BI-OPTIMIZATION OF DURABILITY AND RHEOLOGICAL PERFORMANCE OF OIL WELL CEMENT SLURRY USING LOCALLY SOURCED EXTENDER

A. O. Arinkoola, S.O Alagbe, K.K. Salam*, and B.M. Ajagbe
Department of Chemical Engineering, P.M.B. 4000,
Ladoke Akintola University of Technology (LAUTECH), Ogbomoso. Oyo State. Nigeria

ABSTRACT: Bentonite used during drilling and cementing operations in Nigeria are imported into the country despite the availability of this raw material, which will increase the Gross Domestic Products (GDP) of this country if properly processed and utilized instead of imported bentonite. This investigation evaluated the performance of three selected Nigerian bentonites sourced from the South-Western part of Nigeria for oil well-cementing operation. The raw and beneficiated samples from each location were prepared and characterized using X-ray Fluorescence (IVT-20 XRF) to determine the elemental composition of each sample pre and post beneficiation. The beneficiated sample with properties close to that of Wyoming bentonite was chosen for the oil well cement slurry analysis. The measured parameters used in the analysis of the suitability of local samples used in oil well-cementing operation were compressive strength and rheological properties. Box-Behnken Design (BBD) was used for the study of the optimum quantity of bentonite required for cementing specification and bi-optimization values for both the comprehensive and rheological properties. The results of this investigation showed that all local clay samples in raw form failed the specification of the American Petroleum Institute (API). After beneficiation, Ibeshe Bentonite (IB) had the highest sodium content and the ratio of the exchangeable cations, 190% increment in sodium-ion was recorded in IB after beneficiation and the slurry yield of IB (2.7 ft^3 per sack) was greater than that of Wyoming Bentonite 1.9 ft^3 per sack) when both are subjected to the same experimental condition. Bi-optimization models predicted optimum experimental conditions with an accuracy of between 0.35 and, 1.26 % for both comprehensive and rheological parameters

Keywords: Rheology; cement slurry; extender; compressive strength; beneficiation, clay.

التحسين الثنائي للمتانة والأداء الإنسيابي لملاط الأسمنت النفطي باستخدام موسع من مصادر محلية

أ. ارينكولا و س. الاجبي و ك. سلام* و ب. اجابي

الملخص: يتم استيراد البنتونيت المستخدم أثناء عمليات الحفر والتدعيم في نيجيريا على الرغم من توفر المادة الخام ، مما يزيد من الناتج المحلي الإجمالي لهذا البلد إذا تمت معالجته واستخدامه بشكل صحيح بدلاً من البنتونيت المستورد. قيم هذا التحقيق أداء ثلاثة بنتونايت نيجيرية مختارة تم الحصول عليها من الجزء الجنوبي الغربي من نيجيريا لعملية تدعيم آبار النفط بالاسمنت. تم تحضير العينات الخام والمستفيدة من كل موقع وتمييزها باستخدام الأشعة السينية الفلورية (IVT-20 XRF) لتحديد التركيب الأولي لكل عينة قبل وبعد التخصيب. تم اختيار العينة المستفيدة مع خصائص قريبة من تلك الخاصة ببنتونايت Wyoming لتحليل ملاط أسمنت آبار النفط. كانت المعايير المقاسة المستخدمة في تحليل مدى ملاءمة العينات المحلية المستخدمة في عملية تدعيم آبار الزيت هي مقاومة الانضغاط والخصائص الانسيابية. تم استخدام Box-Behnken Design (BBD) لدراسة الكمية المثلى من البنتونايت المطلوب لتدعيم المواصفات وقيم التحسين الثنائي لكل من الخصائص الشاملة والريولوجية. أظهرت نتائج هذا التحقيق أن جميع عينات الطين المحلية في شكلها الخام فشلت في مواصفة معهد البترول الأمريكي (API). بعد التخصيب ، كان لدى Ibeshe Bentonite (IB) أعلى محتوى من الصوديوم ونسبة الكاتيونات القابلة للتبادل ، وتم تسجيل زيادة بنسبة 190٪ في أيون الصوديوم في IB بعد التخصيب وإنتاج الملاط لـ IB (2.7 قدم مكعب لكل 33 كيس) أكبر من Wyoming Bentonite (1.9 قدم مكعب لكل 44 كيس) عندما يخضع كلاهما لنفس الحالة التجريبية. تنبأت نماذج التحسين الثنائي بالظروف التجريبية المثلى بدقة تتراوح بين 0.35 و 1.26٪ لكل من المعايير الشاملة والانسيابية

الكلمات المفتاحية: الانسيابية؛ ملاط الأسمنت؛ موسع؛ قوة الضغط؛ إثراء؛ ملاط.

*Corresponding author's e-mail: kksalam@lautech.edu.ng

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NOMENCLATURE

A	Extender, %
API	American Petroleum Institute
B	Accelerator, %
BBD	Box Behken Design
BHCT	Bottom Hole Circulating Temperature, °F
BHST	Bottom Hole Static Temperature, °F
BIB	Beneficiated Ibeshe Bentonite
BWOC	By Weight of Cement
BWOW	By Weight of Water
$B_{E,I,L}$	Beneficiated samples from Ewuobi, Ibeshe and Lukosi
C	Antifoam, %
CS	Comprehensive Strength, psi
D	Disoersant, %
FL	Fluid loss, ml
OWCS	Oil Well Cement Slurry
$R_{E,I,L}$	Raw samples from Ewuobi, Ibeshe and Lukosi
PV	Plastic viscosity, cp
UCA	Ultrasonic Cement Analyser
XRF	X-ray Fluorescence
YP	Yield point, lb/100ft^2

1. INTRODUCTION

Cementing operation is a key operation in both exploration and exploitation activities due to the support it gives during the isolation of zones. During this operation, the annular space between the casing and the drilled well is filled with cement slurry which is allowed to set and solidify thereby joining the casing to the formation(Falode *et al.*, 2013). Oil well cement slurry is primarily designed to pass some tests before it can be pumped downhole and these tests vary depending on the type of designed formulation (Salam *et al.*, 2013, 2015). Depending on the operational design to be implemented, suitable additives are added to cement slurry to enhance its properties in order to achieve the desired performance and some of these additives serve as a retardant, viscosifier, extender, antifoam among others.

