Construction and Building Materials 342 (2022) 127906

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Cement-based concrete modified with Vitellaria Paradoxa ash: A lifecycle assessment

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A R T I C L E I N F O

Keywords:
Compressive strength
Concrete
Global warming potential
Lifecycle assessment
Shea nutshell ash
Sustainability

A B S T R A C T

Building sustainable concrete requires an increasing demand for technology, innovation, and alternative binders to cement. The building sector is technologically driven toward sustainable construction materials and their relationship with the environment. Thus, this study designed three grades of cement-based concrete strengths (C 25, C 30, and C 40) modified with an alternative binder, shea nutshell ash (Vitellaria Paradoxa Ash, VPA). The binder (VPA) was varied at 0–20 wt% of Portland limestone cement (PLC) cured at 28 days, examining the compressive strength cost attained sustainability. Moreover, the embodied energy (EE), global warming potential (GWP) and global temperature potential (GTP) of the concrete compositions were evaluated using the inventory of carbon and energy (ICE) method within the confine of cradle-to-site. Also, the sustainability index (S_i) and economic index (E_i) of the concrete mixes were assessed. The results revealed that VPA-cement-based concrete yielded a lesser EE, GWP, GTP, S_i, and Ec_i than the control concrete (Portland limestone cement concrete, PLCC), indicating VPA-cement-based concrete is more sustainable than PLCC. Notwithstanding, an optimum replacement of 15 wt% PLC with VPA is recommended to satisfy all assessments earlier stated for all concrete strength grades. Therefore, these findings can be beneficial in attaining a cleaner built environment and sustainable production. Finally, VPA has proved to be a sustainable building material.

1. Introduction

Rapid industrialization and urbanization have increased the demand for Portland cement (PC) in the building sector. This raises environmental problems and energy consumption in the built environment [1–3]. Majorly, the building sector relies on PC as a binder for concrete production [4,5]. However, the evolution of PC production goes with many environmental burdens associated with climate change and global warming. During PC production, intensive energy is generated due to the limestone heating for clinker production, contributing about 7 % of the world's anthropogenic carbon dioxide (CO_2) emissions into the atmosphere [6–8] and 14 % of the total world energy consumption from the industrial sector [9]. In addition, Huntzinger and Eatmon [10], Li et al. [11], Maji and Adamu [12], and Peng et al. [13] reported that during the PC production, high embodied energy is consumed, generating about 0.82–1.00 metric ton of CO_2 emissions per each ton of PC produced. It is essential to state that buildings consume about 40 % of the world's energy production [14,15]. The energy demand and environmental cost of energy production increase with time [15–17]. Fernando et al. [18] also established that about 80 % of greenhouse gas emissions (GHGe) and energy consumption are produced during the building operation stage. Notably, the increase in GHGe is responsible for climate change. In 2017, approximately 54 $GtCO_2$-eq was emitted due to the high demand for PC and concrete. These are expected to increase in the future [18]. Consequently, PC alternatives are considered the most feasible options for sustainable concrete production in the building sector to mitigate greenhouse gas emissions [1,4], which relate to the building's operational energy and embodied energy (EE) materials. Among these alternatives is the valorization and utilization of agro-industrial waste materials. The agro-industrial waste materials, otherwise called supplementary cementitious materials (SCMs), are greener alternatives to PC due to their lower CO_2 emissions [19].

Blended cement concrete has been reported to reduce Portland cement concrete (PCC) dependency and related emissions. Typically, blended cement composes PC partially replaced with SCMs such as fly ash, rice husk ash (RHA), corncob ash (CCA), silica fume (SF), and ground granulated blast furnace slag (GGBFS). Asim et al. [17], Aprianti et al. [20], and Ashish [21] established that the utilization of SCMs in the

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https://doi.org/10.1016/j.conbuildmat.2022.127906
Received 30 December 2021; Received in revised form 16 May 2022; Accepted 16 May 2022
Available online 23 May 2022

