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Experimental Investigation on Short Term Effect of Calcined Clay on Concrete Strength

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ABSTRACT: The cement and concrete industry faces amassed pressure to cut carbon dioxide emissions associated with cement production. One viable strategy is inclusion of supplemental resources to replace fractions of cement clinker. Calcined Clay (CC) has the potential to partially supplement cement and significantly reduce carbon dioxide emission. Therefore, the short term effect of CC on the strength of concrete incorporating CC is being examined. Natural clay was collected in Ekiti State, Nigeria and calcined at 750°C. Concrete was prepared by mixing sand, granite, cement, CC (varying proportions) and water manually using a developed mix design at 0.5 water binder ratio. The CC0 served as control, while other mixes were labelled CC10, CC20, CC30, CC40 and CC50. Laboratory tests conducted were determination of: oxide compositions of the CC, slump and density of wet concrete, and compressive strength of matured concrete at varying curing durations. Outcome on oxide composition shows that CC contains about 93.7 % of combined silica, alumina and ferrite. The slump ranges between 35-95 mm and decrease with increase in CC content. Wet density for all the mixes were comparable with control. Compressive strength at 28 days was comparable with control at medium replacement levels 10-20% while mixes with 40-50 % replacement recorded 54.8% and 61.3% reduction respectively compared to the control. Conclusively, CC can safely be included in concrete without compromising the strength capability of the concrete. Strides should be made towards the necessary standardization, validation that will encourage the market acceptance of CC as cement replacement.

KEYWORDS: Carbon dioxide emission, mix design, oxide composition, compressive strength

1. INTRODUCTION

Portland cement has been the conventional binding constituent for concrete production and massive volumes of the material are utilized in every construction. The construction sector in the last century has been experiencing an increase in demand for cement at a disquieting rate. CEMBUREAU (2024) stated that global cement output was over 4 billion tons in 2023, with about 6.3% annual increase rate, and is forecast to rise more in the next few years (Amin *et al*., 2022). The production and delivery of construction materials, together with their application in building structures, require substantial energy and generate enormous greenhouse gas emissions contributing to around eight percent of universal carbon IV oxide (CO_2) (roughly 600–700 kg CO_2 per ton of PC; 850 kg CO_2 per ton of clinker (Cheah et al., 2025; Mehta & Siddique, 2018). Ahmed *et al.*, (2020) and Amin *et al*., (2022) uncovered that by application of suitable alternative Supplementary Cementitious Materials (SCM) in place of cement is the most efficient strategy to decrease the building industry's carbon footprint and the supreme apt route to attain ecological balance in binder manufacture is the lessening of clinker element by adding SCM.

Currently, it is almost inconceivable to consider concrete technology without the incorporation of some materials generally termed SCM. Pozzolans are prominent among SCMs that are progressively utilized as cement partial alternatives. Among the pozzolan materials used as cement substitutes are fly ash, silica fume, and ground granulated blast furnace slag (GGBS) (Martinez-Molina *et al*., (2021); Schmidt *et al*., (2021). However, the available volume of these traditional pozzolans represent less than 10 percent of the universal cement manufacture. The paucity of common SCMs has prompted the research on and the application of CC.

Calcined clay is gaining considerable attention as a viable and broadly obtainable alternative SCM. Recent studies demonstrate that CC can substantially reduce the clinker factor in cement and concrete while maintaining acceptable performance (Zunino & Scrivener, 2023). Avet *et al.*, (2025) reported that recent developments have shown that clays containing at least 40% kaolinite content as main mineral can be highly reactive if properly thermally activated. The high hydroxyl group as well as crystal structure site of kaolinite clay are responsible for their notable pozzolanic properties (Kaminskas *et al.*, 2020). CC is prepared by thermally actuating usual kaolinite-rich clay materials. The controlled burning process typically occurs at temperatures between 700 - 900 °C; cement clinker is produced at a much higher temperature (~1450 °C). During the process, kaolinite undergoes dehydroxylation to form an amorphous aluminosilicate phase, popularly known as metakaolin when derived from high-purity kaolin. When applied as cement replacement, CC as a pozzolan reacts with calcium hydroxide generated during cement hydration, bring into being additional calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) phases. The reaction influences strength improvement and microstructural modification (Zunino & Scrivener, 2023).

