Case study

Analysis of co-fired clay and palm kernel shells as a cementitious material in Ghana

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A B S T R A C T

The treatment of clay through a calcination process at high temperatures have been the usual and a common means of producing clay pozzolan as a supplementary cementitious material. However incorporating waste biomass as a component material in clay is very uncommon. This work analyzed the use of palm kernel shells as a component material in clay and were calcined at a high temperature of $800\,^\circ$C. The palm kernel shells were used to replace clay at 10%, 20% and 30% by weight. Strength activity index prescribed by ASTM C311 was used to determine the maximum mixture proportion between calcined clay and palm kernel shells. The calcined clay and palm kernel shell mixtures that gave the maximum strength were subjected to an incremental replacement dosage of Portland cement between 10% and 40% by weight. Test results indicated that the maximum strength mixture proportion between clay and palm kernel shells was obtained at 20% replacement of clay. Moreover the maximum value that showed a better strength performance through the incremental replacement by the calcined material was also at 20% Portland cement replacement. The study recommended the use of palm kernel shells to a limit of 20% clay replacement. The is because at higher content of palm kernel shells in clay calcined at a high temperature, more unreactive crystalline phases are formed that inhibit reactivity of pozzolanic active phases. The use of 20 wt.% of palm kernel shells in clay to produce a supplementary cementitious material provides a sustainable means of waste disposal via construction application.

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1. Introduction

The construction industry of today has well embraced the use of supplementary cementitious materials (SCMs) either in blended cement formation or added separately to concrete mix as a mineral admixture [12]. Using SCMs in concrete formulation is widely known to improve cement based products performance through the filler and pozzolanic effect. The filler effect leads to the generation of portlandite (CH) at the early hydration of cement whereas pozzolanic effect is the reaction that occurs between portlandite generated from cement and the silicate and aluminate phases in SCMs leading to the formation of secondary products such as calcium silicate, calcium aluminate and calcium aluminosilicate hydrates that

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enhance strength properties. Malhotra and Mehta [13] have reported that SCMs utilization provides a sustainable way of disposing waste-byproducts via concrete applications. The application of SCMs in concrete could replace between 20 and 30% of Portland cement and this leads to a significant reduction of harmful anthropogenic gases such as carbon dioxide, NOx and SO_3 produced from the production of cement [14]. It is stated in the work of Yang [15] that one most practical means of producing economical concrete is through the use of SCMs. The most widely used SCMs are industrial by-products which include slag from pig iron production, fly ash from coal combustion plants, and silica fume form ferrous producing plants [12]. Metakaolin produced from high purity kaolin clays at temperatures from 600 to 900 °C are recently introduced SCMs into the world of concrete formation [8,10].

Research findings on the use of supplementary cementitious materials such as calcined kaolinitic clays and heat treated palm kernel shells as possible materials as SCMs have been well documented [8,10,16,6,7]. For palm kernel shells, their ashes are usually obtained from boilers and electricity generation plants or industries [17,6]. These industries operate at higher temperatures ranging from 700 to 900 °C to generate waste palm fuel ashes. However, from extensive search of literature, research regarding co-fired clay and palm kernel shells is very insufficient.

In Ghana, palm kernel shells are obtained from palm oil producers. Until recently, palm kernel shells were perceived as waste material having problems with their disposal especially in palm oil producing areas. Currently, palm kernel shells are used as a source of fuel for many companies in various industrial productions. The waste products have now been identified as a useful energy source, however the waste generation from oil producers far outweighs its consumption by industries. There are huge tonnages of these palm kernel shell wastes dumped on sites around many of the palm oil producing areas in the country. There is the need for some form of attention on the disposal problems regarding the shells in palm oil producing areas of Ghana.

There has been an earlier investigation by Atiemo [1] that has shown that there exists a potential use of the material as a silica component and fuel source in clay pozzolana production. Silicate source from ashes of palm kernel shells is observed as an added advantage to the reactive pozzolanic phases in calcined clays. Production of clay pozzolana in Ghana by CSIR-Building and Road Research Institute consumes palm kernel shells. However, there is a major gap with regard to the optimum use of palm kernel shells in the calcination of clay. Reactive pozzolanic phases are very much dependent on the temperature of calcination. Most biomass materials attain more reactive pozzolanic phases at temperatures below 800 °C. In this work, the main objective was to investigate the contributions of palm kernel shells calcined at the clay calcination temperature of 800 °C. Already Bediako [9] has shown that the optimum calcination temperature for the clay used was at 800 °C. The main hypothesis for this work is this "Does the content of palm kernel shells incorporated in clay calcined at 800 °C affect the calcined material reactivity with Portland cement?"

