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Compressive strength and workability of concrete using natural pozzolana as partial replacement of ordinary portland cement

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ABSTRACT

The increasing cost and scarcity of portland cement has impacted negatively on the delivery of affordable housing and infrastructural development in developing countries like Ghana. This study investigated the use of natural clay pozzolana as partial replacement of portland cement in the production of concrete. Concrete cubes measuring 150mm×150mm×150mm were made from six different concrete mixes prepared by using pozzolana to replace 0%,10%, 20%, 30%, 40% and 50% of portland cement by mass. The workabilities of the fresh concrete mixes were evaluated using the slump test and compacting factor test while compressive strengths of concrete cubes were evaluated at 7, 14, 21 and 28 days. The maximum compressive strength at all ages of testing was obtained at 30% replacement, corresponding to an increase of 3%,12%,24% and 19% compared to the 7-day, 14-day, 21-day and 28-day compressive strengths. Workability decreased with an increase in replacement percentage. Pozzolana can be used to partially replace ordinary portland cement in the production of concrete without compromising strength.

Keywords: cement, pozzolana, concrete, compressive strength, workability

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INTRODUCTION

Concrete is the world's most utilized construction material [1]. The need for infrastructural development in both the developing and developed countries has placed a great demand on ordinary portland cement (OPC), traditionally, the main binder in the manufacture of concrete. Despite the advantages of concrete as a construction material, the production of cement comes at a great cost to the environment [1, 2, 3, 4].

In view of environmental and sustainability concerns associated with the production of cement, the use of pozzolanas to replace part of portland cement is receiving a lot of attention. Replacing portland clinker either partially or entirely is also being investigated as an alternative to carbon dioxide emissions [2]. Up 70% of portland cement can be replaced by using materials such as primarily fly ash, slag, silica fume, natural pozzolanas, rice-husk ash, wood ash, and agricultural products ash [5].Artificial pozzolanas used in modern commercial cement are derived from fly ash produced by coal burning plants; incineration of municipal solid waste etc [6]. .Pozzolanic materials do not possess any cementing properties of their own, but they contain silica and alumina in reactive form. Ancient Romans produced exceptional cement by mixing pozzolanic materials with lime to build structures some of which are standing today [6].

Pozzolanic materials chemically react with calcium hydroxide in the presence of water to form compounds possessing cementitious properties [6]. The pozzolanic reactions are silica reactions in the presence of calcium hydroxide and water to produce calcium silicate hydrates(C-S-H) [7, 8]. C-S-H creates a denser microstructure that increases strength, reduces the permeability of concrete and improves its resistance to chemical attack. The partial replacement of ordinary portland cement by pozzolanas are known to improve the resistance of concrete to sulphates [9]..As additives in modern cements pozzolanas improve mechanical strength and provide resistance to physical and chemical weathering [6]. The addition of pozzolanas reduces pore sizes and porosity leading to increased strength [10]. The aim of the study is to investigate experimentally the effects of partial replacement of OPC with pozzolana on the workability and compressive strength of concrete. This study seeks to contribute to efforts to make use of locally available materials in infrastructural development in line with the Ghana Government's objective of using at least 40% of local building materials in government infrastructural projects.

MATERIALS AND METHODS

The cement used was ordinary portland cement of strength class 32.5R. The cement conformed to [11].The pozzolana used is of ASTM Type N. Table 1 shows the chemical compositions of binders used in the study. Crushed granite of nominal size 20mm used in producing concrete. The water used in mixing looked clean and free from any visible impurities. It conformed to the requirements of [12]. Natural river sand with a specific gravity of 2.53 and a bulk density of $1550kgm^{-3}$ was used. Six different mixes were used for the study. A control mix of ratio 1:2:4 batched by mass using a water-binder ratio of 0.55. The control mix was produced using OPC only as binder while in other mixes, pozzolana was used to replace 10%, 20%, 30%, 40% and 50% of the mass of ordinary cement in the control mix. The details of mix proportions are shown in Table 2.

