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التحكم في السوائل الحرة في تسميت
آبار النفط باستخدام عوامل التصميم

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الخلاصة

زيادة الطلب العالمي على النفط دفع شركات النفط للبحث عن النفط في بيئات ذات ظروف معقدة. في هذه الظروف المعقدة. التصميم السليم والجيد للمزيج الأسمنت ضروري لضمان حياة طويلة للانتاج من البئر. محتوى السوائل الحرة في مزيج الأسمنت هي واحدة من الخصائص الرئيسية التي تؤدي الى تشكيل قنوات في مجوعة السمنت. ولتحقيق عملية تسميت جيدة وعدم إجراء سلسة تجارب مضيعة للوقت وزيادة للكلفة. في هذه الدراسة، يتم تطبيق عامل التصميم، لتصميم عدد معين من التجارب والتحقيق في آثار الإضافات المحتملة على أداء الأسمنت. باستخدام النتائج التجريبية تم تطوير نموذج بسيط للتنبؤ محتوى السوائل الحرة في مزيج الأسمنت. يعطي نموذج معين نتائج دقيقة، وبالتالي يمكن استخدامها لتقليل عدد من التجارب.

Free fluid control of oil well cements using factorial design

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ABSTRACT

As worldwide demand of hydrocarbons is growing fast, the oil and gas companies are forced to explore reservoirs in more hostile environments. In these conditions, proper design of cement slurry is essential to guarantee the long production life of the well. Free fluid content of the cement slurry is one of the main properties, which can leads to the formation of interacting channels through the set cement. The best way to achieve a good cement slurry design is to conduct a series of time consuming and expensive experiments. In this study, factorial design is applied to design a certain number of experiments and investigate the effects of possible additives on the performance of cement. Using the experimental results, a simple model is developed to predict the free fluid content of the cement slurry. The given model shows accurate results and therefore can be used to minimize the number of experiments.

Keywords: Cement; factorial design; free fluid; prediction model.

INTRODUCTION

One of the most problematic and expensive phases of oil and gas well construction is cementing operation. Oil well cements are utilized to fill the annular space between the casing and surrounding rock formation, displace the drilling mud, maintain the structural integrity of the wellbore, prevent the unwanted movement of fluids from one layer to another, isolate productive and non-productive layers and protect the casing against corrosion and shock loads. Failure in cementing operation may endanger the producing life of the well and increase the operational difficulties and expenditure of future workovers (Tabatabaee Moradi & Nikolaev, 2016; Roshan & Asef, 2010).

Oil well cements are subjected to wide ranges of pressure, temperature and depths. Therefore, various compositions of cement systems are designed, based on the available material and geological conditions inside the wellbore. For optimum cement design, different additives are used to provide and improve the properties of the cement slurry, according to the desired technical requirements (Pang et al., 2015). Free fluid content (FFC) of the cement slurry is one of the properties used to evaluate the reliability of cementing and is defined as the separated aqueous phase from a slurry. In practice, it is desirable to minimize the FFC of the slurry, in order to eliminate channels that may form through the set cement and serve as potential pathways for formation fluids. These channels are particularly disadvantageous in horizontal and directional wells, where they are formed along the high side of the annular space. In addition, FFC of the slurry can be interpreted as an indirect indicator of the system sedimentation stability. Many factors affect the FFC of the slurry including temperature, pressure, water-to-cement mass ratio (w/c), type and quantity of the additives. The best way to investigate the effect of each additive and its quantity on the FFC is to conduct a series of experimental runs, which are usually laborious, costly and time consuming.

Factorial design (FD) method considers the various factors and their interaction effects on different physical processes during experimental investigations. For many years, factorial design has been successfully applied to solve complicated engineering issues. Okumo & Isehunwa (2007) used a FD methodology to estimate the viscosity of water-based drilling muds. Awoleke et al. (2012) applied FD to investigate the effects of potential parameters (flow back rate, the presence or absence of breaker, closure stress and reservoir temperature) on the fractures conductivity to reduce the number of experimental runs. The maximum ground level concentration and distance to gaseous pollutants in petroleum operations has been evaluated by an integration of factorial analysis and stochastic simulation in the work of Yun et al. (2002). Some researchers used the factorial design approach to evaluate oil well cement properties. Falode et al. (2013) developed a FD-based model to predict the effects of different additives on the compressive strengths of set cements. Salam et al. (2013) applied a full factorial design and established a regression equation to evaluate slurry's thickening time at elevated pressures and temperatures (6000 psi and 400 ˚C). In another work, Salam et al. (2015) took advantage of factorial design to model the rheological properties of class G cement slurry. In last three works, some properties of the oil well cement are evaluated with the help of factorial design, however FFC of the slurry is not investigated in any of them.