Bentonite is one of the additives used to improve cement slurry performance, it is capable of performing more than one function such as the increase in slurry yield, density, rheology, thickening time and compressive strength (Boniface and Appah, 2014). Optimizing the use of bentonite by locally sourcing it instead of importing will reduce the cost of cement operation and the possibility of replacing cement with locally sourced bentonite without compromising comprehensive strength was demonstrated in the experimental investigation conducted by Ahmad *et al.* (2011) where the quantity of bentonite in cement slurry formulation was varied. The research proved that only 30% of the cement can be replaced with bentonite without compromising the comprehensive strength while the cement formulation also resisted sulphate attack. Oriji *et al.* (2014) tested the suitability of Nigerian Bentonite as an additive in both fresh and saltwater and the results show that in freshwater Nigerian Bentonite promising results are obtained. The performance of Nigerian Bentonite cement slurry produced using freshwater can be improved provided cement slurry designs are tailored towards specific operational requirements while in saltwater (Xantham is a good substitute for bentonite in seawater), the properties of cement slurry are not compatible with the standard set by API.

Cement extenders are routine additives used for reducing slurry density and increasing the yield of cement slurry. Bentonite is a common material used as an extender and the one used for cement in Nigeria is imported despite the under-utilization of deposits of bentonitic clay in Nigeria. The estimates of bentonitic clay deposits discovered in several towns in Nigeria was placed above 700 million metric tons *(*Afolabi *et al.*, 2017). For just this reason and due to the vast resources employed in the importation of foreign bentonite, the Federal Government placed an embargo on the importation of foreign bentonite in 2003 and mandated that locally sourced bentonite be used. As a result, there has been increased research into the possibility of using Nigerian local bentonite as a substitute for the imported clays in oil well operations while still maintaining the standards of the oil industry*(*Abdullahi *et al.,* 2011*;* Nweke *et al.,* 2015*;* Oriji *et al.*, 2014). Bentonitic clay obtained from deposits around the country has been tested in an attempt to find one that meets API specifications. Most of the local clays tested generally have proven to be Calcium based and did not meet with API rheological values. However, their properties are improved with beneficiation (Boniface and Appah, 2014; Dewu *et al.*, 2011; Mesubi *et al.*, 2008).

Apart from bentonite, the suitability of other cheaper materials that can be produced locally and compete with replaced commercially sourced additives without compromising slurry produced have been subjected to experimental investigation. Performance of sodium silicate extracted from coal fly ash from south Africa and imported sodium silicate was compared by Kaduku *et al*. (2015) and the comparison showed that cement slurry produced using locally sourced sodium silicate have a slightly lower density, is easier to pump and have high compressive strength. Similar research on the use of local raw materials instead of imported was conducted by (Boniface and Appah, 2014) in Nigeria and Algeria (Oualit *et al.*, 2018). Both investigations targeted locally cement for the formulation of oil well cement slurry. These two investigations agreed that their respective sourced cement can be deplored for cementing operation provided appropriate additives are added. The optimization of various additives are not investigated (Boniface and Appah, 2014) while the influence of various additives on the performance of cement slurry was not investigated (Oualit *et al.*, 2018). Statistical optimization strategies have been applied for optimal use of variables and influence of each of the variables considered(Adeleye *et al.*, 2009; Salam *et al.*, 2010, 2015).

Bentonite is one of the crucial materials needed during cementing operation due to the different characteristics it exhibited (thixotropic, swelling and absorption properties). Wyoming bentonite is the most commonly available commercial bentonite for cementing and drilling fluid applications (Dewu *et al.*, 2011). The importation of Wyoming Bentonite for oil and gas well-cementing operation has continued to divert some large amount of foreign exchange while Nigeria is having a large reserve of Bentonitic clay deposit which can be beneficiated to upgrade the properties of the clay to that of the standard commercial bentonite for oil well cementing and other industrial uses (Abdullahi *et al.*, 2011). It is therefore of interest to investigate the suitability of Nigeria bentonite as an extender in the design of oil well-cementing slurry and its influence concerning other cement additives on cement slurry performance.

2. MATERIALS AND METHODS

2.1 Materials Acquisition

The selected Nigerian bentonites that were used for this study were sourced from Lukosi (7° 7' 50.952" N, 3° 22' 2.1" E) in Ogun State, Ibeshe (6° 33' 54.504" N, 3° 28' 56.82" E) and Ewu Ebi (6° 32' 51.54" N, 3° 30' 54.828" E) in Lagos State, all in South-West, Nigeria. The class G cement, accelerator, antifoam and mix water that were used were sourced from the cement laboratory of SOWSCO Well Services (Nig.) Ltd, Plot 212, Trans-Amadi Industrial Layout, Port-Harcourt, River State, Nigeria.

2.2 Beneficiation of Clay Samples

From each of the three clay samples, ten sets of 100 g of each sample were set aside for beneficiation using sodium carbonate (Na_2CO_3) as shown in Table 1. To each of the samples (sample with Na_2CO_3), 50 ml of distilled water was added, kneaded and were allowed to stay for 24 h for ion exchange to take place. After allowing the kneaded samples to stay for 24 h each of the samples were oven-dried at 75° for 8 h. The beneficiated samples were re-grounded and sieved again to achieve the 63μm before characterization. The chemical composition of the beneficiated samples was analyzed by using IVT-20 computer-automated X-ray Fluorescence (XRF) spectrometer.

