Journal of the Ghana Institution of Engineering (2023) 23:2
https//doi.org/10.56049/jghie.v23i2.97

CASE STUDY (Presented at 2023 GhIE Annual Conference & AGM)

Improving the sustainability of oil well cementing operations in Ghana: blending Portland cement with pozzolana

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Received: 21st February, 2023 / **Accepted:** 19th June, 2023
Published online: 19th July, 2023

Abstract

Cementing is one of the most critical drilling operations in the oil and gas industry. However, the production and utilization of cement is a major emitter of CO_2 into the atmosphere. Processes and technologies that can reduce the overall carbon footprint of the oil and gas industry while meeting the increasing global demand for energy are of key interest to stakeholders. Furthermore, local cement when compared with imported class G cement is unable to meet the compressive strength requirement of an oil well cement. Therefore, the objective of the present study is to investigate for the first time the capability of natural pozzolana clay from Ghana as a sustainable alternative to improve the physical and rheological properties of local Portland cement for well cementing operations. Pozzolana is a naturally occurring clay that is mainly composed of silica and alumina. To achieve this, well cementing blends of varying percentages with up to 30 % of pozzolana and 70 % of local Portland cement by mass were formulated and examined to determine their rheological properties, free fluid, and compressive strength. The experimental results indicated that blending natural pozzolana material and local Portland cement effectively reduced the free fluid of local Portland by up to 85 % and the plastic viscosity by up to 62.5 %. Furthermore, the addition of pozzolana significantly increased the compressive strength of local Portland cement by up to 188.5 %. Based on the results, it can be concluded that pozzolana can improve the performance of local Portland oil well cement and further reduce the carbon footprint of the oil and gas extraction process by minimizing the quantity of Portland cement used for well cementing operation.

Keywords: Pozzolana, Portland Cement, Rheological Properties, Compressive Strength, Well Cementing

Introduction

to Portland cement in oil well cementing operations. PozThe oil and gas industry has long relied on Portland cement for well cementing and abandonment. Cementing is a delicate and important process during the drilling operation and it can be a primary or secondary operation (Velayati *et al*., 2015). During a primary cementing operation, a cement sheath is placed in the annulus space between casing and formation in order to ensure zonal isolation and provide casing support and protection while secondary cementing is performed when cement is injected into specific locations for reasons such as well repair or well abandonment. (Hunter *et al*., 2007; Piklowska, 2017). For a successful well cementing operation, the water-to-cement ratio must be adequate for the local conditions, the fluid time must be sufficient for cement placement, and the cement slurry must be able to achieve enough strength quickly to ensure a good bond between the casing and the formation. It is important to note that if any of the requirements are not satisfied, there can be blowout with potentially catastrophic consequences, loss of hydrocarbon or injection fluids, contamination of aquifers and corrosion of the casing (Agbasimalo, 2012). The quality and durability of the cement sheath are crucial for the integrity and safety of the oil well as well as the production and recovery of hydrocarbons.

However, there are several environmental concerns associated with the production of Portland cement. Specifically, the production of cement is an energy intensive operation that tends to release significant amount of carbon dioxide (CO_2) and other greenhouse gases into the environment which contributes to climate change (Lüthi *et al*., 2008; Gupta *et al*., 2018). It is estimated that the production of Portland cement is responsible for about 8 % of the total global CO_2 emissions (Ellis et *al*., 2020).

Furthermore, the effectiveness of locally manufactured Portland cement for oil well operation has been studied. A comparative study of local cement in Ghana and imported Class G cement were observed for the purpose of oil well cementing by Broni-Bediako *et al*. (2015). It was identified that the local cement sourced from Ghana that was purposefully manufactured for construction purposes failed to meet the compressive strength and thickening time requirement for an oil well cement slurry sample. Based on the inability of local cement in meeting the physical properties requirement for a successful oil well cementing operation, few studies have focused on the approach of improving the performance of locally manufactured cement. An attempt was made by Broni-Bediako and Amorin (2018) to incorporate universal cement system (UCS) as an additive to address the shortcomings of local Portland cement.

