



# Strength performance and life cycle assessment of high-volume low-grade kaolin clay pozzolan concrete: A Ghanaian scenario

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## ABSTRACT

Concrete, the highest consumed construction material in the world is known to be the third leading contributor to carbon dioxide and other greenhouse gas emissions (GHG) aside from energy generation and transportation. These GHGs are known to be the governor of global warming and climate change. Therefore, the United Nations has taken it vital work to reduce GHG emissions from around the globe. In this work, C30 class of concrete was produced with five different types of binders using replacement levels of cement at 0, 10, 20, 30, 40, and 50 wt%. The formulated concretes containing the pozzolans were compared with OPC concretes in terms of strength performance and total carbon dioxide emissions. The results of the study revealed that concrete containing up to 50% pozzolan meets the C30 concrete grade even at late age curing of 90 days. In terms of carbon emissions, pozzolan concrete proved to be a means of decarbonizing traditional concrete. The OPC concrete recorded the highest carbon emission value of approximately 511 kg CO<sub>2</sub>eq. whereas the 50% pozzolan concrete recorded the least carbon dioxide emission value of approximately 335 kg CO<sub>2</sub>eq. The study recommends the utilization of the pozzolan as a cost-effective means to decarbonize regional concretes for enhanced global sustainability

## 1. Introduction

Since the introduction of the term Sustainable development by the Brundtland commission which was set up in the year 1987 by the United Nations, many industries have become more concerned with the environment [1]. The 1987 Brundtland commission defines sustainability or sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [2]. Economic, social development and environmental protection are the three main pillars of sustainable development. The United Nations Environmental and Development program refers to these three pillars as “the triple bottom line” (TBL). Since the year 1987, sustainable development has been regarded as a top priority in the UN, grown in popularity and now the world has a blueprint known as Sustainable Development Goals (SDGs) [3,4].

Greenhouse gas emissions create serious environmental threats to human beings and push many industries into eco-friendly processes. The greenhouse gases that are threatening the earth include CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>x</sub>, and SO<sub>x</sub> gases. These greenhouse gases trap heat waves from escaping the atmosphere thereby heating up the earth's surface. With these greenhouse gases, aside CO<sub>2</sub> which has a longer half-life, the rest of the gases have a shorter half-life in the atmosphere. This, therefore, makes CO<sub>2</sub> an important greenhouse gas

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worthy of consideration. Climate scientists have stated that anthropogenic activities are causing CO<sub>2</sub> concentration in the atmosphere to climb higher [5]. Indeed, the concentration of CO<sub>2</sub> in the atmosphere acts as a regulator for the amount of water in the atmosphere and is thus the determining factor in the equilibrium temperature of the earth [5]. Earth temperature would remain cooler, similar to the ice age if there is the absence of CO<sub>2</sub> [6]. Global warming is occurring on the earth's surface because the concentration of CO<sub>2</sub> has increased by almost 50% from the time of the pre-industrial revolution, from 280 ppm to around 415 ppm in the year 2021 [7].

The indicators of global warming include more extreme weather events in the future; melting of Arctic Sea ice; Antarctic Sea changes; land ice behavior (including glaciers and ice sheets); weather pattern changes; bird ecology changes (including migration); mammal and insect ecology changes and biodiversity loss; sea life and coral reef changes; marine diversity and intertidal indicators; plant ecology and plant pathogen changes; rising sea levels; and ocean acidification [8]. In solving the problem of global warming and mitigating its effect, the United Nations Framework Convention on Climate Change (UNFCCC) has mentioned that a 2 °C rise in mean global temperature above the preindustrial level must be the maximum limit. The 2015 UNFCCC Paris agreement was organized with the goal of holding the global average temperature increase to well below 2 °C [9]. Many climate scientists are of the view that CO<sub>2</sub> concentrations above 550 ppm could trigger an unbearable condition for human beings on earth [10]. There is an urgent need to reduce the amount of CO<sub>2</sub> entering the atmosphere and if possible, there must be proactive means of removing some of the CO<sub>2</sub> presently in the atmosphere. Researchers have been advocating for a net zero emission by 2050 [11].

Concrete, the most preferred and the second most widely consumed material in the world is a heterogeneous material whose production has an adverse effect on the environment. The global concrete production per year is approximately 26Gt [12]. Concrete production generates a high amount of CO<sub>2</sub> emissions which occur from raw material sourcing and Portland cement utilization. Concrete production is reported to account for 4–8% of the world's carbon emissions [13,14]. Cement a principal component of concrete is also reported to account for about 80% of CO<sub>2</sub> footprint in concrete. However, among building materials which include steel, glass, and wood, comparatively concrete has a very low carbon footprint. The reason for the high carbon footprint is due to the high demand and volumes produced per year.

Population growth and rapid urbanization which is happening in almost every country in the world is expected to push the demand for cement and concrete high. By 2050, the world's population is predicted to increase to about 10 billion, an increase of about 3 billion from the estimated population as of the year 2020 [15]. Ghana as a developing nation is also increasing in population as well as an upsurge in infrastructure and other residential apartment development. The country's cement consumption has increased by 56% from about 4.5 million tonnes in the year 2015 to about 7 million tonnes by the year 2019. It is reported that the Ghanaian cement industry is growing at around 6% per annum. The high demand for cement for infrastructural development in Ghana makes the cement and concrete industry a rich target for decarbonization solutions.