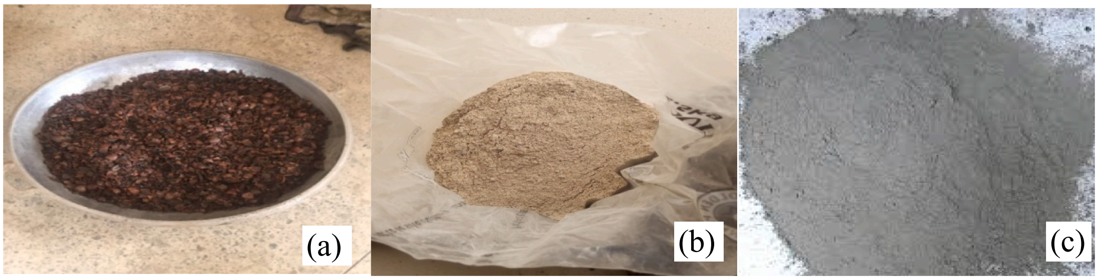


Fig. 1. The materials used are (a) Shea nutshells, (b) VPA, and (c) PLC.

building sector reduces energy consumption and environmental impacts, contributing to energy and environmental preservation and sustainable development. Replacing PC with SCMs is a globally recognized approach to improving concrete properties and environmental effects [22,23]. It is pretty interesting to know that replacing a PC with about 25–50 wt% of SCMs results in about 20–67 % reduction in required energy and 33–80 % reduction in material cost [24]. Also, Flower and Sanjayan [25] stated that about 13–22 % of CO_2 emissions are reduced when SCMs replace PC. Ali et al. [26] reported that the reduction in carbon dioxide emissions depends on the blended quantity of SCMs, source of raw materials, and production processes. From the durability viewpoint, composite concrete modified SCMs such as GGBFS, CCA, fly ash, RHA, SF, and metakaolin (MK) have exhibited better acidic and sulfate resistances than PCC [20,27–30].

Globally, approximately 0.55 million metric tonnes of shea nut were generated in 2017, with Africa and Nigeria producing about 0.55 and 0.36 million metric tonnes, respectively [31]. Shea nutshell ash (Vitellaria Paradoxa ash [VPA]) is obtained from the valorization of a shea nutshell, while shea butter is produced from shea nuts [32]. The shea tree is predominantly found in the savanna regions of sub-Saharan Africa [33]. Statistically, about 16.2 million shea nuts are obtained by the shea industry, out of which 1,760,000 and 680,000 metric tonnes are produced from Africa and West Africa, respectively [34]. The shea nuts contain approximately 50 % butter, while the extractive potential via the traditional mean is 25 % [34]. Furthermore, the multipurpose functions of shea butter cannot be over-emphasized. Shea butter is a suitable ingredient/substitute in pharmaceuticals, detergent, cosmetics, chocolate, beautification, and other confectionery industries [34–36]. Despite the economic and nutritional benefits of shea nuts, their indiscriminate disposal after extraction from the shells has become a significant concern to the environment. The major challenge with this indiscriminate environment disposal includes methane (CH_4) emissions. This is 21 times higher global warming potential (GWP) per molecule than carbon dioxide (CO_2) [37], presenting an intellectual challenge to scientists and researchers for its eco-friendly beneficial recycling. Hatskevich et al. [38] and Rousseau et al. [39] stated that construction is a sector with feasible potential valorizing shea nutshells for building applications. Presently, shea nutshell has no commercial value In Nigeria. Thus, it is discarded as waste, creating environmental pollution.

Recent studies have been tailored to reduce operational embodied energy (EE) and embodied carbon dioxide emissions (EC) of construction materials in the built environment. The embodied energy measures the total energy consumed from direct and indirect operations related to the material within the confines of cradle-to-gate [40]. According to Hammond and Jones [40], cradle-to-gate covers all input and output flow of materials deposited within the ground up to the industry gate of the final processing operation. Also, EC sums the fuel-related carbon emissions together without the feedstock energy retained within the material. In 2019, the global energy-related CO_2 emissions were about 33 gigatonnes (Gt) [41], of which nearly 4.1 Gt was generated by the cement industry [41]. Furthermore, the construction sectors emit about 40 % of direct and indirect CO_2 and consume approximately 33.33 % of global energy [42]. Moreover, nearly a 4.8 % increase in global-energy related CO_2 emissions is projected in 2021 [43]. However, reducing global-energy related CO_2 emissions while producing enough cement to meet demand is challenging due to demand growth. Annual cement production is expected to increase moderately to 2030 without reducing its need [43]. To get on track with the 2030 sustainable development target, a 0.8 % annual decline is necessary by taking advantage of opportunities for agro-industrial symbiosis, including utilizing the alternative binding materials and waste or by-products to produce another value product [44]. These would help reduce the energy embodiments [44–48] and carbon dioxide emissions [49–52]. Therefore, PC replacement by SCMs significantly reduces EE and EC [45,48].