In recent years, there has been growing interest in using pozzolana materials as an alternative zolana is a siliceous or siliceous and aluminous material that can be used as a supplementary cementitious material to Portland cement. Studies have indicated that when pozzolana is used in combination with Portland cement for construction, it improves the strength, durability, workability of concrete and reduces the carbon footprint of cement production (Eshun *et al*., 2018). This is due to pozzolana's ability to react with calcium hydroxide in the presence of water to generate additional cementitious compounds that improves the strength of the concrete structure and reduces porosity. It is important to note that the estimated amount of pozzolana clay deposits in Ghana varies depending on the source, but some studies suggest that the total resources could be about five hundred million of metric tonnes (Bediako and Valentini, 2022; Asamoah *et al*., 2018).

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Fly ash, blast furnace slag, and silica fumes are some of the commonly investigated pozzolanic materials for oil well cementing. A mixture of these materials with sodium or potassium hydroxide and sodium silicate can produce a binder that has optimized mechanical properties for plugging or abandoning a well. Studies by Ahdaya and Imqam (2019), Jiapei *et al*. (2018), Salehi *et al*. (2016), Mahmoud *et al*. (2014), Davidovit (1994), and others have shown that this alternative binder has potential as a replacement for Portland cement in oil well cementing operations.

In addition to the aforementioned materials, researchers have explored other alternative cementitious materials for oil well cementing. Rice husk, for instance, has been studied by Soares *et al*. (2015) and *Rita et al*. (2018) as an additive to improve the mechanical properties of oil well cement matrices. Another study by Novriansyah *et al*. (2016) investigated the effect of activated charcoal obtained from palm kernel shells on the strength development of a cement-nanosilica-charcoal mix. The study found that the addition of activated charcoal significantly increased the compressive strength of the cement mix, with the optimum percentage of charcoal being 5 % by weight of cement. The study also found that the use of nanosilica further enhanced the strength development, with the optimum percentage of nanosilica being 2 % by weight of cement. These results suggest that activated charcoal obtained from palm kernel shells has the potential to improve the strength and durability of Portland cement.

Calcined saudi calcium bentonite has also been proposed as a supplementary cementitious material for oil well cementing by Adjei *et al*. (2021). In their study, they found that this material has excellent binding capacity and can improve the mechanical properties of cement. Similarly, Ledesma et al. (2020) studied the performance of cement systems with zeolite and fly ash as additives for minimizing the degradation effect of CO_2 on carbon capture and storage wells. The results suggest that the use of zeolite and fly ash as additives can improve the mechanical properties and durability of Portland cement. Bechar and Zerrouki (2018) studied the effect of Algerian natural pozzolana on fresh and hardened oil well cement slurry. It was discovered that the use of this material significantly improved the mechanical properties of the cement slurry, making it more durable and resistant to degradation. Finally, Larki et al. (2019) and Adjei et al. (2020) further incorporated pozzolanic material into Class G cement to successfully formulate a lightweight oil cement slurry.

Presently, there is little or no study that has examined the effect of the partial replacement of local Portland cement with pozzolana from Ghana for well cementing operation. Therefore, the purpose of this study is to investigate for the first time the physical and rheological improvement when natural pozzolana from Ghana is added to locally manufactured Portland cement as a sustainable oil well cementing alternative. Therefore, this study presents a unique contribution to the field of well cementing and provides a sustainable solution for the oil and gas industry in Ghana.

Methods and Materials

50 kg bag of EN 197-1 compliant Portland cement with a class rating of 42.5N was obtained from the local market. The cement is manufactured by the Ghana Cement Company Limited (GHACEM). Class 42.5 is a designation for a higher strength type of Portland cement that is typically used in high-strength concrete applications. The local Portland cement was mixed with natural pozzolana obtained from the Building and Road Research Institute (BRRI) of the Council for Scientific and Industrial Research (CSIR) in Ghana at varying weight percent. The chemical composition of local Portland and pozzolana has been compared in Bediako et al. (2011) and summarized in Table 1. The ratio of water used to mix the cement was 0.46 for Class A cement according to API-RP-10B (2005) and API-RP (2013). The amount of pozzolan, local Portland cement and water used for the present study is summarised in Table 2.