To meet the growing need for urbanization and minimize the global upsurge of carbon emissions creating negative environmental burdens, there is a strong motivation to develop more sustainable construction methods with a lower carbon footprint. Currently, efforts are being made by the scientific community to develop and standardize alternative binders with lower footprints considering the fact that Portland cement has a dominant share of carbon footprint in concrete. Examples of such binders being developed include high-volume fly ash/natural pozzolan cement and concrete, limestone-clay cement (LC3), geopolymers, and cementitious and non-cementitious based cement [16–19].

Zhou et al. [20] investigated clay excavated in London as a pozzolanic material for concrete. Their findings showed that 20–30 wt% replacement of CEM I by calcined London clay produced a cementitious binder with 18–27% lower carbon emissions. Pillai et al. [21] investigated the use of limestone calcined clay and pulverized fly ash cement as binders for concrete. They found out that binders with LC3 and PFA produced a much lower carbon footprint than OPC concrete of similar strength. Many other studies have also shown the importance of cementitious and non-cementitious materials in reducing the carbon footprint of concrete. Calcined clays are potentially appropriate materials gaining much attention in the area of cementitious materials used as an SCM for decarbonizing concrete. However, the complexities of clay due to geography, chemistry, and mineralogy create the need for further probing in terms of their suitability as a reactive cementitious material. Researchers are investigating local clay to confirm its reactivity as an SCM in this regard. The lack of the availability of commonly known SCMs in many developing countries such as fly ash and ground granulated blast furnace slag makes calcined clay research an important one in Africa with huge kaolin clays.

In Ghana, the concrete industry is gradually evolving, however, the lack of data on the properties of concrete containing high volume pozzolan, especially with a local calcined clay makes builders very reluctant to use clay pozzolan, although over 500 million tonnes of clay reserves are estimated to be available [22]. The traditional practice of using widely available Portland cement (42.5 R) in West Africa for concrete remains the safe haven for builders because of over-dependence on strict European standards. Over-dependency of Ghana on Portland clinker import (worth approximately 0.5% of the national GDP in 2018 according to World Bank data) has a negative impact on the local economy, as well as on the environment, globally, due to CO<sub>2</sub> emissions associated with trade flows. Meanwhile, blended cement containing calcined clay is becoming a preferred binder choice for the concrete industry. This study seeks to provide useful data that could help builders in Ghana and other West African countries. The push to adopt or adapt new appropriate technologies including cement extenders (calcined clay, fly ash, slags) that could provide economic and ecological benefits to humanity presents a unique case for regional novelty. This novel idea of using locally produced calcined clay falls in line with Sustainable Development Goals 11 (particularly Target 11.c, which promotes the use of local materials for building purposes in developing countries), 12 (sustainable supply of raw materials), and 13, which is an action toward climate change. In this study, a Ghanaian low-grade calcined clay was used together with Portland cement to produce binders for the formulation of concrete. The main purpose of the work was to study the strength properties and life cycle assessment of the low-grade Ghanaian kaolin clay pozzolan combined with Portland cement as binders for concrete.

**Table 1**  
Physical and chemical properties of Portland cement and clay pozzolan.

Chemical composition (%)	Portland cement	Clay Pozzolan
Al <sub>2</sub> O <sub>3</sub>	4.71	13.51
Fe <sub>2</sub> O <sub>3</sub>	3.4	5.84
MgO	1.99	1.74
SiO <sub>2</sub>	19.88	61.89
Na <sub>2</sub> O	0.28	0.72
CaO	62.13	0.21
K <sub>2</sub> O	1	0.49
SO <sub>3</sub>	2.6	
Cl	0	
LOI	2.53	
Insoluble Residue	1.02	
<b>Mineralogy (%)</b>		
C <sub>2</sub> S	16	
C <sub>4</sub> AF	15	
C <sub>3</sub> S	59	
C <sub>3</sub> A	8.2	
Thenardite	0.7	
Calcite	1.1	
<b>Physical properties</b>		
Specific gravity	3.12	2.61
Soundness (mm)	0.64	
Initial setting (min)	160	
Final setting(min)	270	
1d (MPa)	19.95	
2d (MPa)	30.33	
7d (MPa)	37.79	
28d (MPa)	50.85	