2.3 Cement Slurry Formulation and Design of Experiment

Class G cement (Moderate Sulphate Resistant type) was the primary cement used while the accelerator, antifoam, and extender are added as additives. All the additives used are in house additives used by SOWSCO Nigeria limited except the extender, which was replaced by BIB. Cement slurry was prepared based on the formulation tabulated in Table 2.

Table 1. Composition of Beneficiated Samples

S/N	Quantity of each sample of the Nigeria Bentonite (g)	Quantity of Beneficiating Agent ($Na_2CO_{3(aq)}$) (g)	Total Weight of each sample (g)
01	100	1.0	101.0
02	100	2.0	102.0
03	100	3.0	103.0
04	100	4.0	104.0
05	100	5.0	105.0
06	100	6.0	106.0
07	100	7.0	107.0
08	100	8.0	108.0
09	100	9.0	109.0
10	100	10.0	110.0

Table 2. Formulation of Class G Cement Slurry.

Lab. Qty	Unit	Dry Components	Material	Per cent	Pounds	Absolute Volume	Volume (Gallons)	Specific Gravity		
482	g	#1 Cement	Class G	100	94	0.0382	3.5908	3.14	Slurry Yield (ft^3/sack)	1.9
77	g	#2 Bentonite	Imported Bentonite	16	15.04	0.0454	0.6828	2.65	Slurry Density (lb/gal)	13.8
36	g	#3 CaCl2	$CaCl_2$	7.5	7.05	0.0685	0.4829	1.75	Total Fluid, %	82.35%
									Total Fluid, gals	9.3
		Liquid Components								
4.2	ml	#1 Antifoam		0.9	0.821		0.099	0.996		
4	ml	#2 Dispersant		1	0.787		0.0801	1.18		
389	ml	#3 Fresh Water		80.7	75.803		9.1	1		
				Total	193.502		14.0356			

The design of the slurry was carried out according to API standard and desired density, thickening time, fluid loss, and rheological behaviour at the time of pumping, appropriate transition time and enough strength at the time of set were achieved. The concentrations of most solid cement additives were expressed as a percentage by weight of cement (BWOC) while liquid additive concentrations were expressed in gallons per sack of cement as tabulated in Table 2. The calculations for the mass of the components was made according to the recommendations of the API practices and also the slurry density and the slurry yield of the design of cement slurry for each of the runs of the experiments was calculated using the Eqns. (1) to (5).

$$\text{Slurry Density}\left(\frac{\text{lb}}{\text{gal}}\right)=\frac{\text{Total Weight (lb)}}{\text{Total Volume (gal)}} \quad (1)$$

$$\text{Slurry Yield}\ (\text{ft}^3) \quad =\frac{\text{Total Volume (gal)}}{7.48\ (\text{gal/ft}^3)} \quad (2)$$

$$V\text{olume (gal)} = \text{Weight of the component in gallon (lb)} * \text{The absolute volume of component} \quad (3)$$

$$\text{Total Weight (lb)} = \sum \text{Weight of all the slurry components} \quad (4)$$

$$\text{Total Volume(gal)} = \sum \text{volume of all the slurry components} \quad (5)$$

where $7.48(gal/ft^3)$ is the conversion factor for slurry yield.

Beneficiating Agent = $Na_2CO_{3\,(aq)}$

The density of each of the samples of BIB was first determined using mud balance. The cement and solid additives were weighed and uniformly dry blended before mixing with fresh water in the stainless-steel container of the constant speed mixer (4000 rpm). The mixer motor was turned on and maintained at 4000 rpm at a uniform rate, for 25 s and then liquid additives were added. Thereafter, the mixing speed was increased to 12000 for 35 s. The slurries were prepared and kept at room temperature under atmospheric pressure. The process of slurry preparation was adopted for mixing of (17) different formulations based on the change in values of variables tabulated in Table 3 using BBD. The individual and interaction effect of the variables that formed OWC were evaluated, R-square was used to determine how close the model developed values are to the measured data used in model development and validation.

2.4 Rheological properties measurement

A 12-speed rotational Viscometer was used according to API specifications (API 10A, 2010) to evaluate the rheological properties of OWC slurry using the locally sourced beneficiated clay as an extender for each run of the experiment. The slurry was first conditioned to Bottom Hole Circulating Temperature (BHCT) of 100° F using an atmospheric Consistometer. The Plastic Viscosity (PV) and Yield Point (YP) of the cement slurry were computed at both ambient and test temperatures using Eqns. (6) and (7), respectively:

$$PV(cp) = 1.5 * (\gamma_{300} - \gamma_{100}) \quad (6)$$

$$YP\ \left(\frac{Ibs}{100ft^3}\right) = PV - \gamma_{100} \quad (7)$$

where γ_{300} and γ_{100} are viscometer dial readings at 300 and 100 rpm, respectively.

2.5 Compressive strength test Determination

The method that was adopted in this study was non-destructive. In this method, Ultrasonic Cement Analyzer (UCA) (model 4265) was used to analyze the compressive strength of the cement slurry for each run of the experiment at 12 and 24 h. For this research work, the curing condition was at the downhole pressure of 3,500 psi, BHST of 115° F, and BHCT of 100° F.

3. RESULTS AND DISCUSSION

3.1 Characterization of Beneficiated Nigerian Bentonite

The XRF results obtained before and after the beneficiation of the selected Nigerian bentonites using 4.0 g of $Na_2CO_{3(aq)}$ were presented in Table 4. The effect of each dose of $Na_2CO_{3(aq)}$ on each clay sample was monitored and it was observed that after the beneficiation using 4.0 g of $Na_2CO_{3(aq)}$, Ibeshe clay sample was selected for the cement slurry analysis because it has the highest value of the sodium ion content in order to meet API specifications of bentonite. The results of other concentrations (1.0, 2.0, 3.0, 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0 g of sodium carbonate) are not shown because of space constraint. The ratio of Si/Al of the raw sample was less than the 3.1 recommended by API (API 10B) which justified the need for beneficiation as shown in Table 4.