Abubakar et al. [45] evaluated the EE and EC of concrete modified with CCA. The results showed that EE and EC decreased with increasing CCA content in the mixes. González and Navarro [53] stated that about 30 % of CO_2 emissions could be reduced when low impact building materials are utilized. In the same vein, Coffetti et al. [48] reported that the partial replacement of Portland cement with low-embodied carbon and low-energy materials can enormously reduce the overall environmental impact of binders and concrete.

From a sustainable viewpoint, assessing blended cement concrete (BCC) is essential, particularly as the environment and economy become increasingly germane factors in global research and policy. Environmental and economic evaluations of BCC using lifecycle assessment (LCA) offers additional measures for researchers to evaluate the BCC and improve its eco-friendly production. According to the International Organization for Standardization (ISO) [54], a lifecycle assessment is an analytical and established tool used to evaluate the product's environmental impacts throughout its lifecycle. The partial replacement of cement with SCM (VPA) in the construction and building sector reduces the environmental impacts, materials' initial cost, and landfill disposal activities [55,56]. No study has been conducted to evaluate the LCA of cement-based concrete modified with VPA and compare it with Portland limestone cement concrete (PLCC).

This study fills this gap by evaluating the transportation impact (Ti), embodied energy (EE), environmental impacts (En_i), sustainability index (S_i), and economic index (Ec_i) for various mix proportions of BCC of the different strength grades within the confine of cradle-to-site. Cradle-to-site encompasses cradle-to-gate and transport to the site of usage [40]. Specifically, concrete grade strengths C 25, C 30, and C 40 at 28 days of compressive strength were selected, designed, and used for the evaluation. Moreover, transport, energy and emission coefficients were obtained via the inventory of carbon and energy (ICE) and extant literature. The results obtained herein would help establish the critical variables and conditions for impact reduction when considering the environmental and economic prospects of VPA-cement-based concrete production.

2. Materials and methods

2.1. Materials

As indicated in Fig. 1, Sheanut shells (Vitellaria Paradoxa) was valorized, getting approximately 20 wt% ash (VPA). Before the

Table 1
Oxide compositions of materials used.

Binding materials	Oxide compositions (%)										
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	TiO_2	P_2O_5	LOI
VPA	6.62	54.85	18.78	8.10	1.26	1.85	0.75	1.15	1.38	0.25	3.75
PLC	64.70	21.80	5.75	2.88	1.42	0.72	0.14	2.03	–	–	1.38

Table 2
Materials' properties.

Properties	VPA	PLC	Fine aggregate (FA)	Coarse aggregate (CA)
SG (g/cm^3)	2.45	3.15	2.60	2.64
Fineness (%)	7.80	7.50	–	–
SSA (m^2/kg)	495	375	–	–
Mean particle size (µm)	19.25	22.34	–	–
Water absorption (%)	–	–	0.70	0.80
Moisture content (%)	–	–	0.32	0.22

valorization, the shea nutshells were sun-dried for 7 days to aid the heating process. Table 1 presents the use of VPA and Portland limestone cement (PLC) oxide elements. The results showed that VPA met 70 % minimum requirements of silica, aluminate, and ferrite specified by British Standard (BS) EN 450–1[57] and BE EN 8615–2 [58]. The minimum content of 25 % SiO_2 [58] and the maximum contents of 3 % of MgO and 4 % of SO_3 [58] were satisfied. Moreover, a 5 % maximum loss of ignition (LOI) stated in the American Society for Testing and Materials (ASTM C 618) [59] and a 10 % maximum recommendation for any SCM were satisfied [57,58]. Therefore, the VPA used can be classified as Class F pozzolan [59]. In the same vein, the PLC (42.5 R grade) shown in Fig. 1, classified as CEM II [60], satisfied the oxide elements of BS EN 196–3 [61].