## 2. Materials and experimental program

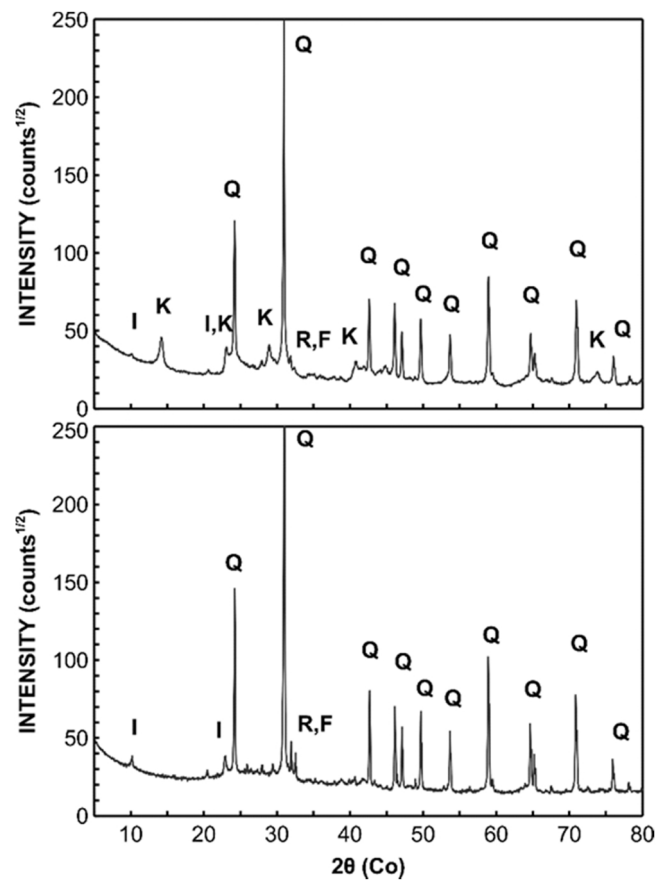
### 2.1. Materials

Materials used included Portland cement, aggregates (coarse and fine), calcined clay pozzolan, a superplasticizer, and potable water. Portland cement class 42.5 R conforming to GS 1118:16 [23] was sourced from a retail market in Fumesua, Ashanti region. The Blaine-specific surface area of the Portland cement was 402 m<sup>2</sup>/kg. The coarse aggregate was a crushed granitic rock obtained from Akani Limited, a stone quarry company at Asonomaso in the Ashanti Region. The specific gravity of the coarse aggregate was 2.69. Pit sand was obtained from Juaben in the Ashanti region. The specific gravity and the fineness modulus of the sand were 2.63 and 3.00 respectively. The pozzolan was obtained from the factory of CSIR-Building and Road Research Institute. The information from the factory indicates that the material is produced at an estimated temperature of 800 °C. The pozzolan had 85% passing through the 75 µm sieve size. The Blaine-specific surface area of the clay pozzolan is 420 m<sup>2</sup>/kg. Table 1 shows the chemical properties, mineralogical and physical properties of the cement and the pozzolan as well as the mechanical properties of the Portland cement. Fig. 1 displays the X-Ray diffraction (XRD) pattern of the raw and the calcined clay pozzolan. The results of the Rietveld analysis, performed on the uncalcined material using the Profex software [24], show that the mineralogical composition consists mainly of quartz and kaolinite, with an approximate concentration of 60% and 30% respectively. The remaining phases comprise minor amounts of illite (3%), feldspar (3%), rutile (1%), chlorite (1%), and goethite (1%). Clay with less than 40% kaolinite content is characterized as a low-grade kaolin type of clay whereas those between 40% and 60% are medium grade and above 70% of kaolinite is classified as high-grade kaolin clay [25,26]. Subsequent to the thermal treatment, all kaolinite peaks disappear, showing that the kaolinitic fraction has converted to metakaolinite.

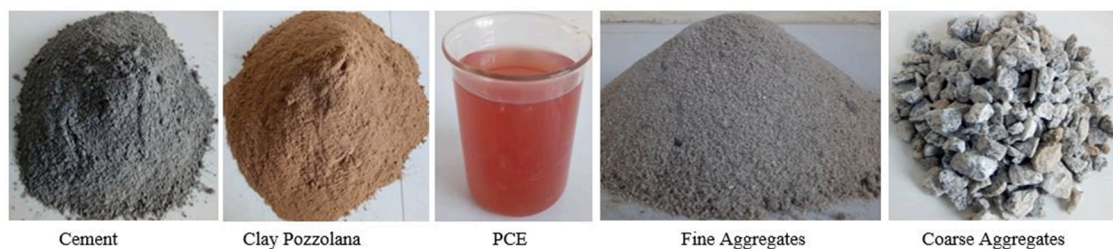
A polycarboxylate ether (PCE), a chemical admixture, in a form of a high-range water reducer containing 20% solid content obtained from Ghana was used. The manufacturer data sheet indicates that the PCE allows the user to reduce water content by up to 10%. Fig. 2 shows the nature of the Portland cement, clay pozzolan, PCE, pit sand, and coarse aggregate used for the work.

#### 2.1.1. Concrete mix design

The concrete mix design was performed using the ACI 211.1 [27] method. Concrete with a strength class of 30 MPa and slump between 75 mm and 100 mm were the specified parameters. Other basic information required for the mix design were maximum aggregate size, the environmental conditions, and the specific gravities of the aggregates, cement, and the pozzolan. Clay Pozzolan was used to replace a portion of cement at a content of 10, 20, 30, 40, and 50 (wt%). The design protocols explained in ACI 211.1 [27] were used to prepare an excel spreadsheet program that aided the computation of the proportioning of the concrete constituents. Table 2 presents the concrete mix proportions of C24/30 concrete.