Table 3. The levels of the variables.

	Independent Variable	Coded variable	Low (wt %)	High (wt %)
1	Extender (BIB)	A	16	31
2	Accelerator	B	5	10
3	Antifoam	C	0.5	1.4
4	Dispersant	D	0.7	1.1

The highest sodium content which is responsible for swelling in the cement slurry was 1.74 wt% which corresponded to that of Ibeshe clay. This value is in a close range to the value reported for the imported bentonite (2.19 wt %) (James *et al.*, 2008). All the clay samples are known to contain alumina (Al_2O_3) and silica (SiO_2); and this is also true of feldspars which decompose to form clays by hydrothermal activities (Mark, 2010). Therefore, after beneficiation, the alumina content and other associated oxides were changed and met the requirements for oil well cementing. Ibeshe clay showed the highest promising potential. The ratio of the exchangeable cations, Calcium / Magnesium for the three selected bentonite [X: (1.30/0.86 = 1.51), Y(0.67/0.43 = 1.55), Z (3.37/2.12 = 1.58)] is greater than 1.0, which shows the three samples are stable as the minimum ratio of Calcium /Magnesium required by the standard is 0.5 (Dontsova and Norton, 2001).

3.2 Slurry density and yield

Slurry density is significant to wellbore hydrostatic pressure. However, deviations from design density may cause changes in all other slurry properties which may cause well problems. The reason why extenders are needed is to maintain optimal cement properties when decreasing the density of the cement slurry to accommodate formation limitations during the cement placement process. The slurry density and yield obtained from the various formulations were presented in Table 5 using the selected beneficiated bentonitic clay sample from the Ibeshe deposit. It was observed that the density ranged from 12.1 – 14 lb/gal while the slurry yield ranged from 1.9 – 2.9 ft^3/sk. The basis of this experiment was the results obtained using the imported Wyoming bentonite as presented in Table 5 which revealed a slurry density and yield of 13.8 lb/gal and 1.9ft^3/sk, respectively. According to API recommendation, the value of density ranged from 11.9 - 15.8 lb/gal and yield ranges from 1.14 – 2.85 ft^3/sk are acceptable for cement slurry design (Nelson, 1990). The results obtained showed that the Beneficiated Ibeshe Clay (BIC) can be used as an alternative for the imported Wyoming bentonite.

3.3 BIB and CS of OWCS

The results obtained for the CS at 12 and 24 h for 17 different runs for OWCSs oil well cement slurries formulated using BBD were presented in Table 5. The values of CS obtained at 12 and 24 h using Wyoming bentonite was 650 and 730 psi, respectively (Table 5). The slurry formulation for run 13 in this study exhibited higher CS of 670 and 770 psi at 12 and 24 h, respectively when compared with that of imported bentonite. Careful observation showed that dispersant, slurry stability and inter fluid chemical reactivity have a tremendous influence on compressive strength. Generally, there is no universal agreement on strength requirement for oil well cement except the minimum values; however, values of compressive strength after 24 h are often requested to ascertain cement slurry set under the borehole condition and for the reason that at 24 h the slurry will have a better strength development. The one-factor effect of the four variables BIB (A), accelerator (B), antifoam (C) and dispersant (D) with the experimental range set in Table 3 was used to the response CS at 12 and 24 h to change in each of the variables was presented in Fig. 1. In Fig. 1(a), the influence of each of the variables on CS at 12 h was presented. The result showed all the variables individually decreased the value of CS when their values were increased from minimum to maximum as set in Table 5. Similar behaviour can observed later in Fig. 1(b) for CS at 24 h, all the variables decreased the CS with an increase in their values except for D. In the case of D, CS increased with an increase in its value from 0.7 to 1.1.

Table 4. XRF Results of the Analysis of Beneficiated Nigerian Bentonites with 4.0 g of Na2CO3.

Oxides	Elements	(James *et al*., 2008)	Lukosi (wt%)		Ibeshe (wt%)		Ewuobi (wt%)	
			R_L	B_L	R_I	B_I	R_E	B_E
SiO_2	Si	48.8	42.95	55.18	45.5	56.72	40	57.8
Al_2O_3	Al	15.54	36.25	20.19	29.85	20.11	27.55	14.84
Fe_2O_3	Fe	6.44	0.15	0.07	1.5	1.96	3.5	1.43
MnO	Mn	0.07	0.02	0.02	0.001	0.01	0.1	0.09
MgO	Mg	3.5	1.4	0.86	0.95	0.43	2.5	2.12
CaO	Ca	5.22	0.9	1.3	0.45	0.67	3.12	3.37
Na_2O	Na	2.19	0.4	1.7	0.6	1.74	0.15	0.7
K_2O	K	0.75	0.65	0.41	0.35	0.32	0.12	0.36
TiO_2	Ti	0.49	0.01	0.01	0.15	0.09	0.25	0.08
P_2O_5	P	0.13	0.01	0.01	0.03	0.04	0.13	0.01
LOI	LOI	15.73	17.25	20.15	20.15	17.83	22.5	19.5

Where R_L, R_I and R_E are raw results for Lukosi, Ibeshe and Ewuobi clay samples while B_L, B_I and B_E are beneficiated results for Lukosi, Ibeshe and Ewuobi clay samples.