Table 1 Chemical composition of local Portland cement and pozzolana (Bediako *et al*., 2011)

Major oxides	Concentration (wt %)	
	Local Portland	Pozzolana
SiO_3	19.7	61.89
Al_2O_3	5	13.51
Fe_2O_3	3.16	5.84
MgO	1.75	1.74
CaO	63.03	0.21
Na_2O	0.2	0.14
K_2O	0.16	1.07
SO_3	2.8	0.14

Table 2 Composition of the cement slurry samples

Sample	Local Portland cement		Natural pozzolana		Water mix
	%	grams	%	grams	ml
A	100	776	0	0	356.96
B	95	737.2	5	38.8	353.85
C	90	698.4	10	77.6	350.75
D	80	620.8	20	155.2	344.54
E	70	543.2	30	232.8	338.38

Experimental procedure

Laboratory experiment of compressive strength, free fluid, plastic viscosity and yield point were conducted on the cement slurry samples of pozzolana and local Portland cement. The density of the fomulated cement slurries were measured using the mud balance. At bottom hole circulating temperature of 65 °C, the rheological characteristics of the prepared cement slurries were measured between 300 and 3 rpm using Equations (1) and (2).

$$\text{Plastic Viscosity } (PV) = 1.5\left(\theta 300 - \theta 100\right) \quad (1)$$

$$\text{Yield Point } (YP) = \theta 300 - PV \quad (2)$$

Where $\theta 300$ is the dial readings at 300 revolution per minute and $\theta 100$ is the dial readings at 100 revolution per minute.

The rheology of the cement slurries was tested using a rheometer. The procedure involved placing the sample in a cup and tilting the rheometer's top housing, followed by immersing the rotor sleeve to a scribed line and tightening the leg lock knot. The sample was stirred for 15 seconds at 600 rpm, and readings were recorded from 600 rpm to 3 rpm at steady indicator dial readings. The experiment was carried out at a bottomhole circulating temperature of 65 °C.

A free fluid test is intended to help determine how much free fluid will accumulate on top of cement slurry between the time it is applied and when it gels and sets up. Therefore, the cement slurry samples were poured into a conical flask and sealed for two hours to identify any fluid on top of the slurry column. The percentage of free fluid was evaluated using Equation (3).

$$\text{Free fluid } (\%) = \frac{(ml \text{ of free fluid}) \times 100}{\text{mass of cement slurry}} \quad (3)$$

A compressive strength test was conducted on the cement samples to examine their resistance to deformation when subjected to loading. The slurry samples were poured into four-square-inch moulds and puddled 27 times per specimen. The specimens were then cured in a Thermo Scientific Precision 180 Series Water Bath at bottomhole static temperature of 150 °F (65 °C) at a loading rate of 0.01 kN/s. The samples were allowed to cure for eight hours, then cooled and crushed with a Carver Model 3851 Manual Press to obtain compressive strength.

Results and Discussion

The results obtained from the rheometer are summarised in Table 3. The rheological properties of plastic viscosity and yield point were then estimated from the dial readings. From Table 3, it was observed that increasing the weight percent of pozzolana in the Portland and pozzolana cement mix slightly reduced the density of the cement slurry. The density of the cement slurry should be between 14.7 to 16 ppg according to Ahmed et al. (2023) and the formulated density all meet the requirement.

Table 3 Rheometer dial readings of the cement slurry samples

Sample	A	B	C	D	E
% of Portland	100	95	90	80	70
% of pozzolana	0	5	10	20	30
Density (ppg)	15.4	15.3	15.3	15.3	15.2
Dial reading at 300 rpm	231	191	183	186	170
Dial reading at 200 rpm	190	190	170	176	155
Dial reading at 100 rpm	135	135	143	150	120
Dial reading at 6 rpm	25	25	74	85	26
Dial reading at 3 rpm	17	17	59	60	20

Plastic viscosity

The plastic viscosity of the cement slurry is an important parameter to monitor and control, as it affects the pumping and placement of the slurry in the wellbore by its resistance to flow at specific shear rate. According to Abbas *et al.* (2014), Igbani *et al.* (2020) and Zahid *et a*l. (2018), the plastic viscosity of slurry must be less than 100 cP, which is desirable to keep cement slurry flowing and pumpable at 65 °C. It was identified in Fig. 1 that the local Portland cement had plastic viscosity value of 144 cp, which makes its slurry difficult to keep flowing and pumpable at 65 °C. By replacing only 5 % of the local Portland with pozzolana in the cement slurry, the plastic viscosity significantly reduced to 84 cp as indicated in Fig. 1. This represents a 41.7 % improvement of the plastic viscosity of the local Portland cement.