**Fig. 1.** XRD patterns of the raw (top) and calcined (bottom) clay pozzolan. Main phase labels: illite (I); kaolinite (K); quartz (Q); rutile (R); feldspar (F).



**Fig. 2.** Constituents used for the concrete mix.

**Table 2**

Constituents of cubic meters of C30 concrete.

Component	0%	10%	20%	30%	40%	50%
Cement (kg)	412	371	330	288	247	206
Agg. (coarse)(kg)	963	963	963	963	963	963
Agg. (fines) (kg)	731	800	793	786	777	769
Pozzolan (kg)	0	41	82	124	165	206
Water (kg)	208	177	177	177	177	177
Ch. Admixture (kg)	0.0	2.6	3.3	3.9	5.2	6.2
Ch. Admixture (%)	0.0	0.71	0.99	1.34	2.10	3.00

**Table 3**  
Embodied carbon of concrete constituents.

Material	Carbon equivalent (kgCO <sub>2eq</sub> /kg)	Reference
Portland cement (42.5 R)	0.9500	Hammond and Jones[27]
Coarse Aggregate	0.00419	Ecoinvent,[32]
Sand	0.00419	Ecoinvent,[32]
Superplasticizer	0.7670	Gursel and Horvath[31]
Calcined clay pozzolan	0.0700	Zhou et al.[20]
Water	0.0000658	Ecoinvent,[32]
Transportation by truck	0.203 <sup>b</sup>	Gursel and Horvath[31]

b=kgCO<sub>2</sub> eq./t-km

## 2.2. Preparation, casting, and curing

The preparation of the concrete mixes was performed by first undertaking trial mixes to determine the slump in accordance with BS EN 12350-2 [28]. A concrete mixer having a volume of about half a cubic meter was used in mixing the constituents. Mixing of the materials was performed by first adding the measured water and the chemical admixture together in a container. The coarse aggregates were measured and poured into the mixer after which about 15% of the volume of the mixing water was poured over the aggregate followed by the addition of the measured fine aggregates and then the Portland cement. After mixing the constituents for about 90 s, the remaining water was added, and the mixing continued for about another three minutes. The water-to-cementitious powder ratio was maintained at 0.5 for all mixes, however, the parameter water content was adjusted for the cement-clay pozzolan binders. For concrete mixes containing the clay pozzolan, the water content was reduced by 10%, and the slump was fixed by adding the PCE. This was done to achieve the workability of concrete without necessarily adding excess water since calcined clay addition to Portland cement is known to increase the water demand. The water content of the control was maintained because there was no addition of admixture. Besides, the water content was appropriate to achieve complete hydration of cement, unlike the cement-pozzolan mixtures. With a solid content of 30%, the addition of admixture effectively increases the effective water content of the mixture. Hence maintaining the same water content as the control concrete would unnecessarily increase the effective water content available for the hydration of the cement-pozzolan concrete binder. After attaining the desired slump per BS EN 12350-2 [28] specifications, the proportions of the mix design used for the slump were scaled up to suit a total number of 15 different metal cubic moulds of 100 mm size. Table 2 shows that six different types of concrete were designed having total binder content ranging between 205.94 and 412.00 kg/m<sup>3</sup>. Concrete produced after mixing in the mixer was first transferred into a metallic mason's head pan and then distributed in a 15-number quantity of a 100 mm cubic mould, consolidated by an electric vibrator, and then stored under a plastic sheet and wet burlap at a temperature of 23 ± 2 °C for 24 h. After 24 h of curing, the concrete samples were demoulded and cured in lime-saturated water for 3, 7, 28, 56, and 90 days.

## 2.3. Compressive strength determination

Compressive strength tests were performed on three concrete samples of each concrete mix after the curing age was attained and the average strength determined. The tests were performed in accordance with BS EN 12390-3 [29]. The compressive strength machine used was with a maximum capacity of 1500KN. It was loaded at a rate of 2.6 KN/sec.

## 2.4. Life cycle assessment

Life Cycle Assessment (LCA) methodology is a tool used to estimate the carbon footprint of products. In this study, the LCA method was used to determine the CO<sub>2</sub> emissions from each concrete mix. Pillai et al. [21] and Miller [12] have explained the four major steps that must be considered in LCA. The steps include 1) defining the system boundary 2) the inventory analysis 3) impact assessment and 4) interpretation/ comparative analysis.

The system boundary defines the scope of analysis which could be defined as cradle-to-gate or cradle-to-cradle. In this work the boundary considered was cradle-to-gate. Cradle-to-gate carbon emission is the total primary CO<sub>2</sub> consumed from direct and indirect processes associated with the concrete within the boundary of ground-to-gate. These include material extraction, quarrying/mining, manufacturing, transportation, and right-through fabrication processes until the concrete is ready to leave the final gate. Emissions as a result of electricity with respect to the production of concrete and the emissions due to energy were omitted because it was difficult to compute the values due to a lack of data in Ghana.