The outstanding benefits of CC arise principally from reduced clinker content, lower calcination temperatures, significant reductions in embodied CO_2 compared with conventional Portland cement systems and the extensive accessibility of apposite clay resources (Avet *et al*., 2025). Cheah et al., (2025) reviewed that CC below 40 % by mass of binder was utilized as a fractional addition for Portland cement in many composite research. Competitive or enhanced compressive strength relative to orthodox concrete were obtained when mix design parameters were applicably adjusted (Avet *et al*., 2025). At higher CC dosage levels, amplified water demand and lowered workability were predicted base on its Particle Size Distribution (PSD) and high specific surface area.

Kaminskas *et al*., (2020) reported that the actuating temperature has no effect on the pozzolanic performance of the CC. The most promising and interesting application of CC knowledge is the development of Limestone-Calcined Clay Cement (LC^3) which classically comprises of about 50% clinker, 30% CC, 15% limestone, and 5% gypsum. The constitution saves more than one-third clinker and simultaneously maintaining or advancing the mechanical performance of the binder. Thus, (LC^3) is tagged a low-carbon cement production (Avet *et al*., 2025; Scrivener, *et al*., (2023).

Like many pozzolans, the incorporation of CC often increases water demand and affects rheological behavior due to its PSD and platy morphology. Studies emphasize the importance of optimized mix design and the use of compatible polycarboxylate-based superplasticizers to achieve adequate workability (RILEM TC 282-CCL, 2021). Addition of 30 % CC in Portland cement cut off up to 27% carbon emissions, retained the workability, improved the 28 and 90 days compressive strength of the merged cement concrete (Zhou *et al*., 2021)

The sustainability dimension of CC extends beyond CO_2 mitigation. Its use encourages local resource utilization, minimizes landfill waste, and supports circular economy principles (Benjeddou *et al.,* 2025). Therefore, understanding CC role requires exploring not only its mineralogical and chemical characteristics but also its broader contribution to mechanical performance and environmental stewardship.

2. MATERIALS AND METHODS

The materials used in this study include cement manufactured in Nigeria by Dangote Cement Plc. (CEM II 42.5 N). The aggregates used were river sand and granite from Ado Ekiti. The sand particles were found to pass through sieves with an opening size of 2.00 mm and retained on 63µm sieves. It was certified to be bereft of harmful chemicals and salt. Granite of maximum grain size 16 mm were used. Drinkable water was utilized. Natural clay obtained from a burrow pit located at the gate area of the Federal Polytechnic, Ado Ekiti. First, the land was cleared and the topsoil layers of earth organic content above the clay were removed, then the clay was carefully extracted at a depth of about 1m to assure quality. The natural clay was pulverized, sundried and ensured was free of moisture. It was calcined at 750℃ in a furnace. A fraction of the powdered CC was utilized to partially substitute concrete mixtures content at different cement replacement levels. Cement was partly substituted with CC in increments of 10 % by weight, 0 %, 10 %, 20 %, 30 %, 40 %, and 50 %. The control was the mixture that was devoid of CC and was labelled CC0 while others containing CC were tagged CC10, CC20, CC30, CC40 and CC50. Concrete was produced in the laboratory by mixing the sand, granite, cement, CC and water manually. The experimental study were conducted at 25 ± 2℃ and 70 ± 5% humidity to ensure stability and avoid fluctuations that could affect the results.

3. RESULTS

i. Oxide Composition

Table 1 depicts the oxide composition of CC as determined using X-ray fluorescence is presented in. The Table compares the oxide compositions of the CC with that of the cement used in the study. The result shows that the sum of the primary oxides (SiO_2 + Al_2O_3 + Fe_2O_3) necessary for pozzolanic reactivity in the CC was found to be 93.71 %. According to ASTM C 618 (2008), for a material to be pozzolanic, the sum of the oxides must be greater than or equal to 70%. This indicates that the CC used in this study is a rich pozzolan with expected high reactivity.

ii. Slump

The slump test was performed (according to ASTM C143 (2015)) to assess the consistency of the fresh concrete. The slump values for concretes with various CC replacement is presented in Figure 1. The result indicates that the slump value decreased with the rise in CC content, suggesting a decreased workability due to the fine nature and higher water demand of the CC compared to cement. The slump of mixes CCO, CC1O and CC20 are at least twice the slump value recorded for mix CC50. The workability of the mixes declined as the SCM fraction advanced. This is connected with the fact that more water is needed form workable consistency as the CC particles. Cheah et al reported similar observation from review.