A further decrease in the plastic viscosity was observed when 10 % of the Portland cement was substituted with pozzolana. From Fig. 1, the plastic viscosity for Sample C was 60 cp accounting for a 58.33 % reduction when 10 % of the slurry was composed of pozzolana. The highest improvement was seen when 20 % of the local Portland was replaced by pozzolana in Sample D. Sample D had a plastic viscosity of 54 cp as indicated in Fig. 1, representing 62.5 % of improvement. However, increasing the weight percent of pozzolana in the mixture to 30 % only reduced the plastic viscosity to 75 cp, implying there is an optimum mix ratio beyond which a reduction in plastic viscosity will no longer be achieved (Fig. 1). The reason why increasing the weight percent of pozzolana in the mixture to 30 % only reduced the plastic viscosity to 75 cp is that there is an optimum mix ratio beyond which a reduction in plastic viscosity will no longer be achieved. This is because the pozzolana particles have a smaller size than Portland cement particles and can fill the voids between the larger cement particles. However, when the weight percent of pozzolana is too high, it can cause an increase in the water demand of the mixture and lead to an increase in plastic viscosity (Lui *et al.*, 2021).

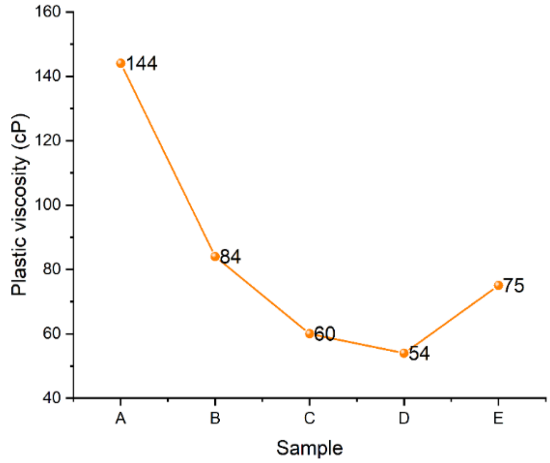

Figure 1 Plastic viscosity of cement slurries

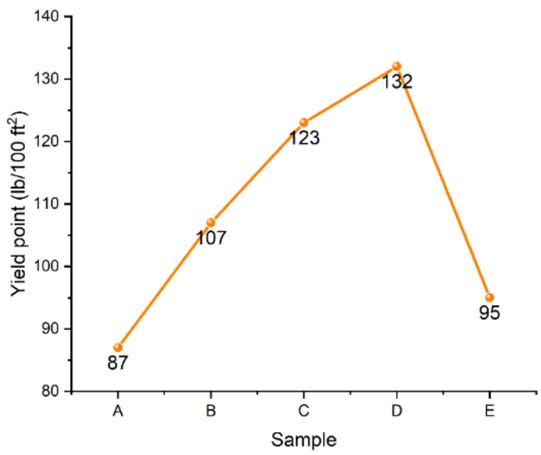

Figure 2 Yield point of cement slurries

Yield point

A yield point of at least 15 lb/100 ft^2 is typically required for a cement slurry to be effective in oil and gas well cementing operations (Salehi and Paiaman, 2009; Crook et al., 1987). The yield point is the minimum shear stress or force required to initiate and maintain flow of the slurry, and a value of 15 lb/100 ft^2 is generally considered sufficient to enable the slurry to flow effectively through the wellbore and achieve good coverage and placement. Based on this understanding, all the formulated slurries achieved a yield point value of more than 15 lb/100 ft^2. From Fig. 2, Sample A had 87 lb/100 ft^2 while substituting 5 % weight fraction of pozzolana in the slurry saw a significant increase in the yield point value to 107 lb/100 ft^2.