In this work, the principle of factorial design has been applied to experimentally investigate the effects of four additives on the FFC of the cement slurries. Results of the experiments have been used to develop a simple mathematical model, which can be used to predict the FFC of the cement slurries and minimize the number of experimental runs.

METHODOLOGY

Several experiments are conducted to measure the FFC of the cement slurries. The cementitious material considered in this work is ordinary Portland cement obtained from local providers inside the Russian Federation. Mineralogical composition of the used Portland cement is presented in Table 1. Four types of additives are used to improve the performance of the slurries. The additives are retarder, fluid loss control agent, weighting material and expansion additive, which are represented by X1, X2, X3 and X4 respectively.

Table 1. Mineralogical composition of the Portland cement

Components of the Portland cement	% by weight
C3S	61.34
C2S	14.61
C3A	5.49
C4AF	16.62

The cement slurries are prepared in accordance with standard procedures, which involved dry premixing of Portland cement, weighting material and expansion additive. The retarder and fluid loss control agent are added directly to water and mixed manually. The prepared dry composition and water was mixed for 3 minutes. The water-to-cement mass ratio for all samples is w/c = 0.5.

In order to measure the free fluid content, prepared slurry was mixed for 20 minutes at a speed of 150 rev./min., and temperature of 25 °C in an atmospheric consistometer. After 2 hours, the volume of released fluid was measured and it was noted as free fluid content. Later the volume of the free fluid is converted to a percentage of free fluid, using following equation (Choolaei et al., 2012):

$$\%FFC = \frac{V_{FF} . \rho}{m_0} \qquad (1)$$

In which V_{FF} is the recorded value of FFC in cm^3, ρ is the density of the cement slurry in g/cm^3 and m0 is the starting mass of cement slurry before stirring in consistometer. The required numbers of experimental runs to develop the mathematical model is calculated by full factorial design, governed by the following equation (Sonebi & McKendry, 2008):

$$N = F^k \qquad (2)$$

In which F is the number of involved factors (four in this work, as four additives are used) and k is the level number, which is two in our case. Using the Equation (2), 16 experiments were conducted to cover all the possible combinations of factors. FFC of the cement slurry is taken as the response variable in the FD. The detailed designs of the experimental runs are presented in Table 2.

Table 2. Experiment details based on the full factorial design

Experiment No.	Factors (additives)				Experiment No.	Factors (additives)			
	X_1	X_2	X_3	X_4		X_1	X_2	X_3	X_4
1	+	+	+	+	9	+	-	-	+
2	+	+	+	-	10	+	+	-	+
3	+	+	-	-	11	+	-	+	+
4	+	-	-	-	12	+	-	+	-
5	-	+	+	+	13	-	-	+	-
6	-	-	+	+	14	-	+	+	-
7	-	-	-	+	15	-	+	-	+
8	-	-	-	-	16	-	+	-	-

In Table 2, the «+» sign indicates the presence of the additive in the desired quantity, and the «-» sign indicates the absence of the additive. The desired quantities of each additive (retarder, fluid loss control agent, weighting material and expansion additive) are selected based on the literature and are presented in Table 3 (Tabatabaee Moradi et al., 2015).

Table 3. Desired quantity of each additive in the cement formulations

Additive	Desired quantity (% by the weight of the blend)
Retarder	15
Fluid loss control agent	1.5
Weighting material	10
Expansion additive	5

Based on Tables 2 and 3, cement slurries are formulated and prepared in accordance with standard procedures. Then the FFC of each formulation is calculated using the explained method. The results of the 16 experiments are presented in Table 4.