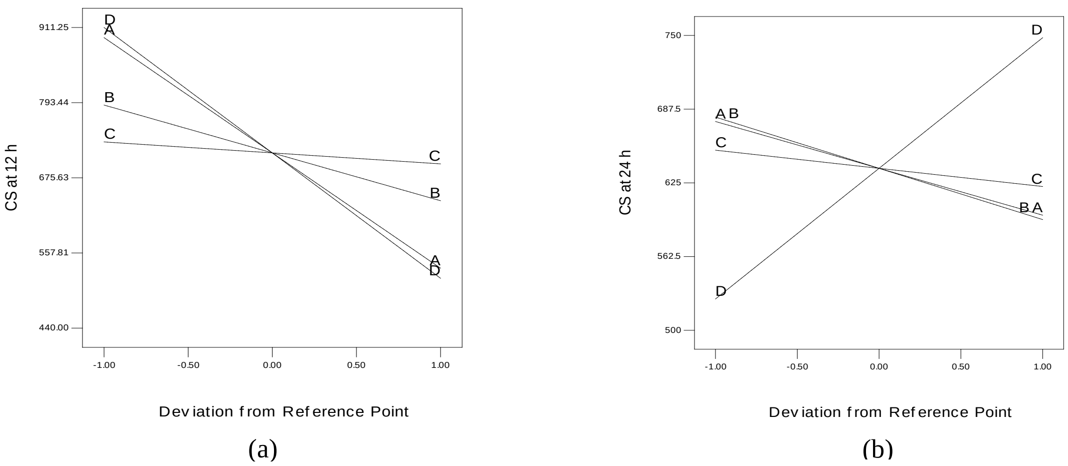

Figure 1. Effect of individual factors (A, B, C & D) on CS at 12 h (a) and at 24 h (b), respectively.

The interactive effect of two variables at a time while the two other variables are kept at their mid-point was used to study the influence of variables on CS. Figs. 2(a) and 2(b) are interactive effects for CS at 12 h while Figs. 2(c) and 2(d) are the interactive effects for CS at 24 h. Fig. 2(a) shows the effect of a simultaneous increase in A and D while B and C are kept constant at their midpoint (7.5 and 0.95, respectively). The figure showed that at a minimum value of D (0.7), an increase in A from 16 to 31 lead to a decrease in CS from 1362 to 460. 39. At the maximum value of D (1.1), an increase in A led to an increase in CS at 12 h from 428.5 to 607.48. At a minimum value of A (16), CS decreased with an increase in D from 0.7 to 1.1 while at a maximum value of a (31), CS increased with an increase in D from 0.7 to 1.1 respectively. Other behaviours of simultaneous change in variables values on CS at both 12 and 24 h are presented in Figs. 2(b), 2(c), and 2(d).

Based on the behaviour of variables both at individual and interactive levels, an empirical model was developed for CS at 12 and 24 hours as presented in Eqns. (6) and (7), respectively.

$$CS_{12} = 714.67 - 180.73A - 75B - 17.21C - 196.58D + 270.13AD + 69.45BD \quad (8)$$

$$CS_{24} = 637.32 - 39.72A - 43.45B - 15.40C + 110.77D + 10.11CD + 40.21AC^2 \quad (9)$$

The R-square values of the empirical models presented CS at 12 and 24 h are 0. 956 and 0.994, respectively. The Analysis of Variance (ANOVA) of the two models for CS at 12 and 24 h was presented in Table 6. The respective model F-value of 18.08 and 82.37 implied that the selected modified model for CS at 12 and 24 h are significant with P-value of 0.3% and 0.2% respectively. The result of the F-values shows that there is a small likelihood that the F- value obtained was due to noise in the data used for this study. It was discovered that for CS at 12 h, four out of the six model terms are significant to model development (model terms are significant to model development provided their Prob>F value is less than 0.05). They are A, B, D, AD, and BD respectively. The lower the Prob>F value, the more influential the model term to the model developed.

AD has the most influential effect on the developed model and that was why its coefficient value in Eqn. (1) has the most numerical strength out of all the coefficient values in that equation. For CS at 24 h, five out of the six model terms are significant to the model developed and D has the most influential effect on the prediction of CS at 24 h.

3.4 Effects of BIB and other Additives on Rheological Properties of OWCS

The laboratory results of replacing imported extenders with BIB in determining PV and yield points for different experimental runs were presented in Table 5 while the result of the experiment conducted with Wyoming bentonite (imported) is presented in Table 7 (control experiment). It was observed from the table the PV of all the OWCS mixed in the laboratory were below 100 (cp) and with the equivalent slurry yield which can be considered as a desirable result to keep cement slurry pumpable within the pre-determined thickening time according to (API RP 10B-2, 2009). No premature gelation of cement slurry is observed for all the cement samples and the values of the YP calculated show that all the slurries are pumpable (Abbas et al., 2014).

The individual effect of the change in additives values on PV and YP of the OWCS is presented in Fig. 3. PV increased with an increase in the values of both B (accelerator) and C (antifoam), respectively, while PV decreased with an increase in A (BIB) and D (dispersant), respectively. In the case of YP, an increase in values of additives A and D (dispersant) decreased the YP of OWCS in this research while the increase in the values of additives B (accelerator) and C (antifoam) increased the value of YP. While C and D have influential effects on YP, both A and B have a mild influence on YP.