A yield point of 123 lb/100 ft^2 was experienced when 10 % of the Portland cement was replaced with pozzolana while the highest yield point of 132 lb/100 ft^2 was recorded for the mixture of 80 % local Portland cement and 20 % pozzolana. Furthermore, it was identified in Sample E, which consisted of 30 weight percent of pozzolana in the slurry, that 95 lb/100 ft^2 was the obtained yield point value. Generally, the increase in the yield point of the formulated pozzolana and Portland cement mix is due to the finely sorted and appropriate distribution of the particles of pozzolana which prevent the settling of cement particles and improves the packing efficiency (Grzeszczyk and Lipowski, 1997; Bechar and Zerrouki, 2018). However, the increase in the yield point was not achieved at a 30 % composition of pozzolana. When the pozzolana content in the slurry was increased to 30 weight percent, it resulted in a decline of the yield point owing to a corresponding rise in the slurry's water demand.

Free fluid

Free fluid is an indication of the any excess or unbound liquid that is present in a cement slurry. Therefore, it is recommended that free fluid must be minimal in a formulated cement slurry. Specifically, the maximum required free fluid value recommended for any slurry should not exceed 2 % in order to prevent poor bonding and lost circulation challenges (Normann, 2017) .

It was observed that the free fluid value for local Portland cement was 0.715 % which is suitable for well cementing operation. However, the partial replacement of the local Portland cement with the natural pozzolana recorded a further decrease in the percent free fluid. According to Fig. 3, a partial replacement with 5 % of pozzolana reduced the free fluid value to 0.237 %, which represents 66.9 % improvement. A further partial replacement of the local Portland cement with 10 weight percent of the pozzolana observed a free fluid value of 0.216 %. This means that the free fluid parameter of local Portland cement can be improved at a rate of 69.8 % by substituting 10 weight percent of the slurry with pozzolana (Fig. 3). When 20 % of the slurry was replaced with pozzolana, it was further observed that the free fluid of the formulated slurry decreased to 0.126 %. It can be deduced that a free fluid value of 0.126 % as shown in Fig. 3 represent an improvement rate of 82.38 %. The lowest free fluid was identified when 30 % of the local Portland cement was substituted with pozzolana during the cement slurry formation. In Fig 3, it was identified that the free fluid for Sample C was 0.11 %, which accounts for 84.6 % enhancement of the local Portland as a substitute for oil well cementing purposes.

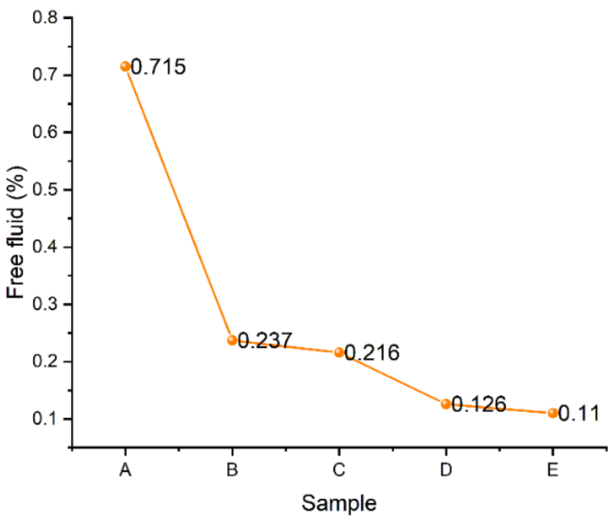

Figure 3 Free fluid of cement slurries

The general improvement of the pozzolana Portland cement can be based on the reaction of pozzolana with the calcium hydroxide produced during the hydration of Portland cement to form calcium silicate hydrate (C-S-H), which is an additional cementitious compound. This leads to a reduction in the porosity and permeability of the hardened cement, which can improve its resistance to fluid migration.