2. Materials and methods

2.1. Materials

The materials that were used for the study included palm kernel shells, clay, Portland cement, sand, a chemical admixture and potable water. The palm kernel shells were obtained from the Konongo area in the Ashanti region of Ghana. The clay used for the study was obtained from Nyamebekyere, a small farming village in the Ashanti region of Ghana. Ordinary Portland cement used was obtained from Ash grove, Chenuate, Kansas-United States. A high range water reducer (HRWR) of polycarboxylate origin was used as a superplasticizer. The sand used conformed to ASTM C778 and the potable water used was from the taps of University of Missouri- Kansas City (UMKC). Table 1 shows the Portland cement properties obtained from Ash grove.

2.2. Methods

2.2.1. Clay and palm kernel shells mixture proportioning and pellet formation

A sample of the clay obtained from the field was air dried for about 3 days and were ground into smaller unspecified sizes. The palm kernel shells were preconditioned by washing them in a barrel and allowing them to dry for 48 h. The dried palm kernel shells were then ground with a hammer mill into smaller particles. Figs. 1 and 2 shows sample grounded clay and palm kernel shells. The proportioning of the clay and palm kernel shells were done based on the bulk densities of the two materials. The percentage of the constituents was by weight. The bulk densities determined for clay and palm kernel shell were 1.32 and 0.9 respectively. Table 2 shows the mixture name and percentage contents of clay and palm kernel shells. After proportioning, small round pellets were formed. The pellets formation was performed in a rotating cylindrical bucket operated by a low speed motor. During rotation, potable water was sprayed on the mixture leading to the formation of pellets or nodules which were further dried in an open space.

2.2.2. Calcination process, milling and sieving

Dried pellets were calcined in an electric furnace (Barnstead Thermolyne 6000 furnace) which was operated at 800 °C for a period of three hours. During the calcination process, pellets samples were put in a ceramic bowl and placed in the furnace. After the three-hour period, the furnace was switched off and the bowl and its contents allowed to cool down in the furnace

Table 1
Properties of Portland cement.

Property	ASTM Type I/II
Physical	
Fineness (m^2/kg)	401.7
Specific gravity	3.13
Chemical	
SiO_2 (%)	20.49
Al_2O_3 (%)	4.26
Fe_2O_3 (%)	3.14
CaO (%)	63.48
MgO (%)	2.11
SO_3 (%)	2.9
$Na_2O + K_2O$ (%)	0.49
LOI (%)	2.2
Mineralogical	
C_3S (%)	56
C_2S (%)	15
C_3A (%)	6
C_4AF (%)	9

for about 24 h. After cooling, the calcined pellets were removed from the bowl and pulverized into a powder material using a laboratory milling equipment. Pulverized materials were then sieved through the 75 μm sieve size using a sieve shaker.

2.2.3. XRD determination

The materials, clay and palm kernel shells were separately analyzed to determine their mineralogical compositions when calcined at 800 °C. Powder X-Ray diffraction data was obtained on a PANalytical X'Pert Pro utilizing copper K-Alpha (wavelength = 1.54056) radiation and operating at 45Kv and 40 mA.

2.2.4. Mortar specimen preparation, curing and testing

Mortar specimens were prepared in accordance with ASTM C109 [5] for both strength activity index and compressive strength test determination. The strength activity index was determined in accordance with ASTM C311 [2]. This standard specify Portland cement replacement of 20% by a pozzolan. The use of the superplasticizer in the mortar formulation was to achieve the desire flow and this was performed in accordance with ASTM C1437 [4]. The curing of the mortar specimens was performed in a lime saturated water bath at temperature of 23 ± 2 °C. For strength activity index determination, mortar specimens were tested at 7 and 28 days whereas those for compressive strength were tested at 3, 7 and 28 days. A total of six and nine mortar specimens were used for the strength activity and compressive strength determinations respectively.

Fig. 1. Milled clay powder.

Fig. 2. Ground palm kernel shells.

Table 2
Mixture name and content of clay and palm kernel shells.

Mix Name	Content (%)	
	Clay powder	Palm kernel shells
PK0	100	0
PK1	90	10
PK2	80	20
PK3	70	30

