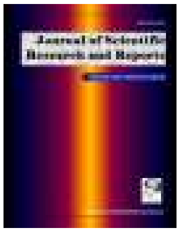

Journal of Scientific Research & Reports
3(23): 3018-3030, 2014; Article no. JSRR.2014.23.008
ISSN: 2320–0227

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Influence of Higher Volumes of Clay Pozzolana Replacement Levels on Some Technical Properties of Cement Pastes and Mortars

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2014/9046
Editor(s):
(1) Shangyao Yan, Convener of Civil and Hydraulic Engr Program, NSC, National Central University, Taiwan.
Reviewers:
(1) Anonymous, Institute for Construction Sciences Eduardo Torroja, Spain.
(2) Anonymous, Minia University, Egypt.
(3) Anonymous, Phranakhon Rajabhat University, Thailand.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=664&id=22&aid=6138

Short Research Article

Received 15th January 2014
Accepted 26th August 2014
Published 16th September 2014

ABSTRACT

Most of the investigations on the utilization of clay pozzolana are limited to about 30% of the material consideration in Portland cement. In this study clay pozzolana was used to replace cement between 30% and 50%. Clay pozzolana was analyzed to determine their chemical and mineralogical composition. Both binder paste and mortar were formulated and results compared to unblended cement system. Some selected technical properties such as water demand, setting times and strength determination were performed. The work also determined the economic benefits of the optimum pozzolana mortars and compared with the unblended mortar mix. Test results indicated that cement-pozzolana system demanded high water, caused an extended setting times as well as strength reduction. Although the strength values were reduced, optimum mix proportions were very good for the formulation of ASTM type M and type S mortar class.

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Keywords: Clay pozzolana; binder paste; mortar class; water demand; setting time; strength.

1. INTRODUCTION

In recent times, Ghana, a West African nation and a developing country have being undergoing massive infrastructural development. These developments include asphaltic construction, residential buildings, hospitals, schools and other social amenities. The country Ghana is a nation of about 24 million people and the authors think that not so much is heard about this country's geographical position hence presents the African map to show its location in Fig. 1. The country lies just above the equator and is on the Greenwich meridian line which passes through the seaport of Tema, about 24 km to the east of the capital city, Accra.

Fig. 1. African map showing the position of Ghana

Among all the numerous constructions on-going, Portland cement remains one of the most important ingredients since it is the principal binding material for concrete and mortar formulation. The fast rate of infrastructural development has led to an annual increase in Portland cement consumption. The Ghanaian Ministry of Trade and Industry has indicated that cement consumption in the country in 2002 rose from approximately 2.2 million tonnes to 2.7 million tonnes in 2006 and then to approximately 3.7 million tonnes in 2011 [1]. This represents a 23% rise between 2002 and 2006 and 37% rise between 2006 and 2011. The consumption of cement is estimated to reach approximately 5.3 million tonnes by 2018, about 43% increase.

In Ghana, the cement industry that helps the construction industry is faced with two main problems. Firstly, the lack of clinker and gypsum producing companies and secondly lack of adequate knowledge on cement alternatives for concrete and mortar formulation. The Ghanaian cement industry depends hugely on imported clinker from Norway in Europe and China in Asia and sometimes from Egypt in Northern Africa. The country has two main clinker processing companies, namely GHACEM limited and West Africa Cement Manufacturers (WACEM) that pulverize the clinker and gypsum into Portland cement. A developing country like Ghana has been spending over $300 million annually as foreign exchange since 2008 to import clinker. Due to this, the construction industry continues to suffer a rising cost of 50 kg bag of cement over the years which have led to a higher cost of construction. The price of cement is also coupled with artificial price adjustments which result from the proximity of cement processing factories to the distribution point. For instance, in Kumasi, the second largest city of Ghana, a 50 kg bag of cement which was $2.30 in 2002 rose to $4.60 in 2006, an increase of 100% and then currently at $12.50 which represent approximately 434% and 172% increase with respect to the years 2002 and 2006. Between 2002 and 2006, the dollar to Ghana cedi equivalence was the same ($1= GH¢1). In view of the aforementioned problems associated to Portland cement, the use of the product does not provide the needed economical benefit to provision of affordable infrastructural development.