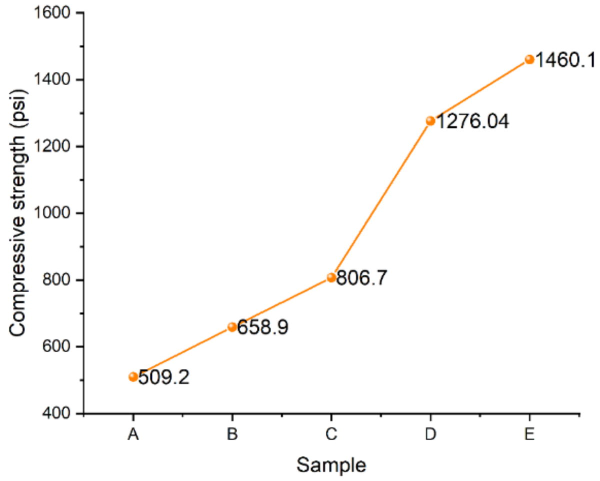

Figure 4 Compressive strength of cement slurries

Compressive strength

The compressive strength for the formulated Portland cement and pozzolana mix has been presented in Fig. 4. Compressive strength is an important property of the cementing material as it indicates its ability to hold the formation in place and maintain well integrity. General industry specification states that 500 psi of compressive strength is required to efficiently stabilize the pipe in the borehole and provide enough resilience for shock loading of drilling operations (Sabins and Sutton, 1986; Al-Yami *et al*, 2008). From the results, all the formulated cement slurry met this standard. The local Portland cement slurry had a compressive strength value of 509.2 psi.

It was observed that the compressive strength was increased to 658.9 psi when 5 % of the Portland cement was substituted with pozzolana (Fig. 4). This represents an improvement of 30 % in compressive strength for local Portland cement. Similarly, a further increase in the compressive strength to 806.7 psi was observed as the weight of the substituting pozzolana is increased to 10 %. This means that the compressive strength of the local Portland cement was enhanced at a rate of 59.4 %. Sample D, which is composed of 80 % local Portland and 20 % pozzolana, obtained 1276.04 psi as its compressive strength. The result depicts an improvement in compressive strength of about 152 % for local Portland cement. Finally, the highest improvement in compressive strength was observed after 30 % of the local Portland was replaced with natural pozzolana in Sample E. From Fig. 4, Sample E recorded a compressive strength value of 1460.1 psi, which shows an improvement of 188.5 % over the local Portland cement.

The continuous increase in the compressive strength as the weight of the substituting pozzolana increases can be attributed to the reaction of the silica in the pozzolana with calcium hydroxide in Portland cement to produce additional calcium silicate hydrate (C-S-H) gel, which is a key component of the cementitious matrix, and it conforms to previous results from Eshun *et al*. (2018), Çelik *et al*. (2008), Celik *et al*. (2014), Antiohos *et al*. (2005), and Bechar and Zerrouki (2018).

Conclusion

The present study investigated the rheological and physical improvement of locally manufactured Portland cement by partially substituting with natural pozzolana clay of up to 30 weight percent. The results showed that the partial replacement of local Portland cement with natural pozzolana can improve the plastic viscosity, yield point, free fluid and compressive strength of local Portland cement. A reduction in plastic viscosity was observed as the weight percent of pozzolana increased, with the highest improvement seen when 20 % of the local Portland cement was replaced. However, beyond a certain mix ratio, a reduction in plastic viscosity was no longer achieved due to increased water demand.

The yield point was found to increase with the addition of pozzolana, but again, the optimum mix ratio was at 20 % pozzolana, and beyond this point, water demand increased, leading to a reduction in yield point. The free fluid of the local Portland was reduced with the addition of pozzolana, and the best improvement of 85 % was seen with a 30 % replacement of local Portland cement with pozzolana. Finally, the compressive strength of the local Portland was significantly increased as the pozzolana was increased in the mix slurry. The highest improvement of 188.5 % in compressive strength was observed at 30 % substitution with pozzolana. These results indicate that partial replacement with natural pozzolana can be an effective and sustainable strategy for improving the properties of local Portland cement for well cementing operations.

Conflict of Interest Declarations

The authors declare there is no competing interest.

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