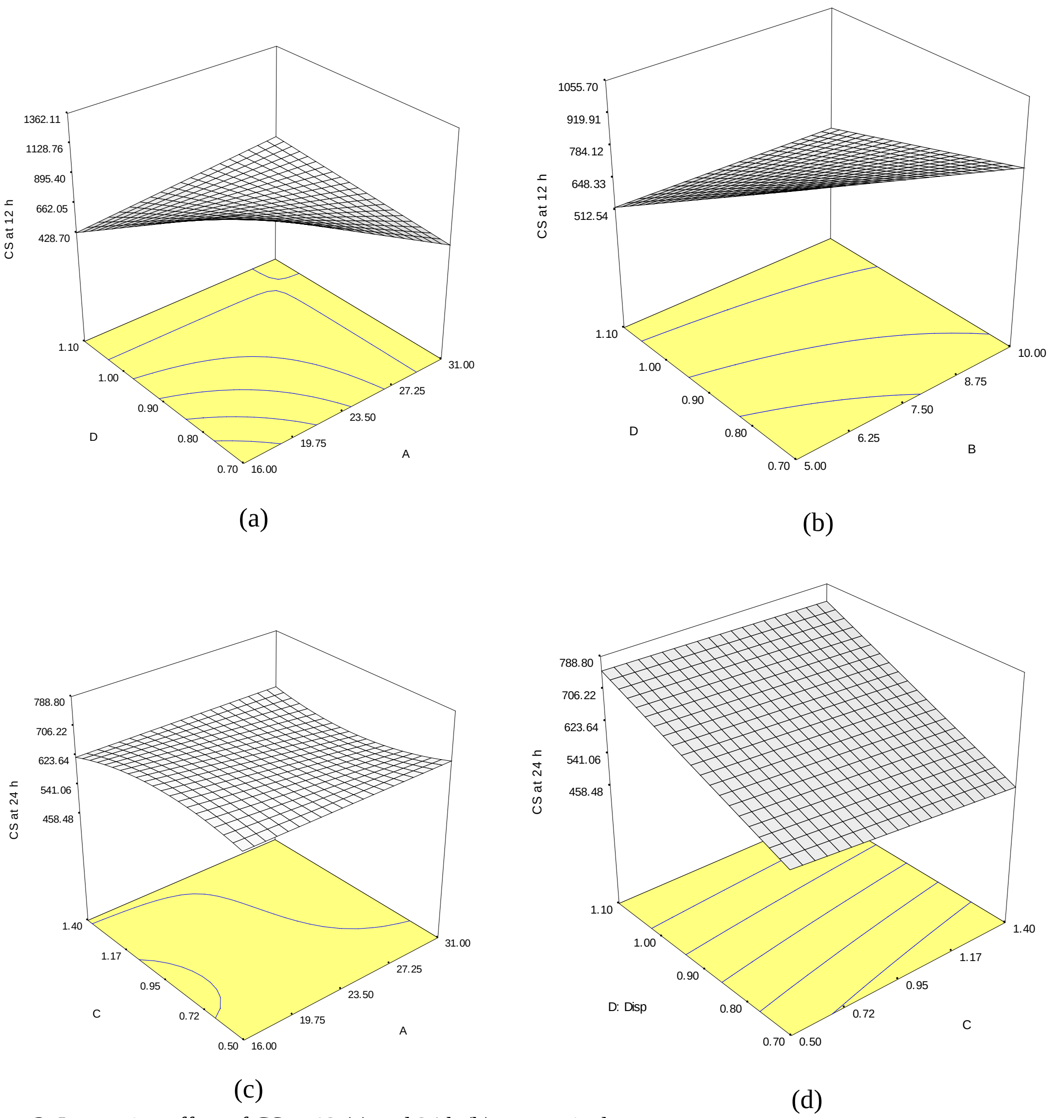

Figure 2. Interaction effect of CS at 12 (a) and 24 h (b), respectively

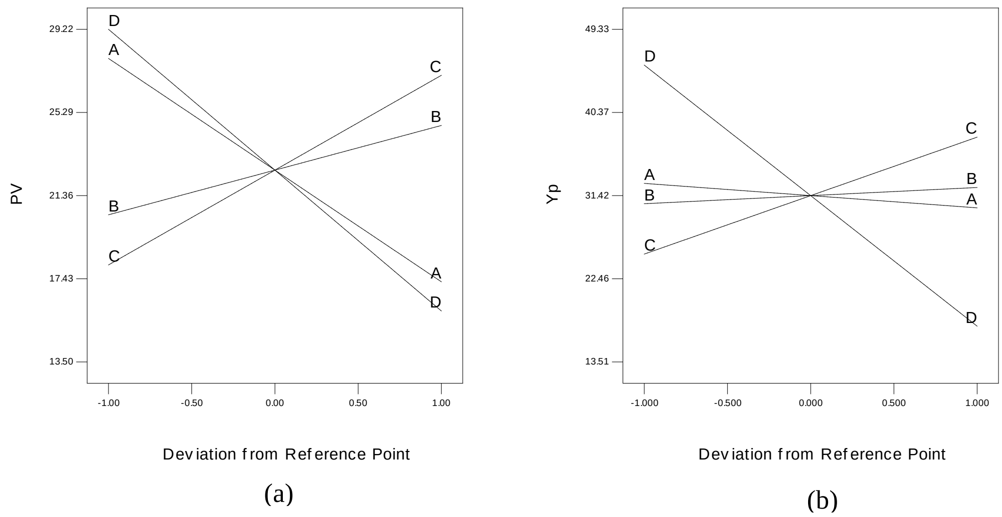

Figure 3. One factor plot of variables against PV: (a), and YP (b), respectively.

Table 5. Cement slurry properties based on an experimental design using BIB as an extender.

		A	B	C	D	Slurry Density	Slurry Yield	CS at 12 h	CS at 24 h	Plastic Viscosity	Yield Point
St Order	Run	(%)	(%)	(%)	(%)	(lb/gal)	(ft^3/sk)	(psi)	(psi)	(cp)	(lbs/100ft2)
9	1	31	5	0.9	0.9	12.5	2.7	600	650	18	29
8	2	16	7.5	0.5	1	13.8	1.9	670	700	15	37
2	3	23.5	7.5	0.9	1	13.6	2	580	600	15	23
7	4	16	5	0.9	0.9	13.8	1.9	620	660	21	33
3	5	31	7.5	1.4	0.7	12.7	2.6	440	500	22.5	27.7
13	6	23.5	7.5	0.9	1.1	14	1.9	520	580	16.5	20.5
15	7	23.5	7.5	0.9	1	14	1.9	550	600	22.5	29.5
10	8	23.5	5	1.4	1	13.8	2	650	720	24	22
4	9	23.5	10	1.4	1	14	1.9	630	700	13.5	25.5
11	10	16	7.5	1.4	1	13.6	1.9	600	680	22.5	22.5
14	11	16	10	0.9	1	13.8	1.9	660	700	21	32
6	12	23.5	5	0.5	1	13.6	2	670	750	16.5	24.5
12	13	23.5	7.5	0.9	1	13.8	2	640	770	19.5	22.5
5	14	23.5	7.5	0.9	1	13.8	2	640	770	19.5	22.5
17	15	31	10	0.9	0.9	12.7	2.6	450	560	16.5	29.5
16	16	31	7.5	0.5	0.8	12.1	3	530	600	16.5	21.5
1	17	23.5	10	0.5	1	13.7	2.1	600	650	22.5	26.5

Table 6. ANOVA table of CS at 12 and 24 h.