Inventory analysis is usually performed by using developed data by some recognized bodies such as inventory from the University of Bath, Ecoinvent, Environmental Policy Act (EPA), IPCC, and other secondary data from researchers [21]. These databases comprise the embodied energy and carbon of products. Embodied carbon of a material defines the total carbon produced in the extraction and transportation of raw materials and their manufacture into a final product.

For the environmental impact assessment, CO<sub>2</sub> emission was considered as the index, and the conversion factors used are given in Table 3. The CO<sub>2</sub> emissions of cement were from the ICE database [30], aggregates (coarse and fine), and water were from the Ecoinvent database whereas the superplasticizers and truck emissions were from Gursel and Horvath [31]. The CO<sub>2</sub> emissions with respect to energy used for cement production were not considered in this estimation.

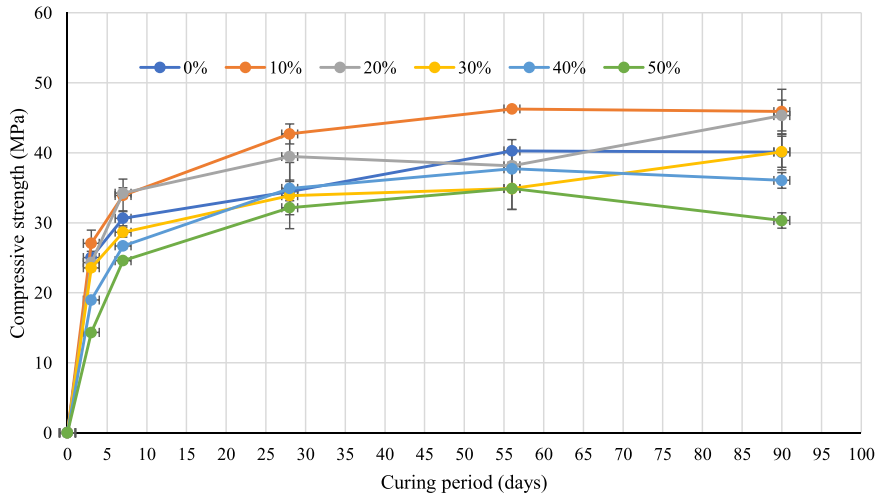


Fig. 3. Evolution of compressive strength in C30 concrete mixes.

In the performance of the LCA, a cubic meter of concrete was considered as the basis. The concrete was considered to occur in CSIR-Building and Road Research Institute, Kumasi, Ashanti region. The Portland cement for concrete batching was considered to be produced in Tema, Greater Accra Region, and transported 263 km by truck. The coarse aggregates were extracted and treated at Asonomaso in the Ashanti region and transported 26 km to the concrete batching site. The sand was sourced from Juaben, Ashanti region, and transported 18.3 km. The superplasticizer was from Adjirigano, Accra, and transported 247 km.

The total carbon emissions for the various mixes of concrete based on a cubic meter were calculated using the coefficient values given in Table 3. Estimations of the environmental impact per the strength obtained at a particular curing period were also deduced. These indices create a relation between the total embodied carbon and the strength performance and it is estimated as the ratio between the EC and the strength at various curing periods of 28, 56, and 90 days

$$EC = \sum_{n=1}^i (CMQ \times EEC) + (Tkm \times EECt) \quad (1)$$

$$EI = \frac{EC}{i - day \text{ compressive strength}} \quad (2)$$

Where  $EC$  = Embodied carbon;  $CMQ$  = mass of the  $i^{th}$  type material;  $EEC$  = Embodied carbon coefficient of the  $i^{th}$  material,  $Tkm$  = total kilometric distance covered to transport material to site,  $EECt$  is the embodied carbon coefficient of the truck,  $EI$  = Environmental impact,  $i$ -day = curing period.

### 3. Results and discussions

The compressive strength of the various concrete mixes is displayed in Fig. 3. The strength development of the pozzolan concrete mixes was compared to the Portland cement mix (Control). The strength evolution of the concrete mixes was characterized by two-early and late strength development. The early strength characterization of cement-based products is usually 3 and 7 days whereas the late ages are 28, 56, and 90 days.

At 3 days, the strength of the 10% concrete mix was approximately 8% higher than the control mix whereas the other mixes (20–50%) were all lower than the control mix by between 2% and 43%. At 7 days, the compressive strength of concrete mixes with 10% and 20% pozzolans was 11% and 12% higher respectively than the control (0%) concrete mix. However, the 30%, 40%, and 50% concrete mixes had lower strength ranging between 6% and 20% compared to the control (0%) concrete mix.

With the late strength ages, at 28 days, the mixes 10% and 20% attained about 24% and 15% higher respectively than the control mix. However, the concrete mixes 30% and 40% as labeled had similar strength as the control concrete mix. The 50% concrete mix was about 7% lower than the control mix. For the 56 days strength evolution, the 10% mix had about 14% extra strength than the control whereas the remaining concrete mixes (20–50%) were all lower than the control mix by between approximately 5% and 14%. At 90 days, both the 10% and 20% mixes showed superior strength to the control, evolving with approximately 14% and 13% higher respectively. 30% concrete mix had similar strength as the control whereas the 40% and 50% mixes recorded about 10% and 24% lower respectively than the control mixes.