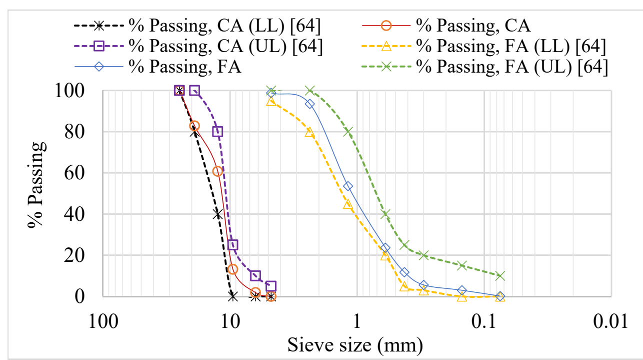
Table 2 shows the specific gravity (SG), fineness, and specific surface area (SSA) of the binding materials used. The SG and SSA were obtained based on the experimental procedures outlined in BS EN 196–3 [61], while fineness was determined based on BS EN 196–6 [62]. The binders' particle size distribution (PSD), determined via the Laser diffraction, Model Beckman Coulter LS-100, was shown in Fig. 2. As shown in Table 2, the VPA's SG and mean particle size are lower than PLC. However, VPA exhibited higher fineness and SSA than PLC, indicating more volume and water addition when VPA is substituted with PLC [63].

These results would help VPA withstand a higher resistance under alkaline conditions [63]. Besides, the reaction of VPA with PLC would enable the concrete to yield a higher performance capacity [63].

Similarly, as presented in Table 2, the aggregates' properties were determined by the experimental procedures highlighted in BS EN 12620 [64]. As indicated in Fig. 3, the grading was evaluated according to the BS EN 12620 [64] 's procedure.

2.2. Sample design quantities, mixture selection, preparation, and test

The sample mix quantities were designed to American Concrete Institute (*ACI* 211.1) [65] 's procedure, considering the physical properties of the constituents used. The design mix quantities are presented in Table 3 for concrete strength grades 25 (C 25), 30 (C 30), and 40 (C 40). Generally, concrete is designed in grades equivalent to classes of strength globally. Therefore, C 25 (25 MPa), C 30 (30 MPa), and C 40 (40 MPa) are concrete grade types that conform to the specifications of water-cement ratio, cement content, slump, and nominal size of aggregate [66–68]. They are widely in the construction and building sector as



LL and UL are both lower and upper limits.

Fig. 3. The PSD of aggregates used.

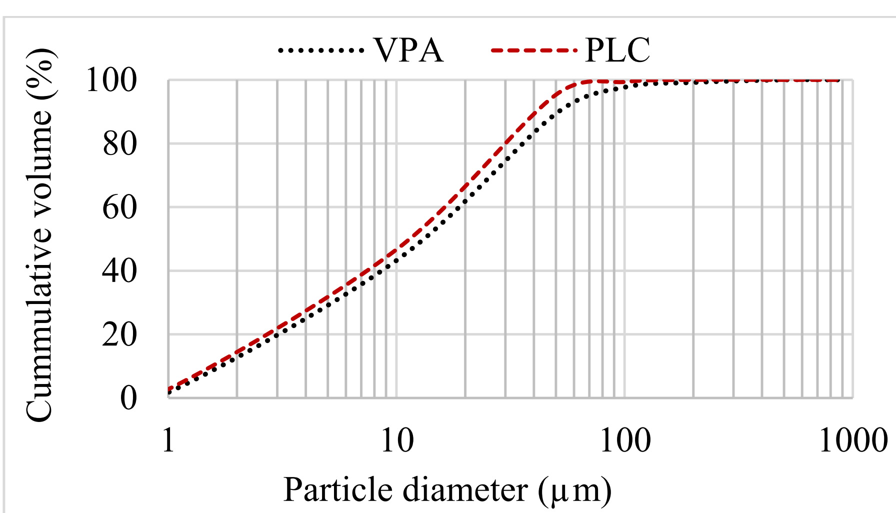


Fig. 2. The PSD of binding materials used.