Most building professionals lack in-depth knowledge with regards to the performance of cement alternatives. Meanwhile, it has already been documented that the developed countries have successfully used mineral admixtures for the construction of dams, bridges, and residential buildings, etc. Examples of such mineral admixtures are industrial by-products like fly ash, silica fume, slags, oil shale ash and natural pozzolanic materials like ashes from volcanic eruption, calcined clays and even ashes from agricultural waste like rice husk, sugarcane and corn cob [2,3,4,5,6,7,8]. In most of these investigations the use of mineral admixtures as an extension of cement binders has proven to be economical, environmentally and technologically beneficial [9,10].

Earlier investigations by Hammond [11] and Atiemo [12] in Ghana have led to the possibility of pozzolana production from bauxite waste and clays. Both investigations indicated that using either bauxite pozzolana or clay pozzolana to replace 30% of Portland cement could produce cost efficient mortar and concrete without any deficiency. In other investigations, Bediako et al. [9] showed that both type M and type S mortar class could be produced with 30% clay pozzolana. The work further indicated that approximately 25% of the cost could be saved as compared to the plain mortar.

With the introduction of ASTM C1157 [13] which does not limit the amount of mineral admixtures as compared to the existing standards like BS and ASTM C109 [14] which restrict the addition of mineral admixtures to 30%, this study seeks to increase the amount of clay pozzolana inclusion with Portland cement more than 30%.

Clay which serves as the main ingredient for pozzolana production is found to be in abundant in Ghana. Kesse [15] has estimated that about 1392 million tonnes of clay exist untapped within Ghana. The main aim of this study is to investigate some technical properties of cement pastes and mortars containing higher volumes of pozzolana.

2. MATERIALS AND METHODS

2.1 Materials

The materials used for the investigation were Class 32.5R Portland limestone cement (PLC), clay pozzolana, natural silica sand and potable water. Ordinary Portland cement was obtained from Ghana Cement Manufacturers (GHACEM) in Tema, Greater Accra region. The cement conformed to the European standards, EN 197-1 [16]. The mineralogical compositions of class 32.5R Portland cement indicating the presence of cement compounds, C_3S, C_2S, C_3A and C_4AF is shown in Fig. 2. The figure shows a higher presence of C_3S, followed by C_2S with C_3S and C_4AF in a small fraction.

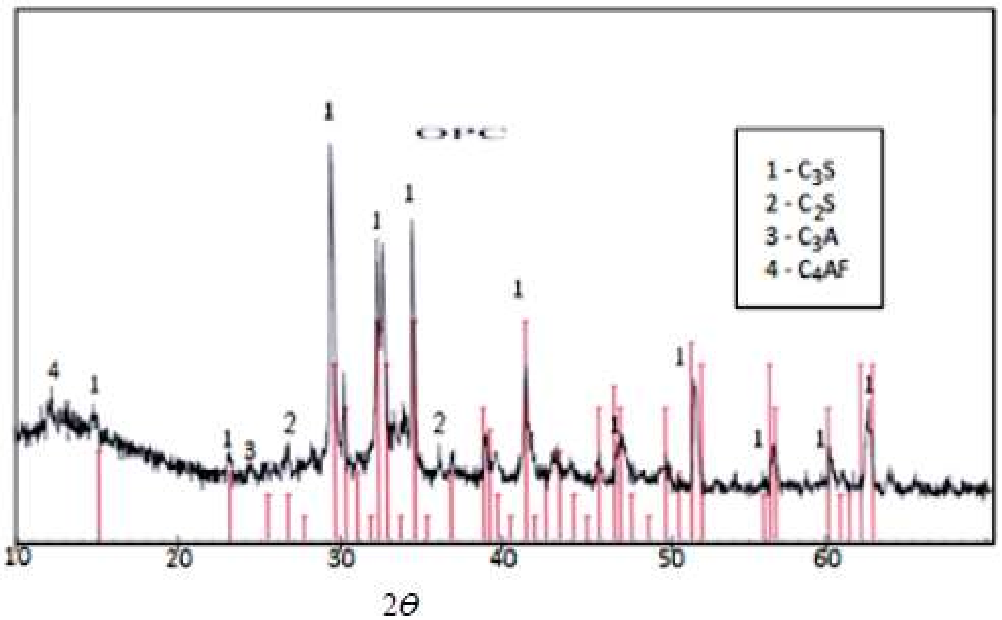

Fig. 2. X-ray diffraction pattern of class 32.5R Portland cement

Clay pozzolana was obtained from the CSIR- Building and Road Research Institute in Kumasi, Ghana. The pozzolana conformed to the type N pozzolan as specified ASTM C618 [17]. The summation of SiO_2, Al_2O_3 and Fe_2O_3 are more than 70%. Table 1 presents the physical, chemical and mineralogical properties present in the Portland cement and clay pozzolana.