The improved performance of the 10% concrete mix at 3 days attaining higher strength than the control and other mixes could be due to the filler effect. With this filler effect, pozzolans create nucleation sites that enhance the precipitation of C-S-H [33,34]. This has the double effect of both accelerating the precipitation of hydrates and refining the pore network, leading to the development of a more compact microstructure, which in turn positively affects mechanical strength. The same filler-effect mechanism can be used to explain



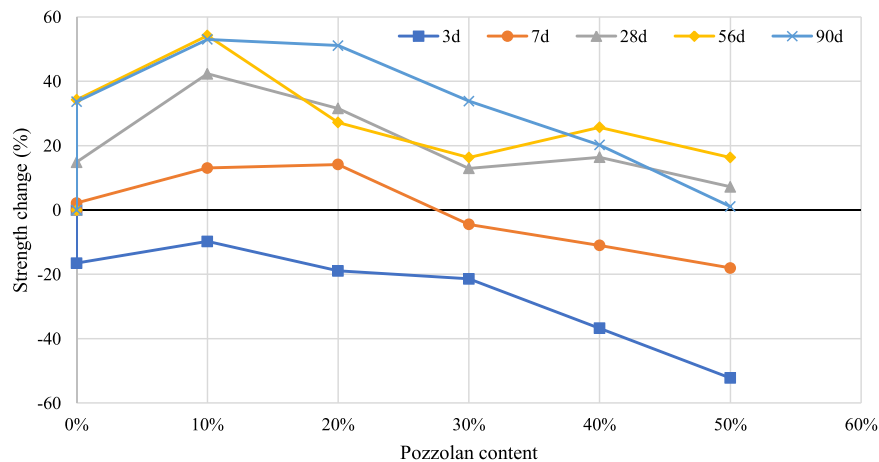


Fig. 4. Percentage strength change of different concrete mixes normalized with the characteristic strength.

Table 4

Total and embodied carbon emissions per cubic meter of concrete.

Component	Concrete mix in a cubic meter						Transportation
	0%	10%	20%	30%	40%	50%	
Cement	391.400	352.450	313.030	273.901	234.772	195.644	53.389
Agg. (coarse)(kg CO <sub>2</sub> eq)	4.035	4.035	4.034	4.034	4.034	4.034	5.278
Agg.(fines) (kg CO <sub>2</sub> eq)	3.063	3.350	3.321	3.292	3.255	3.222	3.715
Pozzolan (kg CO <sub>2</sub> eq)	0.000	2.870	5.766	8.650	11.533	14.416	0.000
Water (kg CO <sub>2</sub> eq)	0.014	0.012	0.012	0.012	0.012	0.012	0.000
ch.admixture (kg CO <sub>2</sub> eq)	0.000	2.024	2.491	3.985	3.985	4.733	50.141
EC (kg CO <sub>2</sub> eq)	398.512	364.741	328.655	293.874	257.592	222.061	112.523
Total (kg CO <sub>2</sub> eq)	511.034	477.264	441.178	406.397	370.115	334.584	

the performance of the 10% and 20% concrete mixes at 7 days. On the other hand, the lower strength of concrete mixes labelled 30%, 40%, and 50% could be attributed to the dilution effect which limits the rate of precipitation of hydrates. The presence of impurities (illite, rutile) and crystalline quartz as shown in the results of the X-ray diffraction analysis of the pozzolan could be among the major factors that contribute to the dilution of the reactive phases of the pozzolan. The dilution effect leads to a lower Ca/Si ratio which makes the hydrates unstable [35].

The 28-day strength performance of up to 20% concrete mixes which maintained a superior strength over the control validates the idea that a pozzolanic reaction occurred between cement hydrates and the pozzolans (10% and 20%). With pozzolanic reaction, products are usually formed to fill spaces created as a result of the chemical dilution effect and therefore leads to strength gain of the concrete. In the same vein, the performances of 30%, 40%, and even 50% concrete mixes could be justified by the occurrence of pozzolanic reaction. Their performances show that some products were formed in the concrete mixes that had a positive impact on the compressive strength. The superior performance of the 10% concrete mix over the control mix at 56 days could be attributed to the lower effect of impurities present in the pozzolan. The other concrete mixes (20–50%) strength values reduced marginally meaning that the effect of crystalline products in the pozzolan was minor. Pozzolans with a limited number of crystalline phases are active, hence don't bind the lime from cement [36]. The 90 days enhanced performances of 10%, 20%, and even 30% concrete mixes compared to the control mix show that there was more space to fill pores of the concrete with pozzolanic products occurring from pozzolanic activity. On the other hand, the effect of dilution revealed the decreased strength of the 40% and 50% concrete mixes compared to the control. Beyond 30%, the lime needed for pozzolanic reaction was exhausted in the concrete matrix hence the reduction in strength [37].