Table 3
Design mix quantities.

Concrete grade	Mix ID	Replacement level	Binder (kg/m^3)		Aggregate (kg/m^3)		Water (kg/m^3)
			PLC	VPA	FA	CA	
C 25	V0	0 %	312	0	885	1045	190
	V1	5 %	296	16	881	1045	190
	V2	10 %	281	31	877	1045	190
	V3	15 %	265	47	873	1045	190
	V4	20 %	250	62	869	1045	190
C 30	V0	0 %	352	0	850	1045	190
	V1	5 %	334	18	845	1045	190
	V2	10 %	317	35	841	1045	190
	V3	15 %	299	53	836	1045	190
	V4	20 %	282	70	832	1045	190
C 40	V0	0 %	452	0	762	1045	190
	V1	5 %	429	23	756	1045	190
	V2	10 %	407	45	751	1045	190
	V3	15 %	384	68	745	1045	190
	V4	20 %	362	90	740	1045	190

Conditions: Nominal maximum size of CA = 19 mm well-graded;
Slump = 25–75 mm;
Exposure = Normal;
Target air content = 2 % (non-air-entrained concrete);
W/C - Water-cement ratios = 0.61, 0.54 and 0.42 for C 25, C 30, and C 40 MPa, respectively.

reinforced concrete in structural elements (C 25 and C 30) and as special concrete and construction (C 40) [69].

The mixing was done based on the standard specifications [70,71]. The samples were made of 150 mm^3 cubes for compressive strength, compacted in layers by applying 35 S, and cured under 25 ± 3 °C and 65 % relative humidity for 28 days. An average of three tests was used for the analysis.

The concrete compressive strength (fc) was tested at 28 days of curing, following the BS EN 12390–3 [72] 's procedure and relevant studies [73–75] via the 2000 kN maximum capacity compressive testing machine, Model: YES 2000. For the analysis, an average of three samples crushed was used.

3. Assessment methodology and data

3.1. Goal and scope

The study assesses the T_i, En_i, EE, S_i, and E_i of cement-based concrete modified with VPA and compares it with PLCC (100 % PLC concrete). The concrete mixes were designed and prepared based on 25, 30 and 40 MPa grade strengths and tested at 28 days. Kyoto Protocol established carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and hexafluoride (SF_6) as six categories of GHG [76]. However, fossil fuel combustions are the direct consequence of emissions in the construction industry [18,77–80]. Thus, this research assessment considered carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) as GHG emissions. These emissions are converted into CO_2 equivalent (CO_2-eq) through global warming potential (GWP) [40,78] and global temperature potential (GTP) [81]. Consequently, this study considered only GWP and GTP as environmental impacts.

3.2. Functional unit and assessment boundary

The study's functional unit is one cubic metre (1 m^3) of 25, 30 and 40 MPa concrete strength grades. The functional unit of concrete's GWP, GTP, and EE are $kgCO_{2\text{-}eq}/m^3$, $kgCO_{2\text{-}eq}/m^3$, and MJ-eq/m^3, respectively. Moreover, the concrete's sustainability and economic indexes are set to ($kgCO_{2\text{-}eq}/m^3$)/MPa and (\$/m^3)/MPa functional units, respectively. The study's boundary is within cradle-to-site confine, encompassing cradle-to-site and material transportation [40]. This assessment considers blended cement concrete (BCC) and Portland limestone cement concrete (PLCC) for production. On the other hand, Hammond and Jones [40] asserted that the determination of complete boundary conditions is not always possible for EE and EC data in the original materials due to the complex characteristics of some data and discrepancies across the constituents. However, incomplete data usually have enough information for evaluating EE coefficients [40]. The assessment boundary encompasses the emission process related to the production of concrete constituents for the two types of concrete. The concrete components are PLC, VPA, FA, CA, and water (W). During the extraction and transportation of raw materials, energy is consumed. Thus, the study assessed energy consumption and transportation emissions. The study's boundary for concrete production is shown in Fig. 4.