Table 4. FFC of the 16 cement slurries

Experiment No.	Retarder	Fluid loss control agent	Weighting material	Expansion additive	FFC (%)
1	+	+	+	+	4.25
2	+	+	+	-	3.5
3	+	+	-	-	4.1
4	+	-	-	-	6.96
5	-	+	+	+	3.6
6	-	-	+	+	3.21
7	-	-	-	+	3.1
8	-	-	-	-	2.74
9	+	-	-	+	7.3
10	+	+	-	+	6.4
11	+	-	+	+	7.62
12	+	-	+	-	7.85
13	-	-	+	-	3.48
14	-	+	+	-	2.9
15	-	+	-	+	2.5
16	-	+	-	-	1.01

Covering all 16 possible combination of factors, the response variable is calculated by experimental method. The results of experiments, presented in Table 4, are used to develop a mathematical model. The model includes the main effects of each factor and the interaction effects. In the developed model, there are four main effects, six two-factor interactions, three three-factor interactions and one four-factor interaction. The model has the following form:

$$\begin{aligned} FFC = cte. + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 \\ + \alpha_5 X_1 X_2 + \alpha_6 X_1 X_3 + \alpha_7 X_1 X_4 + \alpha_8 X_2 X_3 + \alpha_9 X_2 X_4 + \alpha_{10} X_3 X_4 \\ + \alpha_{11} X_1 X_2 X_3 + \alpha_{12} X_1 X_2 X_4 + \alpha_{13} X_1 X_3 X_4 + \alpha_{14} X_2 X_3 X_4 \\ + \alpha_{15} X_1 X_2 X_3 X_4 \end{aligned} \quad (3)$$

Using the experimental data and applying the multiple linear regression method, the coefficients of the Equation (3) are found. The coefficients for main and interaction effects of the factors are presented in Table 5. The mathematical model, which can be used to predict the FFC of the slurry, simplifies as:

$$FFC = 2.72 + 28.13X_1 - 1.05\,X_2 + 7.4\,X_3 + 7.1\,X_4$$
$$-5.02\,X_1X_2 + 10\,X_1X_3 - 2.67\,X_1X_4 + 7.67\,X_2X_3 + 15.07\,X_2X_4 - 126\,X_3X_4 \quad (4)$$
$$-117.3X_1X_2X_3 + 73.8\,X_1X_2X_4 + 80\,X_1X_3X_4 - 21.3\,X_3X_4$$
$$-108.24\,X_1X_2X_3X_4$$

Table 5. Coefficient of main and interaction effect of factors

Coefficients	Value	Standard Residuals	Degree of freedom	Mean square	F – value
cte.	2.72	0.51	1	2.34	55.681
	28.13	1.26	1	9.6879	230.53
	-1.05	0	1	1.9189	45.661
	7.4	-1.52	1	0.2322	5.526
	7.1	-1.01	1	0.3789	9.016
	-5.02	-1.02	1	0.28521	6.7866
	10	-0.76	1	0.42	9.99
	-2.67	-1.26	1	0.1141	2.714
	7.67	-1.01	1	0.61201	14.563
	15.07	0	1	0.59408	14.136
	-126	-1.01	1	0.06021	1.4327
	-117.3	-1.52	1	2.3256	55.339
	73.8	-1.01	1	0.0441	1.0494
	80	-0.76	1	0.07062	1.68
	-21.3	-0.51	1	0.08122	1.9328
	-108.24	-0.63	1	0.05214	1.241

RESULT AND DISCUSSION

The results of 16 experiments are used to develop a simple linear mathematical model, which includes the main and interaction effects of four factors. The coefficients are presented in Table 5, which shows the standard residual, degree of freedom, mean square and F-value for all possible combination of main and interaction effects. To verify the validity of the developed model, analysis of variance (ANOVA) has been carried out. The model R-squared, adjusted R-squared and mean square values are calculated as 0.999, 0.991, and 0.04202 respectively. These values show that the model has a good accuracy. Figure 1 shows the performance of the developed model. It is evident from the Figure 1 that the model can be used as an effective tool to evaluate the FFC of the cement slurries with less time consuming and expensive experiments. A good knowledge of the FFC is essential before cementing operation to guarantee a high quality cementing job, in which possible pathways channels in the set cement are eliminated.