Table 1 Chemical composition of OPC and pozzolana

Component	Ordinary portland cement % (by mass)	ASTM Type N Pozzolana%(by mass)
LOI	2.04	1.18
SiO_2	18.24	78.71
CaO	60.82	>0.01
Al_2O_3	4.88	12.72
$Fe2O_3$	3.47	4.49
MgO	3.20	0.33
SO_3	3.25	>0.01
Na_2O	0.02	0.31
K_2O	0.44	0.91

Table 2.Concrete mix details

Percentage replacement (%)	Mass of constituents(kg)			
	Cement	Pozzolana	Sand	Crushed Granite
0	7	0	14	28
10	6.3	0.7	14	28
20	5.6	1.4	14	28
30	4.9	2.1	14	28
40	4.2	2.8	14	28
50	3.5	3.5	14	28

The slump test [13] and compacting factor test [14] were used in assessing the workabilities of the fresh concrete mixes. No test measures workability directly, but there are tests that measure properties related to workability. Workability is related to the compatibility, mobility and stability of fresh concrete [15]. Casting of concrete was done in cast iron moulds measuring 150mm × 150mm × 150mm internally. A total of seventy-two cubes were made. The specimens were made in accordance with[16]. After casting, the moulds were covered with plastic sheet to prevent water loss through evaporation. Demoulding was done after 24 hours and the specimens immersed in a curing tank to cure for strength gain. Curing improves both the physical and mechanical properties of concrete. The compressive strengths were determined by crushing concrete cubes at 7, 14, 21 and 28days of curing using a 1,500kN Matest compression testing machine (Fig 1).

Figure 1. Compressive Strength Testing

Before crushing, the concrete cubes were removed from the curing tank and placed in open air in the laboratory for about two hours. The results presented are the average of three tests. All tests were conducted at the Materials Laboratory of the Department of Civil Engineering of the Cape Coast Polytechnic.

RESULTS AND DISCUSSION

Workability

The results of workability tests are presented in Table 2.

Table 2 Results of workability tests

Workability	Cement Replacement (%)					
	0	10	20	30	40	50
Slump (mm)	20	18	16	14	10	8
Compacting Factor (%)	0.88	0.80	0.74	0.76	0.69	0.62

From the results it can be seen that as the percentage replacement of OPC with pozzolana increases, the workability of concrete decreases. Replacing cement by an equal mass of pozzolana causes an increase in volume since the density of cement is higher than that of pozzolana.This therefore increases the water demand and as the pozzolana content increases the workability reduces since the quantity of water remains the same for all mixes. The results also showed the interrelationship between the results of the compacting factor test and the slump test.

Compressive strength

The results of the compressive strength tests are presented in Table 3.

Table 3. Compressive Strength (Nmm^{-2})

Age at testing(days)	Pozzolana Replacement (%)					
	0	10	20	30	40	50
7	16.4	16.1	15.6	16.9	13.1	10.6
14	18.1	17.8	17.3	20.2	13.8	11.4
21	19.1	18.3	17.5	23.7	15.8	12.9
28	21.7	19.6	17.9	25.9	16.1	13.6

The variation of compressive strength of concrete is presented in Fig 2.It seen that the variation of strength shows similar trends with respect to pozzolana replacement. In general, the compressive strength reduced from the control concrete (0% replacement) to 20% replacement. A further rise in replacement increased the compressive strength until a maximum strength was reached at 30% replacement of OPC with pozzolana. On further increase, the strength reduced as percentage replacement increased. This trend is similar at all ages of testing.. It is also seen that the strength of concrete increases with age.