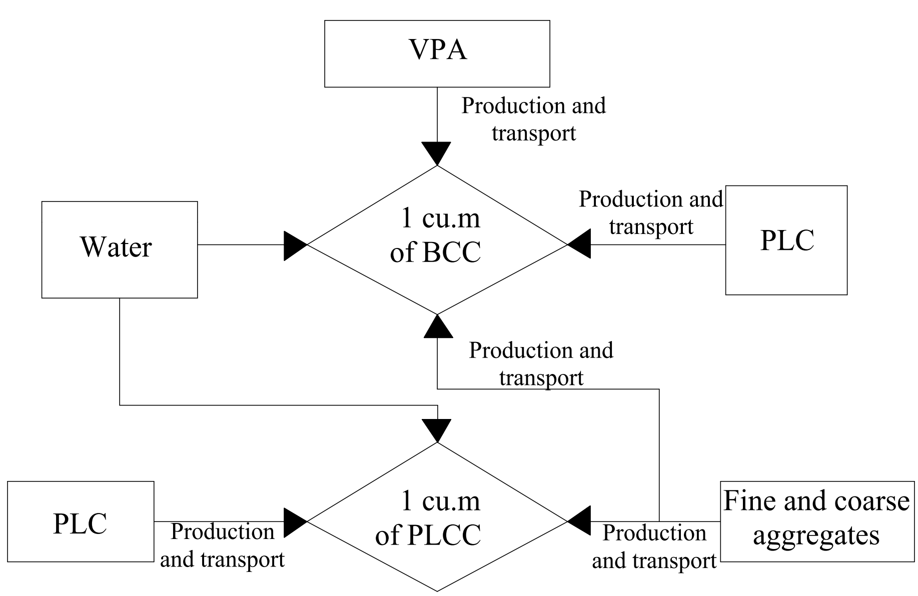


Fig. 4. Assessment boundary for BCC and PLCC productions.

Table 4
EE coefficients (EE_c) for concrete constituents (cradle-to-gate).

Constituent	EE_c (MJ-eq/kg)	Reference
PLC	5.50	Hammond and Jones [40] Office of the Energy Efficiency [87] Alcorn [88] Reddy and Jagadish [89] Van Deventer et al. [90]
VPA	1.48	Eq. [1]
FA	0.081	Hammond and Jones [40] Jamieson et al. [46] Alsalman et al. [91] Langer [92]
CA	0.083	Hammond and Jones [40] Jamieson et al. [46] Alsalman et al. [91] Langer [92]
Water	0.01	Hammond and Jones [40]

3.3. Inventory data

The inventory data was used to obtain the transportation, EE, GWP, and GTP coefficients via the inventory of carbon and energy (ICE) and extant literature. Compared with other methods, the inventory approach exhibits higher accuracy and greater flexibility when applied to real-world case studies [40,82,83]. Also, the inventory method avoids the complex procedures which entail chemical equations by using energy coefficients and emission factors. The most commonly used SCMs in blended cement concrete production are agro-industrial wastes. Compared to other waste materials, agro-industrial wastes need low energy for their manufacture. Previous studies assumed that waste materials possess zero EE and embodied carbon dioxide emissions (EC) when evaluating the total EE and EC of 1 m^3 of concrete [45,84–86]. Although, shea nutshell has zero EE and EC at the collection point. However, the shea nutshell is dehydroxylated at about 350 °C for 2 h, producing VPA. Consequently, the shea nutshell's dehydroxylation results in energy consumption and carbon dioxide emissions. Therefore, the EE and EC of the VPA were determined from the EE of fuel (kerosene) used to heat the furnace following the method adopted by Abubakar et al. [45] as follows:

An 11-litre of kerosene was used to heat the furnace.

$$EE\ of\ VPA = \frac{d_k \times v_k \times EE_k}{m_{vpa}} \tag{1}$$

where:

d_k = density of kerosene (kg/m^3);
v_k = volume of 11-litre of kerosene (m^3);
EE_k = embodied energy of kerosene (MJ/kg);
m_{vpa} = mass of VPA obtained from 11-litre of kerosene used (kg).
Thus,

$$EEofVPA = \frac{780 \times 11 \times 0.001 \times 3.45}{20} = \frac{29.60}{20} = 1.48MJ - eq/kg$$