3. Results and discussions

3.1. X-ray diffraction

Figs. 3 and 4 show the XRD patterns for palm kernel shells and clay calcined at 800 °C respectively. The main peaks that were present at that temperature for palm kernel ashes were muscovite (M), quartz (Q) and hematite (H). However the peaks relating to quartz showed a high diffused pattern whereas muscovite and hematite showed a lower diffuse intensities. For the calcined clay, two main peaks occurred, quartz and muscovite with quartz given a high intensity.
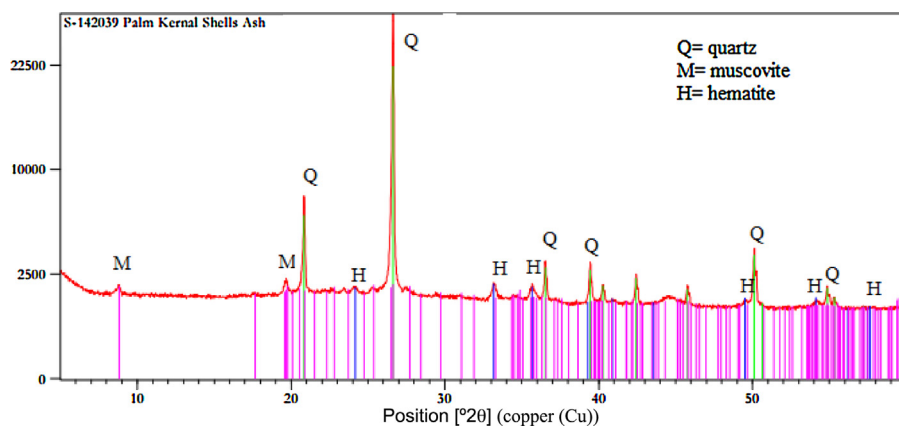

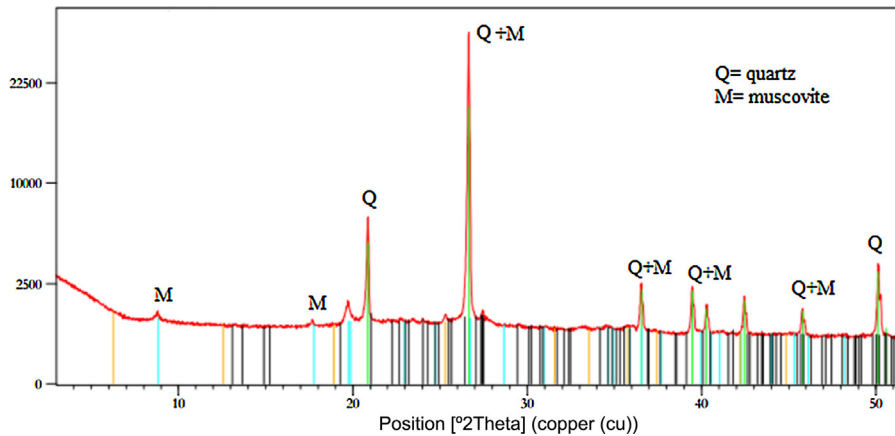**Fig. 3.** Palm kernel shells calcined at 800 °C.

Fig. 4. Clay calcined at 800 °C.

The two materials calcined at 800 °C showed a predominantly quartz phases, an indication of the presence of silicate content present in the two materials. Though there were siliceous materials occurring in the calcined materials yet their reactivity with Portland at this stage could not be confirmed.

3.2. Strength activity index

Table 3 presents the mortar mixture proportions used to determine the strength activity index of the calcined materials. The HRWR content in the mixture indicated that higher content of palm kernel shells (PK3) containing 30% of shells in clay demanded less of the water-reducing agent than the PK2 and PK1 which contained 20 and 10% of palm kernel shells in clay mixture respectively (see Table 2). The flow properties attained for all the mortar mixtures were within the specified range of between 105% and 115% as provided by the ASTM C1437 [4].

Fig. 5 shows the strength activity index of the calcined materials. Calcined materials containing 10, 20 and 30 wt.% of the shells, labelled as PK1, PK2 and PK3 were compared to the control labelled as PK0. The figure showed that all the mortar mixtures met the ASTM C618 [2] specification for strength activity index at 7 and 28 days. The standard specifies that at 7 and 28 days, the strength activity of mortars must be more than 75%. From the figure clay material that was replaced by 20 wt.% of ground palm kernel shells (PK2) and calcined at 800 °C attained the maximum strength at 7 and 28 days compared to the control mortar (PK0) and the other mortars, PK1 and PK3. The reason for the strength activity performance of PK2 could be attributed to higher pozzolanic active phases in the calcined material. Beyond 20% palm kernel shells in calcined clay strength properties declined. The decline in strength may be attributed to the many unreactive phases such as muscovite and hematite that were introduced to calcined clay from higher content of the shells.

3.3. Compressive strength

Fig. 6 shows the compressive strength of mortars prepared with the calcined material containing 20 wt.% of palm kernel shells (PK2) which gave the maximum strength activity index. The calcined material was used to replace cement at 10, 20, 30 and 40 wt.% and labelled as 10PK2, 20PK2, 30PK2and 40PK2 respectively. At early 3 days' strength test, 10PK2 attained the maximum strength. However the 7 and 28 days strength of 10PK2 and 20PK2 were very similar though each of them had strength values surpassing the control mortar. A student *t*-test performed between 10PK2 and 20PK2 showed that there was no difference between the two strength values which is indicated from the predictive (P) values (see Table 4).