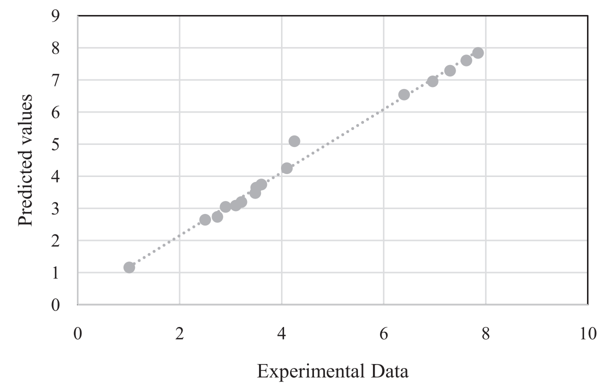

Fig. 1. Comparison of experimental and predicted values of FFC

To confirm the results of the model, the singular and mixed effects of additives on FFC of the cement slurry are investigated. The singular effects of each additive on the FFC are presented in Figures 2-5. The retarder, weighting material and expansion additive have the identical effect on the FFC of the cement slurry, as increasing their proportion leads to increased values of FFC. By increasing the proportion of the fluid loss control agent, a decrease in the FFC of the cement slurry is observed, which is in agreement with the literature. These observations confirm the results of the developed model.

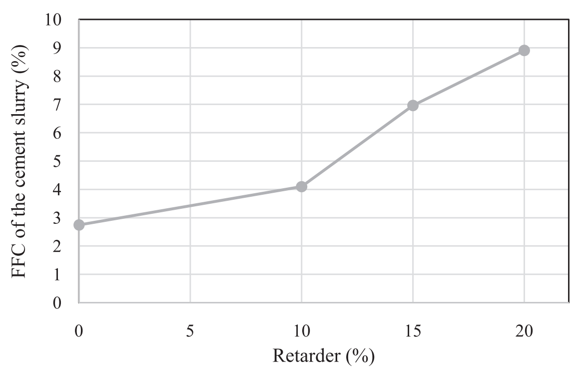

Fig. 2. Effect of retarder on the FFC of the cement slurry

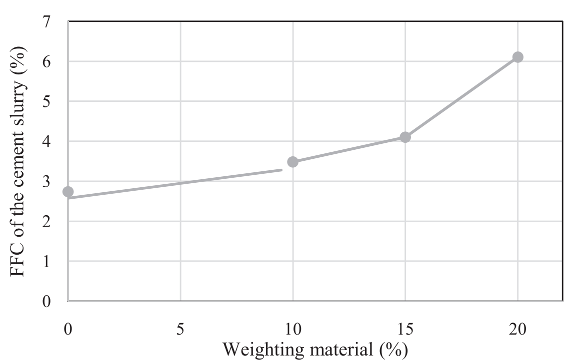

Fig. 3. Effect of weighting material on the FFC of the cement slurry

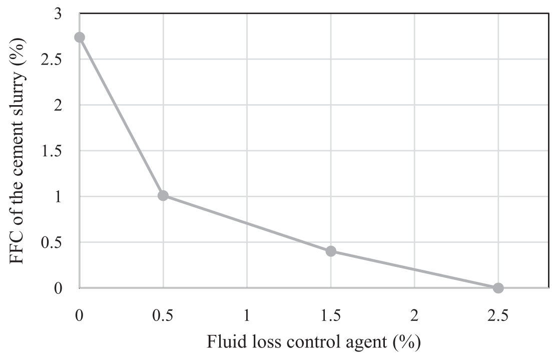

Fig. 4. Effect of fluid loss control agent on the FFC of the cement slurry

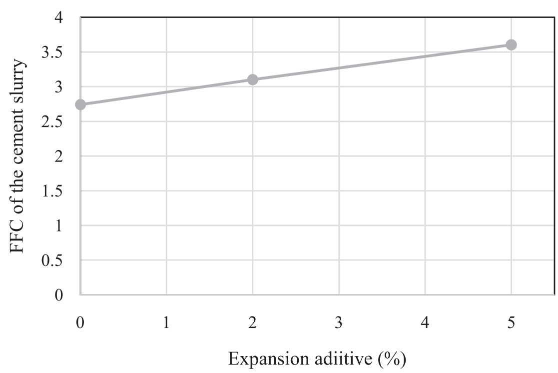

Fig. 5. Effect of expansion additive on the FFC of the cement slurry

The mixed effects of additives on the FFC are also investigated. The surface behavior of combination of all four variables on the response variable is described in 3D plots (Figure 6). The results confirm the validity of the model.