Hammond and Jones [82] developed the relationship between the EE and EC equivalents (EC_e), EC_e and CO_2, and EC and EE, as illustrated in Eqs. (2) – (4), respectively.

$$EC_e(kg) = 0.021 \times EE \tag{2}$$

$$EC_e = 3.67 \times CO_2(kg) \tag{3}$$

$$EC(kg) = 0.0057 \times EE \tag{4}$$

Applying Eq. 15:.$EC(kg) = 0.0057 \times 29.60 = 0.169 kgofCO_2$

$$ECofVPA = \frac{0.169}{20} = 0.0084kgCO_2 - eq/kg \tag{5}$$

Aggregates, which represent about 75 % of the concrete volume, have been ignored in the assessment of EE and GHG emissions of Portland cement concrete (PCC) and blended cement concrete (BCC) by previous studies [45,84,86], claiming that PCC and BCC have approximately the same quantity of aggregates in the mix. However, the source materials in PCC (mainly PC) and BCC (mostly PC and SCMs) differ, resulting in volume differences occupied by aggregates [85] due to the difference in the specific gravity of PLC and SCMs [65]. Consequently, the volume occupied by aggregates in PCC and BCC of the same quantity of source materials is different based on the absolute volume method

Table 5
GWP coefficients (GWP_c) for concrete constituents (cradle-to-gate).

Constituent	GWP_c ($kgCO_2$-eq/kg)	Reference
PLC	0.95	Flower and Sanjayan [25] Hammond and Jones [40] Robayo-Salazar et al. [81] Boesch et al. [93] Kong and Sanjayan [94]
VPA	0.0084	Eq. [5]
FA	0.0051	Kathirvel and Sreekuma [5] Hammond and Jones [40] Robayo-Salazar et al. [81] Rajamane et al. [95]
CA	0.0052	Hammond and Jones [40] Yang et al. [79] Robayo-Salazar et al. [81]
W	0.001	Hammond and Jones [40] Robayo-Salazar et al. [81] Kellenberger et al. [96]

Table 6
GTP coefficients (GTP_c) for concrete constituents (cradle-to-gate).

Constituent	GTP_c ($kgCO_2$-eq/kg)	Reference
PLC	0.91	Robayo-Salazar et al. [81] Boesch et al. [93]
VPA	0.0093	Robayo-Salazar et al. [81]
FA	0.0041	Robayo-Salazar et al. [81] Kellenberger et al. [96]
CA	0.0010	Robayo-Salazar et al. [81] Kellenberger et al. [96]
W	0.00040	Robayo-Salazar et al. [81]

Table 7
Transportation coefficients (T_c) for different modes of transportation.

Transportation mode	Impact group			Reference
	Energy demand (MJ-eq per tonne-km)	GWP ($kgCO_2$-eq per tonne-km)	GTP ($kgCO_2$-eq pertonne-km)	
Truck, road	2.275	0.159	0.166	Fernando et al. [18] Sandanayake et al. [77] Keller [97] Pervez et al. [98]
Freight, rail	0.325	0.039	–	Fernando et al. [18] Sandanayake et al. [77] Bribian et al. [99]
Transoceanic, ship	0.216	0.0165	–	Fernando et al. [18] Sandanayake et al. [77] Pervez et al. [98]

Table 8
Average transport distance (ATD) of each construction material.

Material	Production/collection source	ATD (km)	Contact coordinates
PLC	Ibese, Nigeria	62.0	7.00546, 3.04870
VPA	Owode-Yewa, Nigeria	17.0	6.71228, 2.97523
FA	Ota, Nigeria	3.5	6.71228, 2.97523
CA	Abeokuta, Nigeria	81.0	7.14761, 3.36195
W	Covenant University, Nigeria	0	6.68733, 3.15802

[65]. Furthermore, no superplasticizer was used. Thus, admixture energy demand was not included in this assessment. Therefore, Tables 4-7 present the EE, GWP, GTP, and transportation coefficients (factors) for the constituents of concrete produced based on the ICE and extant literature, respectively.