The X-ray diffraction of the clay pozzolana calcined at 700^{o}C is also shown in Fig. 3. The figure indicates the presence of crystalline compounds, quartz in a form of an associated material with the clay through natural means or carrying of the clay from the clay site. Natural sand was obtained at Fumesua in the Ashanti region of Ghana. The particle size distribution is presented in Fig. 4.

Table 1. Physical, chemical and mineralogical properties of PLC and CP

Properties	OPC	CP
Physical		
Specific gravity	3.14	2.58
Blaine fineness (m^2/kg)	338	410
% passing 75 (µm)	92	99.6
Chemical		
SiO_2, %	19.7	61.89
Al_2O_3, %	5	13.51
Fe_2O_3, %	3.16	5.84
CaO, %	63.03	0.21
MgO, %	1.75	1.74
K_2O, %	0.16	1.07
Na_2O, %	0.2	0.14
SO_3, %	2.8	0.14
LOI, %	2.58	10
SiO_2+ Al_2O_3+ Fe_2O_3, %	-	81.23
Mineralogical		
C_3S, %	59.6	-
C_2S, %	12.6	-
C_3A, %	7.86	-
C_4AF, %	9.49	-

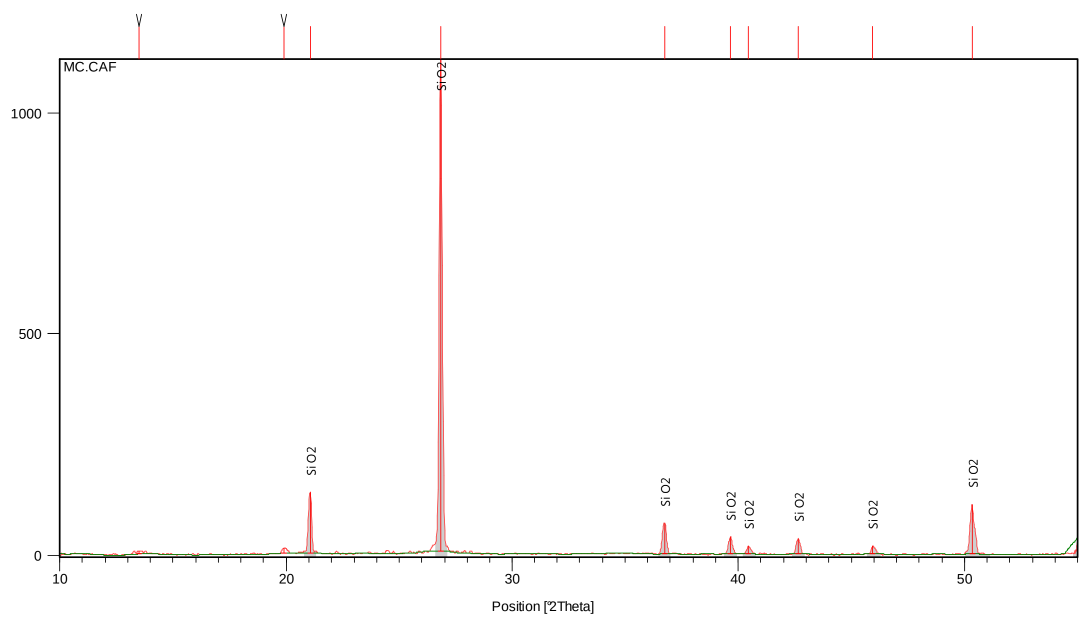

Fig. 3. X-ray diffraction of clay pozzolana

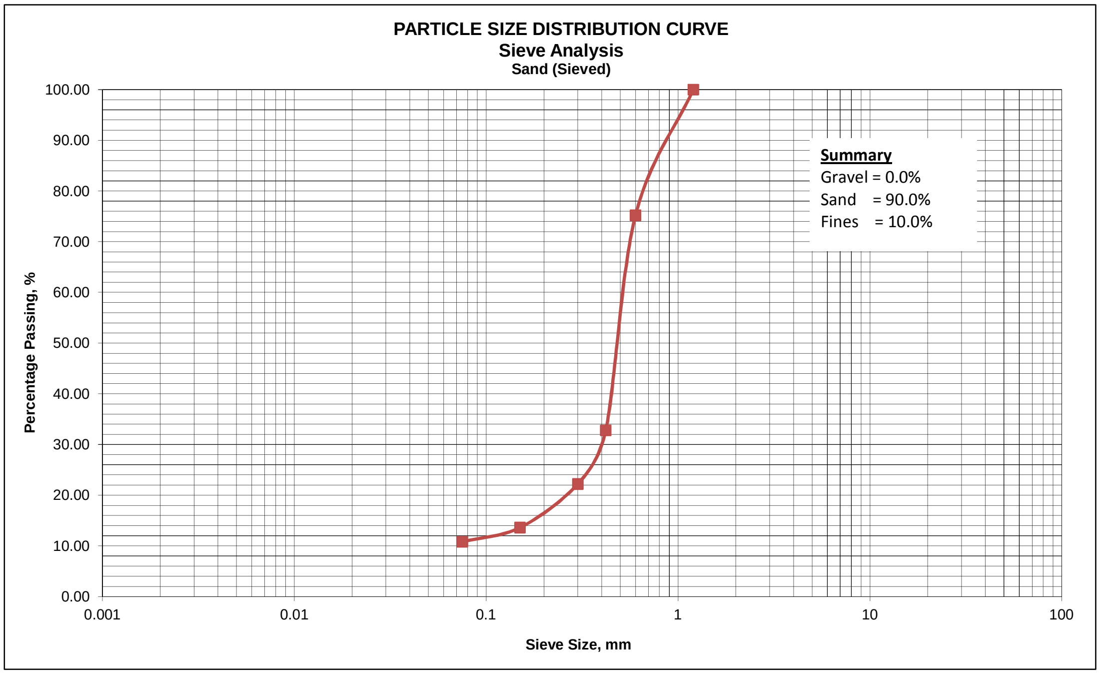

Fig. 4. Particle size distribution of natural silica sand

2.2 Methods

2.2.1 Setting times and water demand

Water demand and setting times, both initial and final setting times as well as compressive strength were determined and analysed. Clay pozzolana was used to replace PLC at 30%, 35%, 40%, 45% and 50% to formulate both binder paste and mortar. Table 2 indicates the mix composition of cement/binder pastes and mortars. The determination of water demand and setting times were performed on the plain and formulated binder paste in accordance with EN 197-1 standard which employs the use of the Vicat apparatus.

Table 2. Samples of different mixes of OPC and CP

Sample	Content (%)	
	OPC	**CP**
CP0	100	0
CP30	70	30
CP35	65	35
CP40	60	40
CP45	55	45
CP50	50	50

2.2.2 Mortar preparation, mixing, casting and curing