Table 1: Oxide Composition

Oxide Composition	Calcined Clay (mg/cm^2)	Cement (mg/cm^2)
SiO_2	48.04	18.00
Al_2O_3	32.11	5.70
CaO	0.47	68.30
TiO_2	2.90	0.22
Na_2O	0.00	0.71
Fe_2O_3	13.56	4.10
K_2O	0.52	0.10
MnO	0.04	0.04
MgO	0.00	1.43

Loss on ignition	2.36	1.40
Specific Gravity	1.78	
Color	Pink	Grey

The chemical action of superplasticizer in the mixes (especially mixes with higher CC percentages) could have improved workability without increasing the water-cement ratio, making the paste appear more fluid and cohesive. However, it was not applied since the earlier mixes was devoid of any admixture.

In general, concrete mixes with lower CC replacement showed higher cohesion and reduced bleeding, while higher replacements exhibited decreased flow and uniformity. The variation observed is unswerving from the observation of (Olonade *et al.*, 2023;Zunino & Scrivener, 2023) that reported the inclusion of chemical admixtures at higher pozzolanic replacement levels could alter the rheological behavior of fresh concrete, improving apparent workability while slightly reducing mix stability.

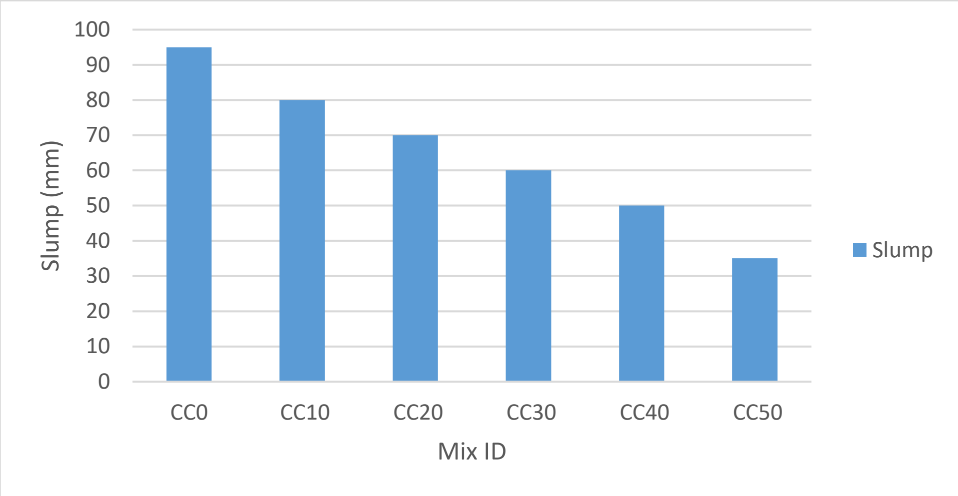

Figure 1: Slump Values for Concrete with Calcined Clay Replacement

iii. Wet Density

The wet density of freshly prepared concrete was determined immediately after mixing and casting to evaluate the mass per unit volume of each mix. BS EN 12350-6 (2019) was considered the standard for the test. Wet density values were determined using the formula:

$$\text{Wet Density} = \frac{\text{Mass of Concrete (kg)}}{\text{Volume of Mould (m}^3\text{)}} \qquad \text{(i)}$$

The average results obtained for the different percentages of CC replacement are shown in Figure 2. The wet density of the concrete mixes ranged between 2.35–2.44 kg/m³, showing variations with CC content. The values are within the acceptable range of 2.3–2.6 kg/m³ normal-weight concrete. The trend revealed that the density initially decreased as the replacement increased up to 20%, due to the lesser specific gravity of CC compared to cement. However, a slight increase at higher replacements (30–50%) may be due to better compaction and rearrangement of fine particles within the matrix, which enhanced packing density.

The general reduction in wet density at lower replacements aligns with similar reports by Ajagbe *et al*., (2023) and Pillai *et al*., (2020), they reported that the inclusion of pozzolanic materials typically reduces the mass per unit volume of fresh composite because of the lighter nature of the materials used. This slight reduction in density can be beneficial in applications where lightweight yet strong concrete is desired.