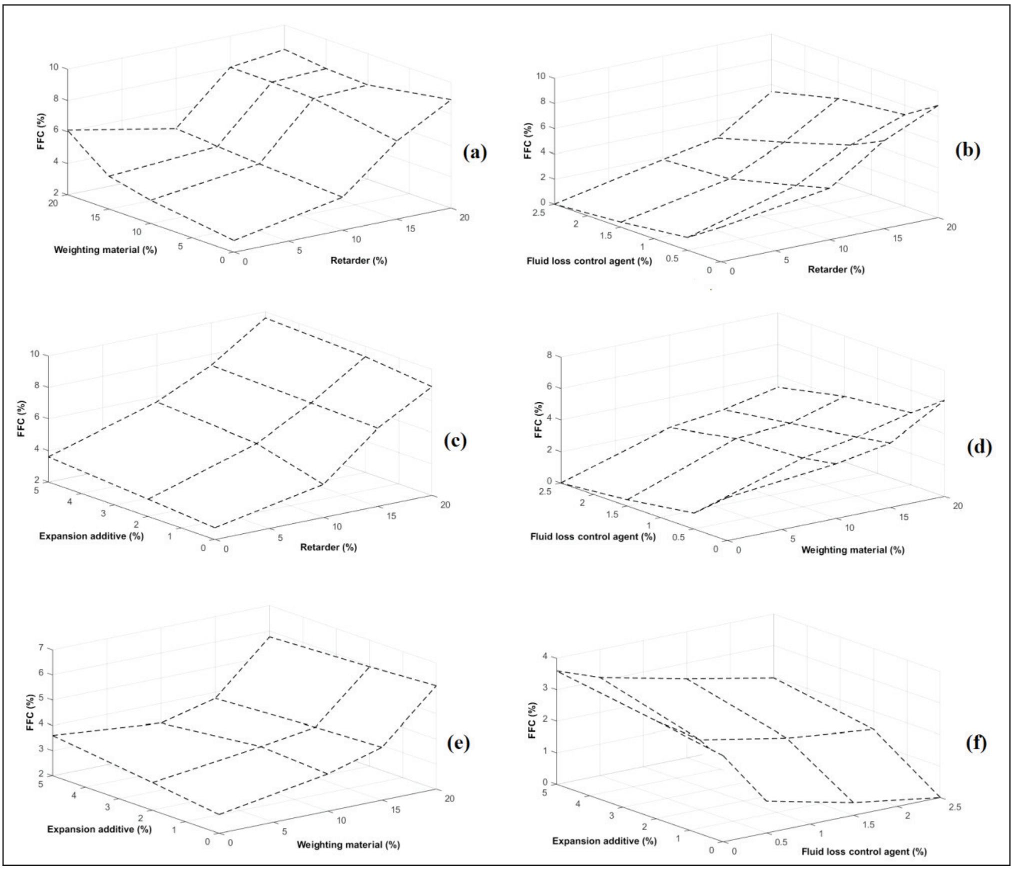

Fig. 6. Surface behavior of combination of all variables on the FFC

CONCLUSION

In this study, a simple mathematical model is developed by the use of factorial design to evaluate the free fluid content of the cement slurry. The model consider the effects of each additive, as well as the interaction effects between them. The FFC of the cement slurry varies with the proportions of additives.

The model has a good accuracy (R^2 =0.99) and therefore it can be used to predict the FFC of the slurries with the proposed additives in this study. Using this model, a fewer number of experiments are required to design proper cement slurry. To neglect the effects of temperature and pressure on the FFC values, the tests are conducted in identical thermobaric conditions, as the FFC is a function of both pressure and temperature.

This investigation can be extended to other important characteristics of oil well cement that affect the quality of cementing operation such as thickening time, fluid loss, consistency, viscosity, strength properties and etc.

ACKNOWLEDGMENT

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