Compressive strength test were determined on plain and blended mortars. The preparation of the mortar was performed in accordance with ASTM C109 standard [14] which uses a Hobart mixer. The mortar specimens were prepared at 1:3 binder to sand ratio and a water to cement ratio of 0.50 at normal temperature (25ºC±1ºC). The prepared mortar mixes were filled in a 70.6 mm metallic cube moulds and arranged on an electric vibrator which was turned on for 2 minutes to ensure good compaction of the mortar. After casting, the mortar specimens were covered with a wet cloth in order to control water evaporation from the mortar during the hydration process for 24 hrs.

Strength activity index (SAI) was determined on an average of 3 mortar specimens after curing in potable water for 3, 7 and 28 days. The SAI was determined as a ratio of the reference mortar to that of the blended pozzolana cements. The 28 days strength results of the blended pozzolana cements were sampled out and analyzed based on the ASTM C91 [18] strength specifications for masonry cement.

3. RESULTS AND DISCUSSION

3.1 Water Demand

Fig. 5 presents the water demand results of the plain and blended cement paste containing clay pozzolana. It shows blended or formulated cement paste at 30% and 50% of CP attained a higher water demand which is between 25% and 32% more than the control paste (0%). Similar trends have been attributed to fineness and porosity of calcined clay [19,20]. An increase in the number of finer particles within a cement matrix increases the surface area of particles. In the work of Ganesan et al. [8], they found that the higher the surface area, the higher the water demands. The high water demand of blended cement paste as compared to the control paste is attributed to these explanations, the higher fines and the porous nature of CP.

The results of blended paste with content ranging from 30% to 50% indicated that water demand for CP30, CP35 and CP40 remained the same at 35%. The reason could be that the distribution of fine particles in the cement matrix remained almost equal, therefore accounting for the same water quantity. CP45 attained 36% water demand with CP50 attaining a water demand of approximately 37% which was the highest. With CP50, it could mean that more CP content provided more porosity and an increased surface area that led to the higher water demand.