CS at 12 h			CS at 24 h		
Terms	F-Value	Prob > F	Terms	F-Value	Prob > F
Model	18.08	0.003	Model	82.37	0.002
A	32.4	0.0023	A	30.41	0.0117
B	17.83	0.0083	B	92.08	0.0024
C	1.97	0.219	C	11.04	0.0449
D	13.19	0.015	D	67.93	0.0037
AD	18.39	0.0078	CD	1.8	0.2722
BD	2.12	0.2054	AC^2	17.55	0.0248

Table 7. Cement slurry properties using Wyoming bentonite as an extender.

Thickening Time (mins)			Rheology (rpm)						PV (cp)	YP (lb/100ft^2)	Compressive Strength (psi)		Fluid loss (ml/30 mins)
50 Bc	70 Bc	100Bc	600	300	200	100	6	3			12 h	24 h	
290	325	345	50	45	40	35	10	10	15	30	650	730	20

Table 8. ANOVA table of PV and YP.

PV			YP		
	F-Value	Prob > F		F-Value	Prob > F
Model	275.51	0.0003	Model	16.26	0.0008
A	452.26	0.0002	A	1.5	0.2608
B	73.13	0.0034	B	1.84	0.2173
C	413.02	0.0003	C	11.97	0.0106
D	299.93	0.0004	D	46.49	0.0002
AB	230.55	0.0006	AC	19.51	0.0031
AC	464.19	0.0002	AD	6.63	0.0368
AD	246.5	0.0006	CD	12.87	0.0089
BC	1383.54	< 0.0001			
BD	123.82	0.0016			
CD	434.18	0.0002			

The interaction plots of the combinations of the four additives and their corresponding influence on both the PV and YP were presented in Figs. 4(a), 4(b), and 4(c) describe the interactions of additives and their response on the PV calculated while Fig. 4 (d), 4e, and 4(f) described the interactions of additives on YP. The simultaneous effect of change in values of A and B on PV was presented in Fig. 4(a). In this plot, PV values were reduced with an increase in A from 16 to 31 at both minimum and maximum values of B (5 and 10). However, the values of PV increased from 22.41 to 33.28 when B was varied from 5 to 10 for a minimum value of A (16). For interaction between a variety of values of C and D shown in Fig. 4(b), PV significantly increased with an increase in D from 15 to 43.45 at a minimum value of C (0.7). At maximum value of C (1.1), PV values decreased from 21.17 to 10.65 when D was increased from 0.5 to 1.4. The response of PV to an interaction between B and C was presented in Fig.4 (c). Figures 4(d), 4(e), and 4(f) describe the interactions of additives and corresponding response on the YP calculated from the experimental data obtained from the laboratory. The simultaneous effect of change in values of A and C on YP was presented in Fig. 4(d). In this 3-D plot, the values of YP values decreased with an increase in A from 16 to 31 at both minimum and maximum values of C (0.7 and 1.1). However, at a maximum value of A (31), YP increased with an increase in C from 17.38 to 42.82. In the case of simultaneous variation of A and D shown in Fig. 4(e), YP increased from 38.33 to 52.62 for an increase in A from 16 to 31 at a minimum value of D (0.7) while at a maximum value of D (1.1), YP decreased with increase in A. For interaction between variation in values of C and D shown in Fig. 4(f), a minimum value of D favour increase in YP while YP decreased with an increase in C at maximum D. Based on the behaviour of variables both at the individual and interactive level, empirical models were developed for PV and YP as presented in Eqns. (10) and (11), respectively.

$$PV = 22.57 - 5.28A + 2.11B + 4.48C - 6.66D - 3.32AB - 4.14AC + 11.53AD - 4.13BC - 6.47BD - 9.74CD \qquad (10)$$

$$YP = 31.42 - 1.32A + 0.88B + 6.30C - 14.06D + 6.42AC - 8.47AD - 14.29CD \qquad (11)$$

The analysis of the empirical models developed for both PV and YP shows that their R-square values are 0.99 and 0.94, respectively. The adequate precision of both PV and YP are 53.37 and 15.48, values that show that the values are adequate for the developed models since the values are greater than four (4). The ANOVA of PV and YP was tabulated in Table 8. The respective model F-values of 275.51 and 16.26 implied that the selected modified models for PV and YP are significant to the developed models with 0.3% and 0.8% likelihood of the F- values reported was due to noise. The model terms. A, B, C, D, AB, AC, AD, BC, BD and CD are significant model terms for the empirical model developed for the prediction of PV while terms C, D, AC, AD, and CD (five out of seven model terms) are significant model terms used for the empirical model developed for the prediction of YP, respectively.

3.5 Bi-Optimization Studies

A numerical optimization technique based on desirability function was carried out to determine the workable optimum conditions for the design of oil well cement slurry using BIB as an extender in OWCS formulation. In order to provide an ideal case for oil well cementing, the additives were set in range based upon the requirements of the design. The values for the lower and upper limits of the additives were stated in Table 3. The desirability value was 1. The simulated (predicted), experimental and control experimental results are tabulated in the simulated result was achieved using the specified values of the variables: A (30.17), B (5.4), C (1.17) and D (0.9). The experimental and the simulated values for the properties tested in this study are close which suggested that the models developed are predictive and can determine to a high degree of accuracy the rheological and mechanical properties of class G OWC.