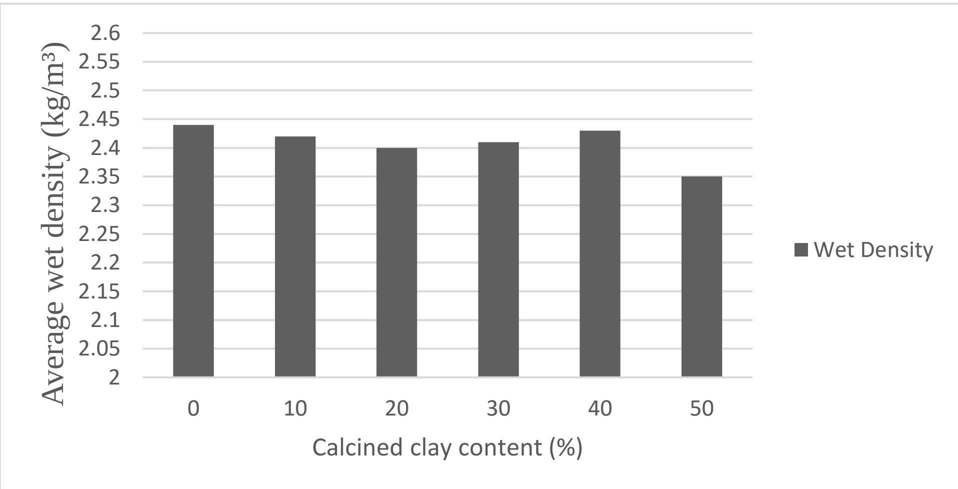

Figure 2: Wet Density of Concrete Containing Calcined Clay

iv. Compressive strength

The compressive strength results for all the concrete mixes incorporating varying percentages of CC (0%, 10%, 20%, 30%, 40%, and 50%) are depicted in Figure 3. The Figure reveals clear trends related to the effects of both curing ages and replacement levels.

On the influence of curing durations, it is notable that all the mixes demonstrated steady advancement in the compressive strength as they improved with increase in curing ages. For instance, at 7 days maturity, mixes CC0, CC10 and CC40 recorded 13.76 N/mm^2, 12.60 N/mm^2 and 7.95 N/mm^2 respectively and at 28 days maturity, advancement in their respective compressive strengths were measured as 33 %, 28 % and 15 %. This performance is connected with the generation of hydration products which increases with curing duration. The progression of compressive strength with advancement in curing duration and maturity age was also reported by researchers like Olulope & Ajagbe (2025), and Musbau *et al*., (2021). It is also observed that the control mix CC0 and mix CC10 had competitive compressive strength values at all the ages investigated though CC0 recorded the highest values at each duration. This is attributed to the effect of high cement content with no supplementary material inclusion in the control mix.

Considering the effect of CC content replacing cement in the concrete mixes, all the mixes incorporating CC recorded lower strength compared to the mix CC0 control. It is notable that the compressive strength decreased with increase in the CC content. For instance, at 14 days maturity, the percentage reduction in the compressive strength of the control mix CC0 in comparison with that of CC10, CC20, CC30, CC40 and CC50 were 20.5%, 24 %, 35 %, 51.25 % and 62 %, respectively. The trend is similar across all the ages investigated. This observation is attributed to dilution effect in which much cement content is replaced with excess CC. For instance, the values of mix CC0 at 7 days is more than twice the values of CC40 and CC50 while at 28 days, the attained design strengths is more than 2.5 times the value of CC50 at both 14 and 28 days maturity. This observation is due to the reduced cement available for hydration products (Scrivener, *et al*., 2023).