3.2 Setting Times

The setting times, both initial and final for the plain or control paste and the blended paste are shown in Fig. 6. For the intial setting time (ISt), the Figure shows that it generally occurred at an extended time, between 20% and 128% more as compared to the control paste (0%). This may be attributed to the decrease in PLC which is responsible for stiffening.

With the blended CP paste, there was a gradual increase with the ISt at CP30, CP40 and CP45, however the trend showed a decrease with ISt above 40% CP. The gradual increase of ISt from 30-40% can be due to decrease in cement and pozzolanic effect whilst the slight retardation of ISt between 40% and 50% may be as a result of the formation of new cementing compounds which speeds up the reaction process. This is sometime cause by filler action which is activated by enough pozzolanic materials in a cement matrix.

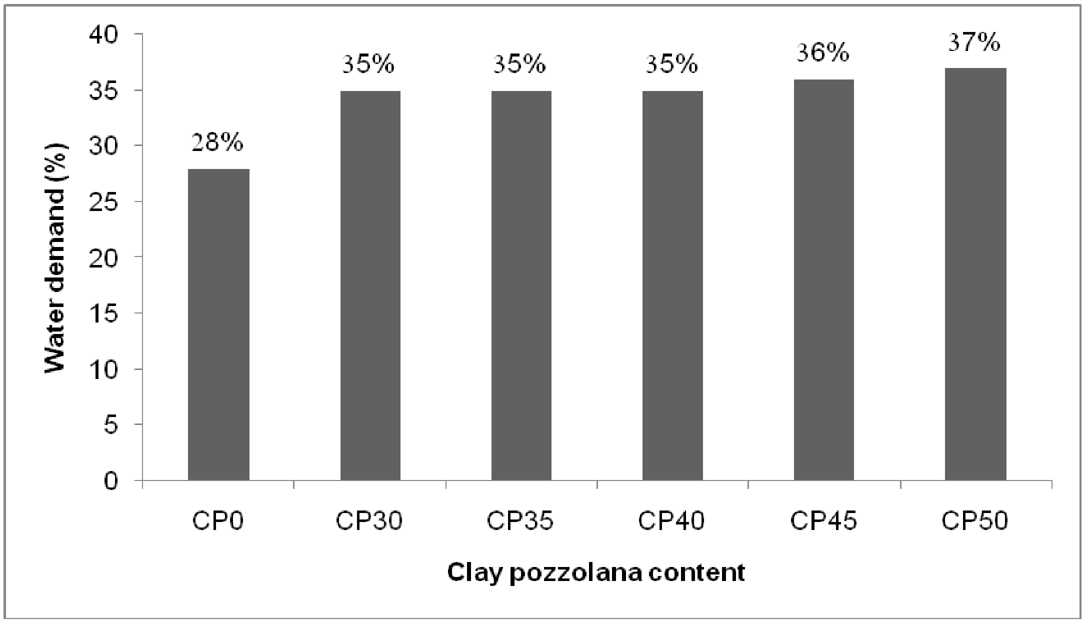

Fig. 5. Water demand for plain and blended CP paste

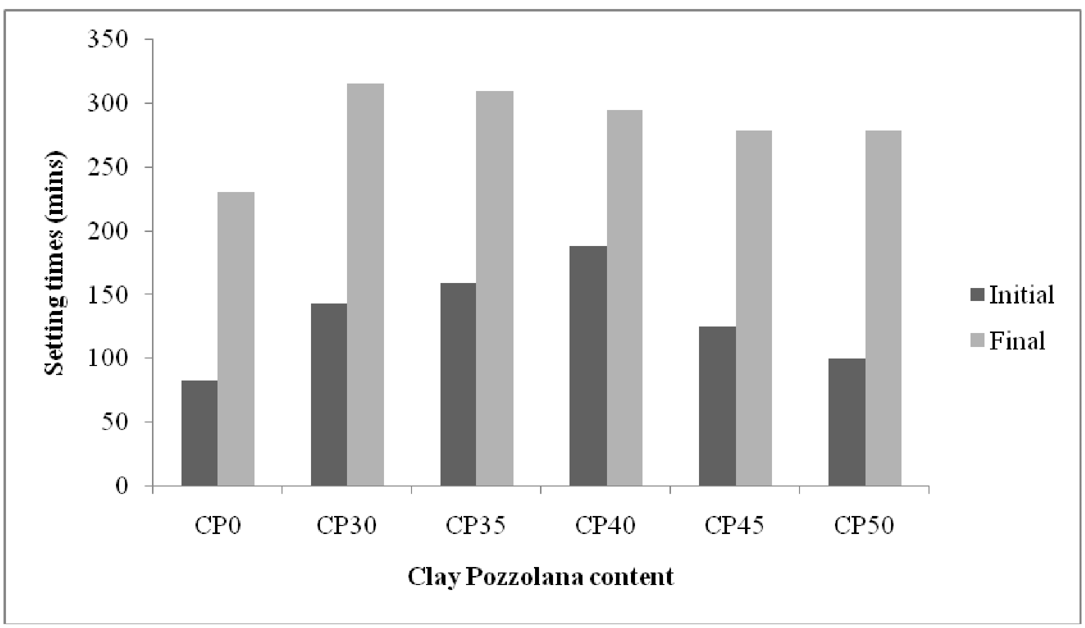

Fig. 6. Setting times of plain and blended CP paste

With respect to the final setting time (FSt), it also showed an extended FSt, between 21% and 37% as compared to the control paste (0%). Considering the trend of the blended CP paste, FSt showed a gradual decline between 30% and 45% CP content. At CP50, the FSt was the same as that of CP45 at a time of 279 minutes.

The FSt results indicated that there wasn't much deviation with respct to time of the blended CP paste as compared with the plain mortar. Though the decrease in the stiffening agent accounted for the retardation, however the effect of pozzolanic reaction could also account for the decrease with respect to the blended CP paste.

3.3 Strength Analysis

