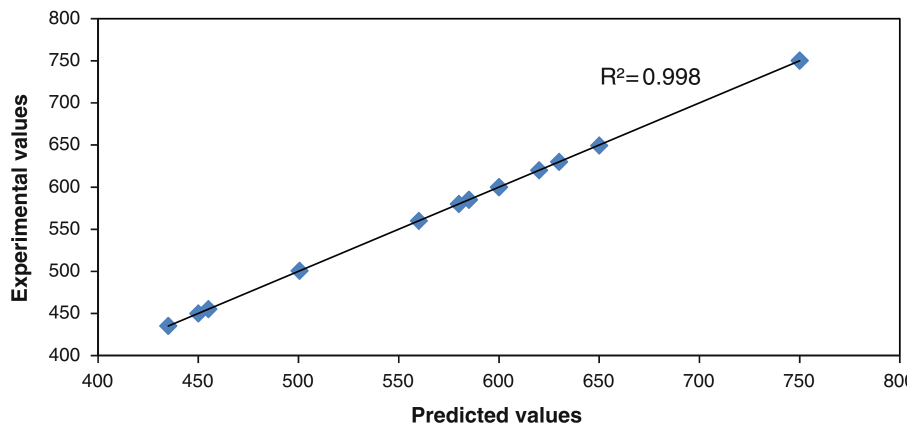

Table 5 Analysis of variance of randomized full factorial design

Contrast	Coeficient	(Contrast)	Sum of square	Residue	DOF	Mean Sq	*F* value
I	584.375	349,783,506.3	10,930,734.57	0	1	10,930,735	1.55E + 08
X_1	36.17188	1,339,806.25	41,868.94531	0	1	41,868.95	595,469.4
X_2	1.328125	1,806.25	56.4453125	0	1	56.44531	802.7778
X_1*X_2	6.859375	48,180.25	1,505.632813	0	1	1,505.633	21,413.44
X_3	26.85938	738,740.25	23,085.63281	0	1	23,085.63	328,329
X_1*X_3	40.01563	1,639,680.25	51,240.00781	0.5	1	51,240.01	728,746.8
X_2*X_3	−3.76563	14,520.25	453.7578125	0.125	1	453.7578	6,453.444
$X_1*X_2*X_3$	−16.7969	288,906.25	9,028.320313	0	1	9,028.32	128,402.8
X_4	16.98438	295,392.25	9,231.007813	0	1	9,231.008	131,285.4
X_1*X_4	33.76563	1,167,480.25	36,483.75781	0	1	36,483.76	518,880.1
X_2*X_4	13.73438	193,160.25	6,036.257813	0.125	1	6,036.258	85,849
$X_1*X_2*X_4$	−25.6719	674,862.25	21,089.44531	0	1	21,089.45	299,938.8
X_3*X_4	13.14063	176,820.25	5,525.632813	0.125	1	5,525.633	78,586.78
$X_1*X_3*X_4$	−1.14063	1,332.25	41.6328125	0.125	1	41.63281	592.1111
$X_2*X_3*X_4$	37.39063	1,431,612.25	44,737.88281	0	1	44,737.88	636,272.1
$X_1*X_2*X_3*X_4$	−13.0781	175,142.25	5,473.195313	0.125	1	5,473.195	77,841
Residue			1.125	1.125	16	0.070313	
Total					31		

slurry experienced a threshold value approximately at 6 %. Below this amount, the compressive strength remains fairly constant at 600 psi. Above this value, the compressive strength begins to fall gradually and at approximately 8 % proportion a value of 580 psi representing a decrease of 20 psi was observed. To maintain the compressive strength of the cement, say at 600 psi for a particular application, the designing of the slurry must ensure that the threshold values of these additives are not exceeded.

Figure 3 shows the parity plot between the experimental values and the model prediction values. The graph can be used to validate the developed model. The alignment of the values along the 45^{o} line reflected the accuracy and adequacy of the model to navigate the sample space. The straight line gives a correlation coefficient of 99.8 %. This suggests that all the selected model terms are significant and the selected model is sufficient to describe the experimental results perfectly.