### 3.1. Attainment of characteristic strength with varying pozzolan content

Fig. 4 shows the plot of percentage strength change against the concrete mixes. The characteristic strength, 30 MPa is normalized and indicated on the vertical axis as a 0% strength change. For the 3 days of curing, the concrete mixes (0–50%) trailed the characteristic strength between 16% and 52%. At 7 days, 0%, 10%, and 20% concrete mixes had percentage strength changes of approximately 2%, 13%, and 14% respectively higher than the normalized characteristic strength. However, for the 30–50% concrete mixes, their compressive strengths trailed the characteristic strength between 4% and 18%.

With the late strength development (28, 56, and 90days), all the percentage strength changes were higher than the characteristic strength ranging from about 7–42%. The 10% concrete mix recorded the highest strength change of about 42% and the 50% concrete

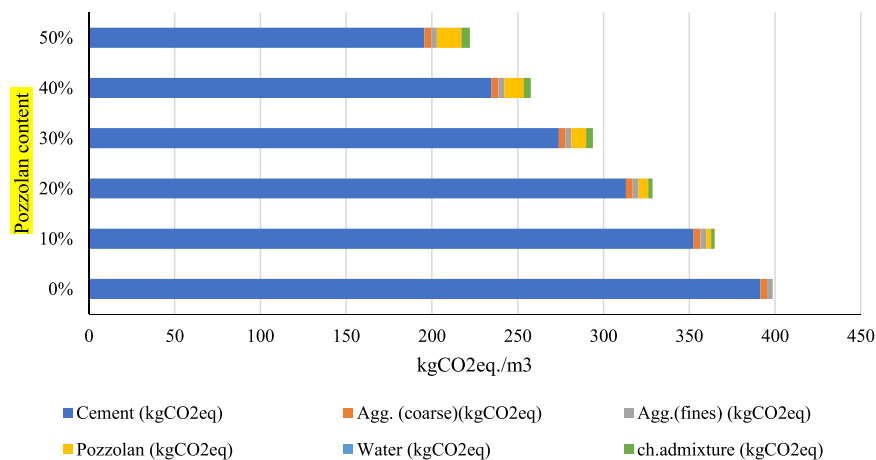


Fig. 5. Carbon emissions per cubic meter of concrete.

mix recorded the lowest being 7%. A similar trend was observed with the 56- and 90-day strength change of the different concrete mixes compare to the control. The percentage strength change for the 56 days was between approximately 16% and 54% whereas that of the 90 days was between approximately 1% and 53%. Again, at 56 and 90 days, the highest percentage strength change was the 10% concrete mix whereas the 50% mix recorded the lowest percentage strength change. Though the 50% concrete mix recorded the lowest percentage strength change, its strength attainment was marginally higher than the characteristic strength at long-term strength development of 28, 56, and 90 days. The lower strength of 50% concrete could mean that the pozzolan content needed for the pozzolanic reaction was far exceeded in the concrete matrix. This explanation falls in line with that of Aramburo et al. [37].

### 3.2. Life cycle assessment

Table 4 presents the total carbon emission of the processes involved in producing a cubic meter of the different concrete mixes. Rows 7 and 8 are the estimated sum of embodied carbon and the total carbon content deduced by adding the EC to the emissions as a result of transportation of the constituents. The table shows that transportation of cement and superplasticizers which are about 53 and 50 kg CO<sub>2</sub>eq is very high and therefore has a higher impact on the total carbon emission. Therefore, sourcing these constituents regionally could significantly reduce the overall carbon dioxide emissions per cubic meter of concrete.

Fig. 5 shows the embodied carbon associated with the different constituents making a cubic meter of different batches of concrete mixes. As expected, the highest emission was from the Portland cement concrete. However, the emissions were reduced progressively with increasing content of the clay pozzolans in the concrete mixes. The figure also shows that emissions resulting from other constituents were very marginal compared to the emissions from PC. Moreover, the carbon emission from the combined effect of the other constituents aside from cement (aggregates, pozzolans, water, and admixtures) increased significantly ( $p = 0.000888$ , see Appendix 1) with increasing pozzolan content in the mix. With the inclusion of carbon emissions resulting from the transportation of the concrete constituents to the embodied carbon per cubic meter of the mixes, the total carbon emission decreased progressively with increasing pozzolan content.

The total carbon dioxide emissions and the environmental impact (EI) per strength for all the concrete mix at 28-, 56- and 90-day curing are displayed in Fig. 6. The overall carbon emissions showed a progressive decrease with increasing content of the pozzolan from 0% to 50% at all the curing periods of 28, 56, and 90days. For the performance of the EI, the pozzolan concrete obtained lower impacts than the OPC concrete. The 50% concrete mix had the least environmental impact at 28- and 56-days curing. However, at 90 days, its impact was a little high than the other pozzolan concretes (10–40% mixes). A similar trend was obtained by Miller [38] in the use of fly ash and GGBS for concrete.

The performance of the EIs of the pozzolans and OPC concretes which indicated lower carbon impacts than the OPC concrete could be attributed to pozzolanic reaction. The study of Miller [38] revealed that pozzolanic reaction contributes more to strength development and thereby reduces the carbon emissions per cubic meter to compressive strength ratio for the concrete mixtures.

## 4. Conclusions

This study investigated two different binders, OPC and OPC-pozzolan binders that were used to formulate normal-grade concrete with characteristic strength of 30 MPa. Compressive strength and total carbon emissions from the different concrete mixes were determined. From the study, the following conclusions were made.