The strength activity index (SAI) which is presented in Fig. 7 gives an idea of the pozzolana reactivity with cement. The figure indicates a general trend which is a reduction in the activity index as pozzolana content in the matrix increases at all curing days. The SAI of mortar specimens containing 30%, 35% and 40% at 7days were smaller than what was attained at 3 and 28 days respectively. This could be attributed to the dormant nature of pozzolana and cement reaction which can persist between 7 and 14 days. It is also obvious from the results that the reduction in the cement grains and the filler effect of the higher pozzolana volumes caused the gross reduction of the SAI values. The strength decrease with higher content of CP has been attributed to the effect of dilution [21]. Here, the dilution effect is explained by Johari-Megat et al. [21] as the reduction in cement content since portions of cement is taken up by a seemingly inactive pozzolan.

The strength development against curing time shown in Fig. 8 also confirms the strength decreasing trend of the mortar as pozzolana content also increased. Fig. 9 again indicates that strength development of mortar cubes were significantly influenced by the age of curing. At each replacement level the compressive strength significantly increased with increasing curing time which occurred at 3, 7 and 28 days. This shows the formation of new products from cement-pozzolana reaction through hydration.

Fig. 9 presents the 28 days compressive strength of both plain and blended CP mortars observed from the strength results. From the figure, it is shown that mortars with CP content between 30% and 50% indicated compressive strength higher or equal to type S mortar which is 14.5 MPa. Though CP30-CP50 are appropriate for a type S mortar, however economical benefit would make one opt for either CP45 or CP50. Table 3 indicates the types of masonry mortars, their use and minimum strength attained at 28 days.

Table 3. General recommendation on masonry mortar type selection based on ASTM C91

Masonry mortar type	Location	Building segment	28days compressive strength (MPa)
Type M	Exterior above grade Interior	load bearing walls load/non load bearing walls	20.0
Type S	Exterior at or below grade	foundation walls, retaining walls manholes,sewers, pavements, patio, parapet walls	14.5