Statistical analysis of the model

The summary of the weight of the factors used for the 16 experimental run in real percentage is shown in Table 4. It was a systematic design of variables used from low to high values in real values. The summary of the main and interaction effects between the factors used for the development of the model is shown in Table 5. It also showed the residual, degree of freedom, and mean square and *F* value for the various combinations of the interaction effects, leading to the development of the model. The deviation of the developed model from the experimental values was obtained by the analysis of variance with the calculation of the sum of contrast and mean square value of 1.125 and 0.070313. The coefficient of each of the main variables and their corresponding interaction effect show the contribution of each effect in the equation ti its contribution to the developed model.

Conclusion

A factorial design method has been successfully employed in this study to develop a model to predict the compressive strength of cement. The effects of four different additives were considered individually as well as their interaction with each other during the development of the model. The compressive strength varies according to the proportion of the additives included during the design and formulation of the cement slurries for carrying out specific drilling operations.

The model developed has a correlation coefficient of 99.8, standard error of 0.1325, and accuracy of 99.8 %. The model can be used to determine the behaviour of cement slurry when any of these additives are in underused or added in excess of the required quantity.

Recommendation

This investigation can be extended to other properties that affect cementing operations such as thickening time determination, rheological investigation, and effect of contaminants on cement performance.

Acknowledgments We wish to thank the management of SOWSCO Well Services (Nigeria) Limited, plot 212 Trans Amadi Industrial Layout Phase II, Port-Harcourt, Rivers State, for allowing us to make use of their cement laboratory to conduct the experimental section of this research work.

References

Adeleye JO, Salam KK, Adetunde IA (2009) Analysis of rheological properties of treated Nigerian clay using factorial design. Eur J Sci Res 37(3):426–438

American Petroleum Institute (API) (1997) API recommended practice 10B, recommended practice for testing well cements. Exploration and Production Department, 22nd edn

Bayu S, Muhammed TF, T Roby (2010) Effect of lignosulfonate and temperature on compressive strength of cement. In: Proceedings of world geothermal congress 2010 Bali, Indonesia, pp 1–3

Benjamin I, Joe M, Daniel B (2010) Strength retrogression in cement under high temperatures. In: SGP- TR-188, unity fifth workshop on geothermal reservoir simulation. Stanford, California, pp 1–8

Cheong Y, Gupta R (2005) Experimental design and analysis methods of assessing volumetric uncertainties. In: SPE 80537 paper first presented at the 2003 SPE Asia Pacific Oil and gas conference and exhibition, Jakarta, Indonesia, pp 9–11 (Paper peer approved 18 April 2005)

Herianto A, Fathaddin MT (2005) Effects of additives and conditioning time on comprehensive and shear bond strengths of geothermal well cement. In: Proceedings of world geothermal congress. Antalya, Turkey, pp 1–7

Isehunwa OS, Orji HI (1995) Analysis of mud filtration properties using factorial design. In: SPENC 9515, paper presented at the SPE Nigerian council annual conference, Lagos, Nigeria

Labibzadeh M, Zahabizadeh B, Khajazfuly A (2010) Early-age compressive strength assessment of oil well class G cement due to bore pressure and temperature changes. J Am Sci 6(7):38–46

Peake WT, Abadah M, Skander L (2005) Uncertainty assessment using experimental design: Minagish oolite reservoir. In: SPE 91820 prepared for preparation at the 2005 SPE reservoir simulation symposium held in Houston, Texas, pp 1–8

Sauki R, Irawan S (2010) Effect of pressure and temperature on well cement degradation by supercritical CO_2. Intern J Eng Technol 10(4):53–61

White CD, Willis BJ, Narayanan K, Dutton SP (2001) Indentifying and estimating significant geological parameter with experimental design. In: SPE Journal, pp 1–14

Xi F, Qu J, Lv G, Tan W, Wang C (2010) Study of deep water cement experimental method and cement slurry. International Offshore and Polar Engineering Conference Beijing, China

Zhou Y, Jia J (2010) A new type cement slurry system for deep and high temperature wells. EJGE 15:1989–1995