1. Binder made using 50% cement and 50% pozzolan obtained compressive strength of approximately 32, 34, and 30 MPa at 28, 56, and 90 days respectively. The results obtained at all curing periods meet the 30 MPa grade concrete



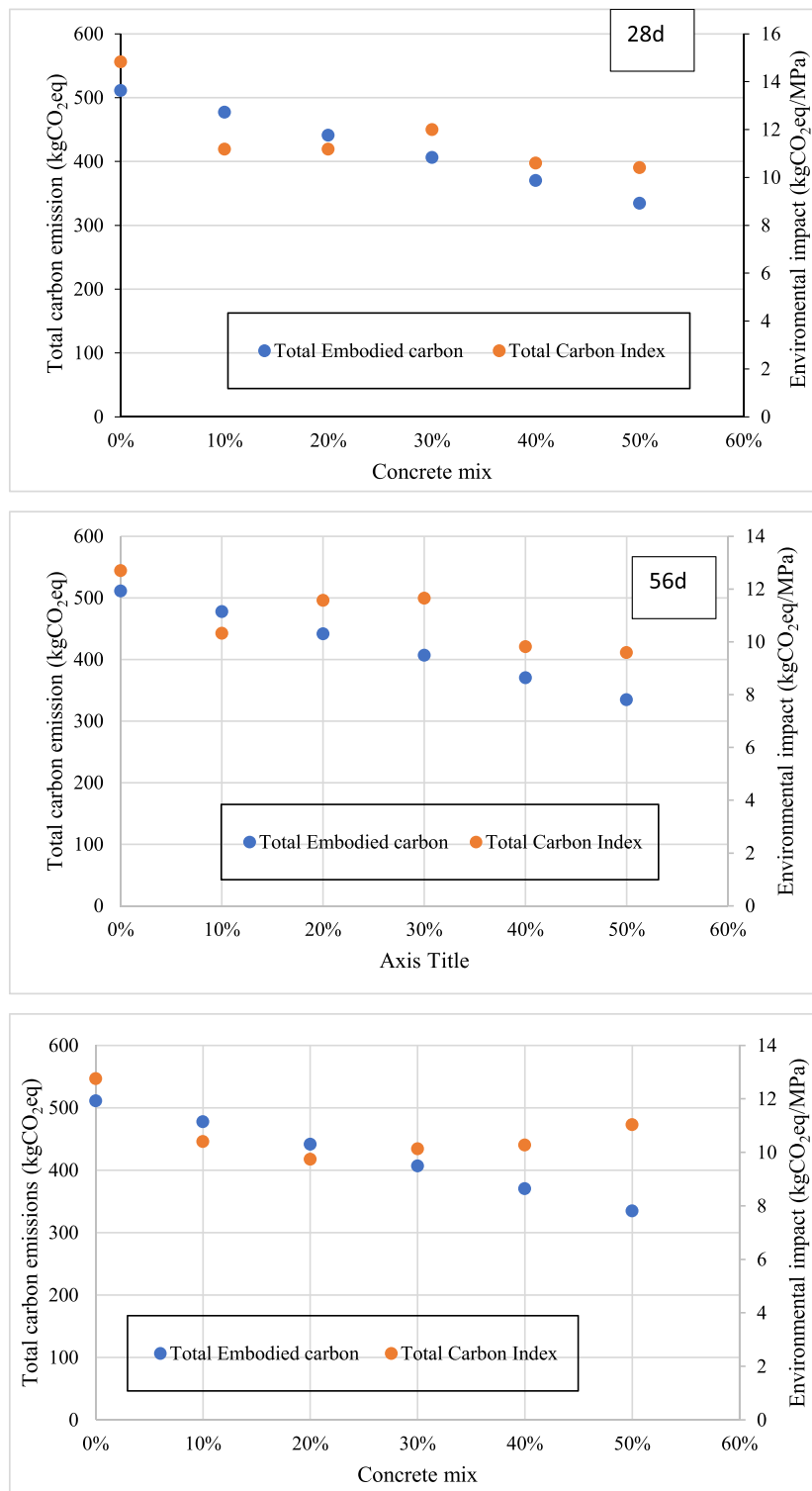


Fig. 6. Total carbon emission and carbon index at 28, 56, and 90 days.

- The embodied carbon of the different concrete mixes progressively reduced with increasing pozzolan content in a cubic meter of concrete. OPC concrete mix had the highest embodied carbon of approximately 399kgCO<sub>2</sub>eq whereas the 50% concrete mix had the least of approximately 222kgCO<sub>2</sub>eq

3. The total carbon emissions considering the transportation scenario of the cement and superplasticizer had a significant impact on the concrete.
4. The environmental impacts of the concrete mixes at 28, 56, and 90 days were lower in the pozzolan concrete than the OPC concrete.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix 1

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	159.8332	4	39.95829	7.250522	0.000888	2.866081
Columns	50.47734	5	10.09547	1.831846	0.152244	2.71089
Error	110.2218	20	5.511091			
Total	320.5323	29				

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