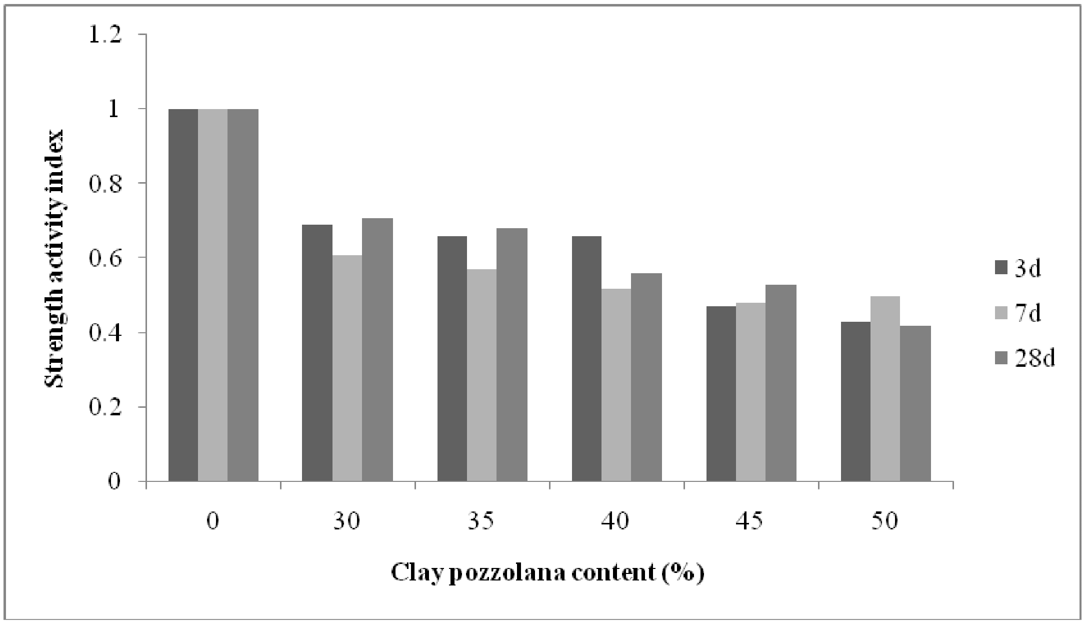

Fig. 7. Strength activity index of plain and blended pozzolana cement

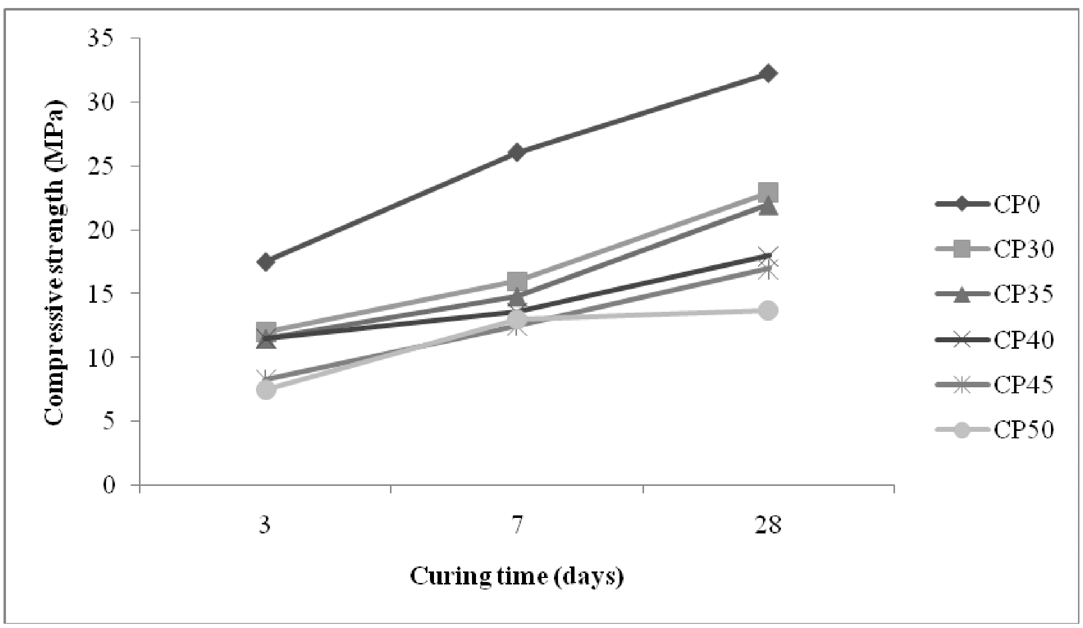

Fig. 8. Compressive strength against curing time of plain and blended pozzolana cement

Fig. 9 shows that CP30 and CP35 had a 28 days compressive strength of 23 MPa and 21 MPa respectively, higher than a type M mortar with a minimum strength of 20 MPa. This blended CP mortars could be appropriate for this ASTM type mortar class.