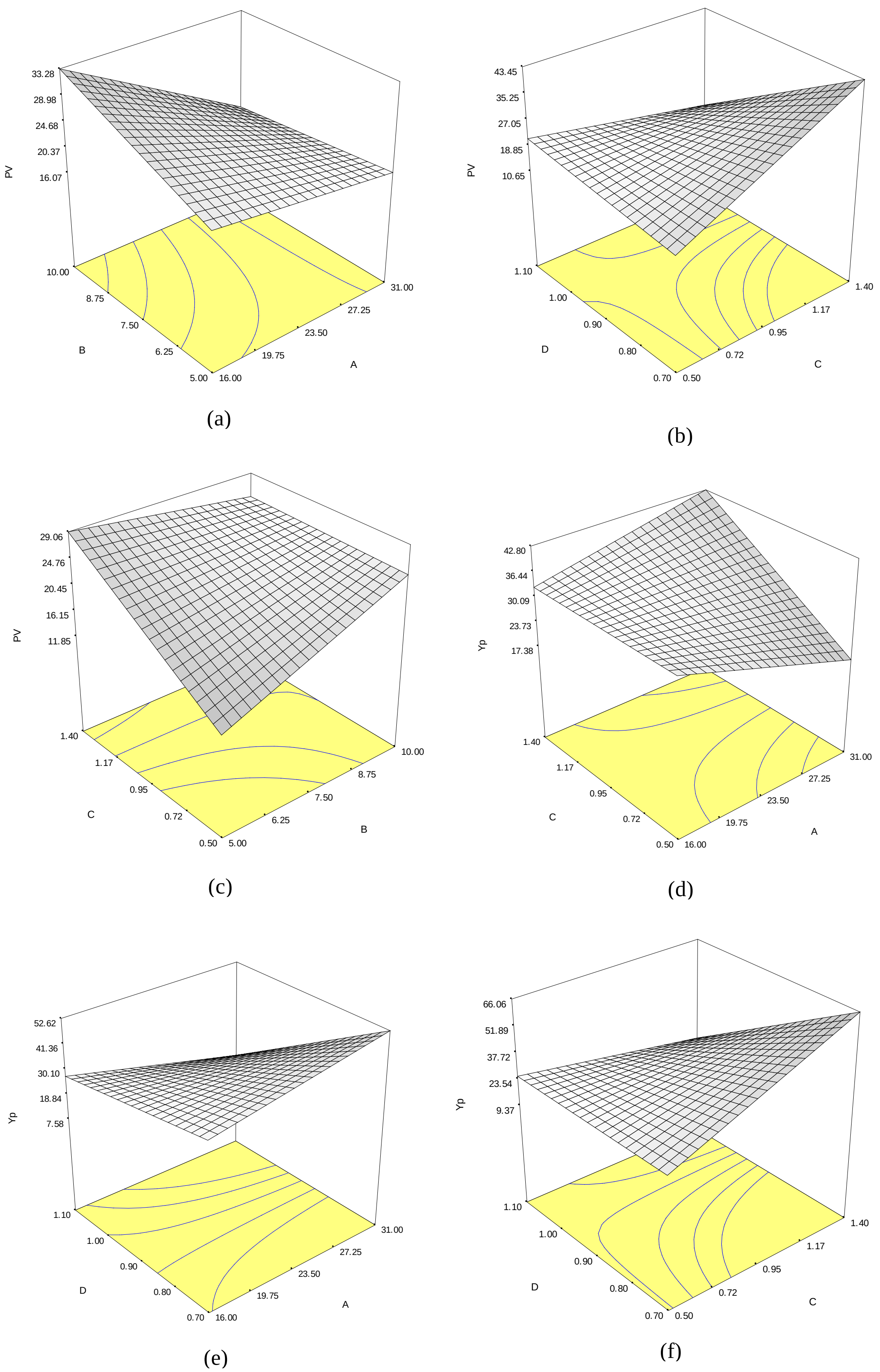

Figure 4. 3D surface plots of PV (a, b, and c), and YP (d, e, and f), respectively.

Table 9. Validation of developed models.

	CS (psi)		PV (cp)	YP *(lb/100ft^2)*
	at 12 h	at 24 h		
Simulation value	592	640	16	29
Measured value	601±1.44	637±1.26	15±1.01	30±0.35
Control (100% cement)	650	730	15	30

4. CONCLUSION

For the utilization of locally sourced bentonite as an extender during oil well-cementing operation, the following deductions were drawn:

- The sodium ion concentration of BIB increased from 0.6 to 1.74 wt% when beneficiated with 4 g of sodium carbonate and it was the highest for the three clay samples beneficiated.
- All the seventeen (17) formulated cement slurries designed Box-Behnken design proved to have required rheological properties according to API standard using BIB as an extender.
- The thickening time and fluid loss values obtained for all experimental runs are within the acceptable range according to the API standard.
- All the values obtained from laboratory analysis for compressive strength after 24 h periods can structurally hold casings at BHST of 115F and BHCT 100 F.
- The slurry yield of 2.7 ft^3 per sack was recorded using BIB and was greater than that of Wyoming imported bentonite (1.9 ft^3 per sack) when both formulations are subjected to the same experimental condition (run 1).
- The model developed from the bi-optimization studies predicted both the comprehensive and rheological parameters within 1.44%, 1.26%, 1.01% and 0.35% for CS at 12 h, CS at 24 h, PV and YP, respectively.
- All the submissions are laboratory-scale deductions; therefore, it is recommended that this research be subjected to practical placement modelling for confirmation of the results presented.

CONFLICT OF INTEREST

The authors declare that there is no conflict of the interaction of any form on this manuscript.

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