20PK2 was the suitable choice as the appropriate ordinary Portland cement replacement material since higher content of calcined material usage affect cement cost positively. The achievement of maximum strength at 20% cement replacement meant that dosage was just enough to convert cement hydration product i.e calcium hydroxide into calcium silicate and

Table 3
Mortar mixture proportions.

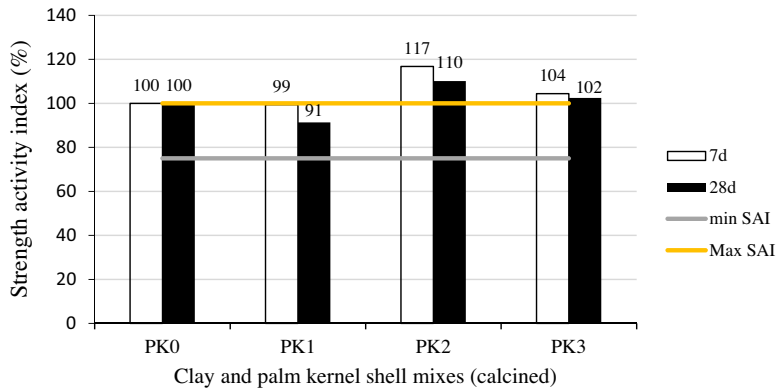| Mix Name	Mass (g)			water/binder (w/b)	HRWR (%)	Flow (%)
	OPC	Pozzolana	Water			
PK0	500	0	242	0.485	0	107
PK1	400	100	242	0.485	0.3	107
PK2	400	100	242	0.485	0.3	111
PK3	400	100	242	0.485	0.2	107

Fig. 5. Strength activity index of calcined clay and palm kernel shell mixtures.
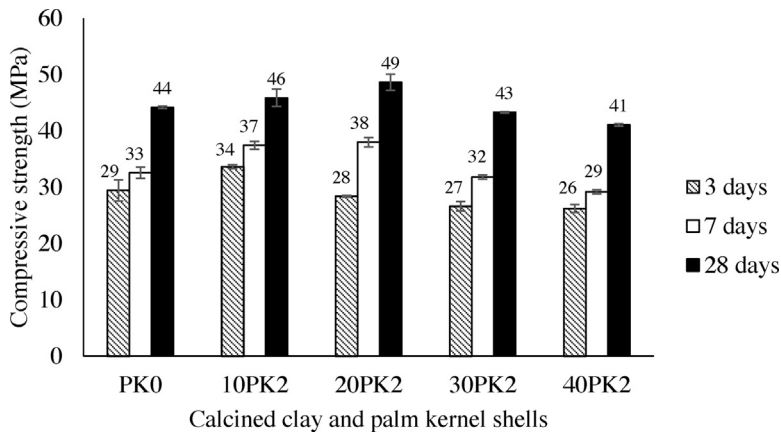

Fig. 6. Compressive strength of calcined clay and palm kernel shells.

aluminate hydrates which enhance strength properties [11]. Beyond 20% of cement replacement, strength of mortars decreased. This could be explained that beyond 20%, the calcined materials behaved as inert fillers with little contribution to strength enhancement.

4. Conclusions and recommendations

4.1. Conclusions

The following conclusions could be drawn from the study

Table 4
t-Test: Two-Sample Assuming Unequal Variances.

	10PK2	20PK2
Mean	38.96	38.33
Variance	39.15	102.58
Observations	3	3
Hypothesized Mean Difference	0	
df	3	
t Stat	0.09	
P(T < = t) one-tail	0.47	
t Critical one-tail	2.35	
P(T < = t) two-tail	0.93	
t Critical two-tail	3.18	

1. Palm kernel shells calcined at 800 °C yielded unreactive crystalline phases that could contribute to less active pozzolanic phases in calcined clay.
2. The optimum content of palm kernel shells in clay that yielded high pozzolanic active phases after calcination was at 20%. This shows that the active pozzolanic phases developed between clay and palm kernel shell mixtures depend on the quantity of palm kernel shells incorporated in the clay.
3. The maximum compressive strength of calcined clay and palm kernel shell mixture used to replace ordinary Portland cement was attained at 20%.

4.2. Recommendations

The following recommendations were made from the study

1. A further study on the hydration kinetics between the calcined material and Portland.
2. There is the need for durability and sustainability analysis on the calcined material.

Acknowledgement

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