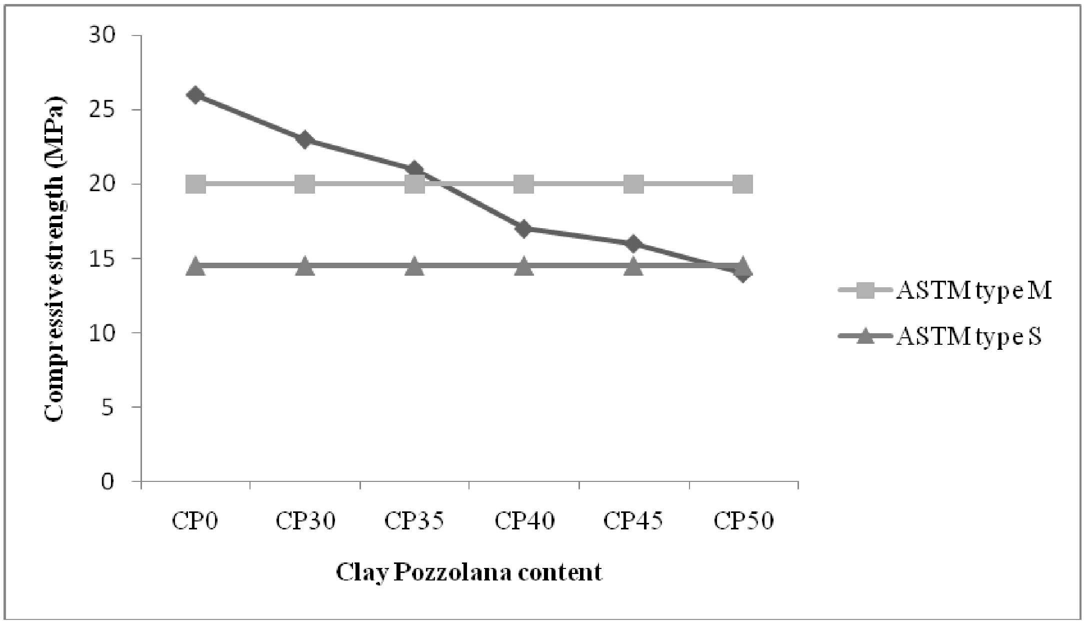

Fig. 9. Compressive strength of plain and blended CP mortar at 28 days

3.4 Economic Benefits of Blended Pozzolana Mortar System

The economic benefit of pozzolana utilization could be achieved through an optimum mix design between Portland cement and pozzolana. In Fig. 9, the optimum mix for a type M and type S mortar mix is at 35% and 50% pozzolana content respectively. Table 4 shows the cost analysis of using 35% and 50% pozzolana content for a type M and S mortar class. The cost analysis was determined based on the following assumptions:

- Clay pozzolana cost per 50kg - GH¢6.00
- Cement cost per 50kg - GH¢20.00
- Sand cost per m^3 - GH¢25.00
- $1.00 - GH¢2.00
- Mortar thickness - 13mm

The Table indicates that there is an overall reduction in the cost per m^3 of pozzolana included in Portland cement as compared to the unblended ordinary Portland cement mix. Blended pozzolana mortar mix containing 35% and 50% caused significant materials cost reduction of 19% and 28% respectively with respect to the unblended mortar mix.

Table 4. Cost per m^3 of unblended and blended pozzolana cement

Cost (Gh¢)	1:3 mortar mix		
	OPC	**CP35**	**CP50**
OPC	234.28	156.19	92.25
Clay pozzolana	0	23.43	35.14
Sand	55.58	55.58	55.58
Total	289.85	235.19	207.86

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

Based on the investigations from the experimental works, the following conclusions are made

1. Clay calcined at 700^{o}C indicated the presence of crystalline phases overshadowing the amorphous nature of silica.
2. Clay pozzolana used was finer than ordinary Portland cement. This increased the surface area of cement-pozzolana system hence increased the quantity of water needed for normal consistency.
3. The setting times, both the initial and final of the blended CP paste occurred at an extended time than the control paste.
4. Blended pozzolana cement mortars that contained 35% and 50% pozzolana content were found to be the optimum mix for a type M and type S mortar class respectively.
5. The cost savings made from CP35 and CP50 as compared to the unblended mortar is 19% and 28% respectively. This will provide economic alternatives for builders on the choice of masonry binders.

4.2 Recommendations

Some aspects of technical works have not been exhausted and those works could compliment the results achieved in this study. These works include the flowability, durability and some aspect of qualitative analysis using XRD, TG/DTA and SEM/EDX on hydrated phases of binder pastes. The authors recommend further investigations be made to exhaust these areas.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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