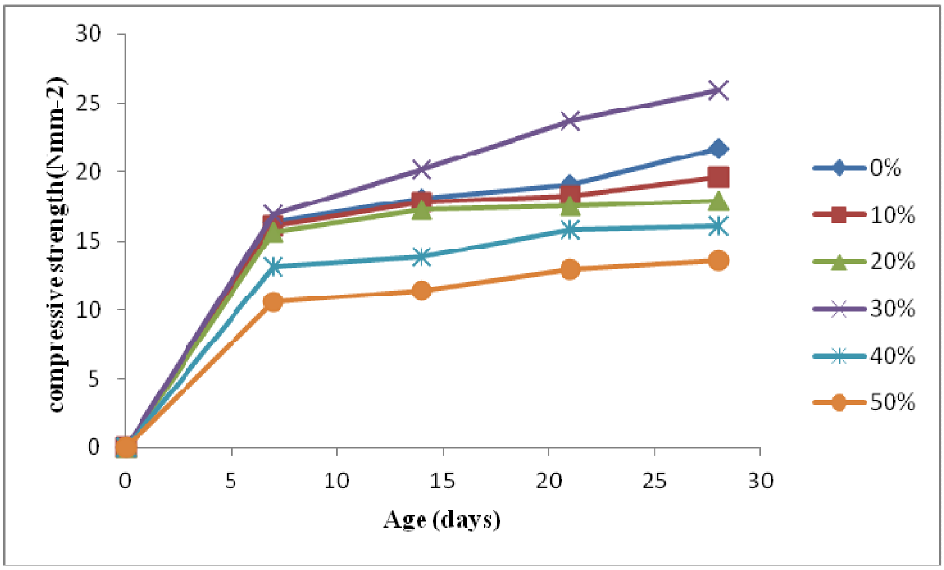

Figure 2. Variation of compressive strength with age

Pozzolanic reaction begins immediately after hydration of cement and continues for a long time thereby increasing strength. Concrete attained its maximum strength at a pozzolana replacement of 30%**;** corresponding to an increase of 19% in the 28-day strength compared to the control concrete. Similarly, the 7-day, 14-day, and 21-day compressive strengths respectively show increases of 3%, 11% and 24% compared to the compressive strength of the control concrete (Fig 3).

Concrete derives its strength from the pozzolanic reaction between silica in pozzolana and the calcium hydroxide liberated during the hydration of OPC. At low percentages of replacement, the quantity of silica is low, therefore, only a limited quantity of C-S-H can be formed, though a large quantity of calcium hydroxide is liberated due to the relatively large quantity of portland cement. However, at high percentage replacement, the quantity of pozzolana in the mix increases. C-S-H formed reduces due to liberation of a small quantity of calcium hydroxide from the hydration of the relatively small quantity of portland cement available. The strength of concrete at both low and high percentage replacement is therefore low. An optimum level of replacement exists at which compressive strength is the highest. It can also be concluded that the strength of concrete depends on the relative proportions of silica in pozzolana and ordinary portland cement available.

From Fig 2, it is seen that the average rate of strength growth is constant for the first seven days, after which, the average rate of growth reduces to a constant, but relatively lower rate. The rate of strength gain with respect to time is highest for concrete with 30% replacement of OPC by pozzolana. This is due to optimum reactions which take place at 30% replacement of OPC by pozzolana.

The variation of the relative compressive strength of concrete with is presented in Fig 3. It can be seen that, with the exception of concrete with 30% pozzolana replacement, as the age increases the strength ratio decreases even though the strength of concrete increases with age. This is due to the rate of increase of the compressive strength of control concrete, which is higher than concrete at all pozzolana replacement levels with the exception of 30% replacement.

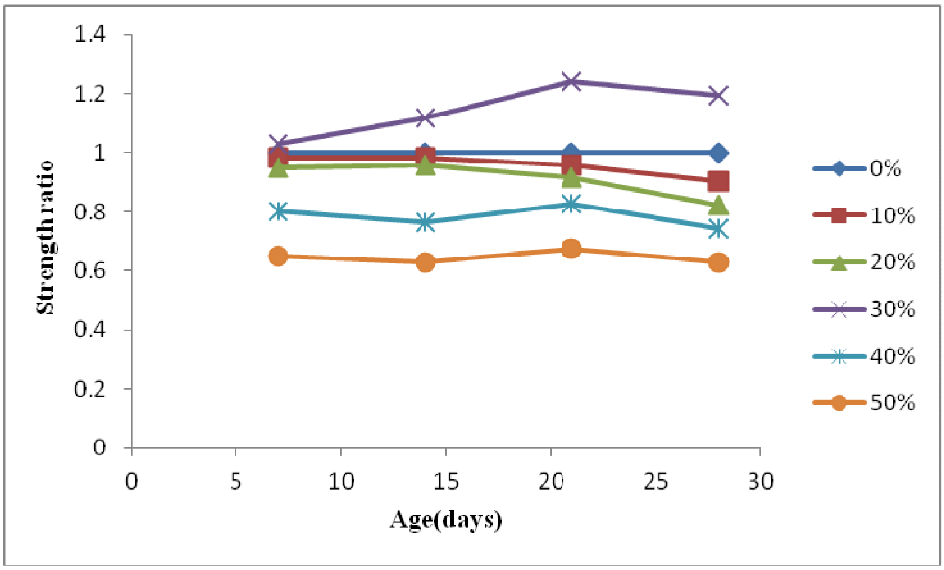

Figure 3. Relative compressive strength of concrete

CONCLUSION

At the end of the study, the following conclusions are drawn:

- Replacement of cement with pozzolana significantly increased the strength of concrete
- Replacement of 30% of the mass of cement with pozzolana achieved the maximum value of compressive strength.
- The 7-day, 14-day,21-day and 28-day compressive strengths at 30% replacement respectively showed increases of 3%, 11%,24% and 19% compared to the compressive strength of the control concrete at those ages
- Increase in pozzolana replacement decreased the workability of concrete

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