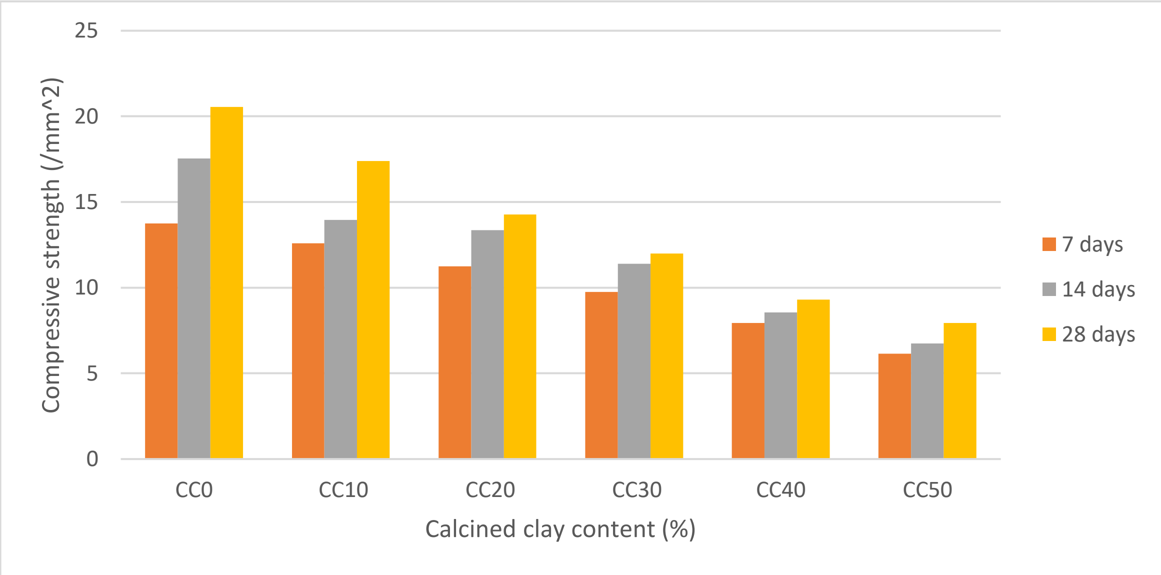

Figure 3: Compressive strength of calcined clay concrete

However, despite the reductions, all mixes demonstrated steady strength gains with curing age, highlighting the long-term contribution of the CC's pozzolanic reaction. These finding aligns with Ezeh, *et al*. (2023), who reported that compressive strength increased with CC content up to an optimum of 10%, being highly competitive with the control mix and generating over 70 MPa at 91 days, before the value began to decrease at higher replacement levels. The environmental condition of the location of the clay might have influenced the properties of the material.

It is commonly reported of most pozzolans that they exhibit lower early-age strength but later develop comparable higher strength values at older maturity ages. Similarly, the current study did not show any initial improvement at low replacement levels; even the 10% replacement mix exhibited though comparable but marginally lesser early-age strength than the control, reflecting the delayed commencement of the pozzolanic reactivity of the CC (Musbau *et al*., 2021).

Also, Ezeh *et al*., (2023) reported slight strength advancement at 5 and 10 percent replacement, followed by a debility at greater percentages. The present study mirrors the overall pattern of strength reduction at high replacement levels, although no early gain was observed. The observed differences in early-age behavior may be accredited to variations in the oxide compositions and CC reactivity, differences in calcination temperature and processing methods, mix design, water-cement ratio, and other factors.

In general, low to moderate replacement levels (not more than 20%) give a real-world balance between sustainability and allowable compressive strength, maintaining 28-day strengths of 14.3-17.4 MPa. Higher replacement levels (30–50%) reduced strength at all ages due to cement dilution, although the pozzolanic activity of CC still supports gradual long term strength gain. Overall, the results confirm that CC can be commendably applied as a partial cement replacement, particularly at lower percentages, achieving an environmentally friendly concrete mix without significantly compromising structural performance. Zhang *et al*., (2024) reported similar observation.

4. CONCLUSIONS

The study concludes that:

- application of CC is a strategic mean of reducing carbon dioxide in cementitious binder. Lower clinker content directly translates to lower embodied carbon.
- Low to moderate replacement levels (10–20%) provide a poise between early-age strength and pozzolanic contribution, maintaining adequate 28-day compressive strength.
- High additional levels (30–50%) significantly reduce early and later-age strengths due to dilution of cement, though they may improve microstructure and long-term durability if curing is extended.
- The optimal CC replacement level for structural concrete in this study is around 10–20%, where sustainability benefits are gained without severe compromise to compressive strength.

5. RECOMMENDATION

Field application of CC as partial cement replacement should be conducted to confirm the performance. Standardization and validation of the CC–cement should be worked out as quickly as possible to encourage the public or market acceptance of the material.

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