3.4. Impact assessments

3.4.1. Transportation impact (T_i)

Fuel energy is consumed, and greenhouse gasses are emitted while transporting construction materials. Consequently, the energy and GHG are embodied in the construction materials. All materials were transported by truck; hence road was applied as the mode of transportation for these impact assessments. The relationship, as illustrated in Eq. (6), was used to evaluate the transportation impacts (T_i) of EE (TiEE, MJ-eq/m^3), GWP (TiGWP, $kgCO_2$-eq /m^3), and GTP (TiGTP, $kgCO_2$-eq /m^3) of the concrete constituents used [78,99,100].

$$T_i = \sum_{i=1}^{n}\left(\frac{m_w \times d_t \times T_c}{1000}\right) \tag{6}$$

where:

T_i = Transportation impact.
m_w = material's weight (kg);
d_t = distance travelled by the truck (km);
T_c = transport coefficients for energy demand (MJ-eq/tonne-km), GWP ($kgCO_2$-eq/tonne-km), and GTP ($kgCO_2$-eq/tonne-km).

Table 8 presents each concrete constituent's collection source, average transport distance, and contact coordinates from the manufacturer/producer to the laboratory. The average transport distances were calculated by locating the material source and measuring the distances on the goggle map [11].

3.4.2. Embodied energy (EE)

Energy consumption source requires many variables to produce 1 m^3 of concrete (BCC and PLCC). These variables are binders and SCMs (PLC and VPA), FA, CA, and water. Thus, the embodied energies of the BCC and PLCC were evaluated via the data sourced primarily from ICE and relevant literature. The relationship illustrated in Eq. (7) signified the cradle-to-gate equation, while Eq. (8), indicating the cradle-to-site relationship, was used to calculate the EE of concrete constituents [18,40,78,82,83,100].

$$Cradle-to-gate = (1+m)\sum_{i=1}^{n}(m_w \times EE_c) \tag{7}$$

$$EE = (1+m)\sum_{i=1}^{n}(m_w \times EE_c) + TiEE \tag{8}$$

where:

EE = embodied energy (MJ-eq/m^3);
m_w = material's weight (kg);
m = wastage factor (%) of EE, taking as 22 % [83];
EE_C = embodied energy coefficients (MJ-eq/kg);
TiEE = transport impact of embodied energy (MJ-eq/m^3).

3.4.3. Global warming potential (GWP)

The GWP is an environmental impact metric that assesses the cumulative effect caused by various GHG emissions comprising short- and long-term gases that could change the average atmospheric temperature [81]. Therefore, the cradle-to-site relationship, as illustrated in Eq. (9), was used to determine the GWP environmental impact related to the constituent, transportation, and production processes of the concrete (BCC and PLCC) [40,78,82,83].

$$GWP = (1+n)\sum_{i=1}^{n}(m_w \times GWP_c) + TiGWP \tag{9}$$

where:

GWP = global warming potential ($kgCO_2$-eq/m^3);
m_w = material's weight (kg);
n = wastage factor (%) of GWP, taking as 19 % [83];
GWP_C = global warming potential coefficients ($kgCO_2$-eq/kg);
TiGWP = transport impact of global warming potential ($kgCO_2$-eq/m^3).

3.4.4. Global temperature potential (GTP)

The GWP is an environmental impact metric that evaluates the absolute change in global temperature in response to the GHG emission pulse for a given period [81]. Therefore, the cradle-to-site relationship, as illustrated in Eq. (10), was applied in the determination of the GTP environmental impact related to the constituent, transportation, and production processes of the concrete (PLCC and BCC) [40,78,100].

$$GTP = (1+n)\sum_{i=1}^{n}(m_w \times GTP_c) + TiGTP \tag{10}$$

where:

GTP = global temperature potential ($kgCO_2$-eq/m^3);
m_w = material's weight (kg);
n = wastage factor (%) of GTP, taking as 19 % [83];
GTP_C = global temperature potential coefficients ($kgCO_2$-eq/kg);
TiGTP = transport impact of global temperature potential ($kgCO_2$-eq/m^3).

3.5. Sustainability index (S_i)

Achieving the BCC's extensive application as an alternative concrete to PLCC requires an investigation into the sustainability efficiency of the concrete mixes [102]. The sustainability index (S_i) of the concrete compositions was evaluated with the concrete's 28-compressive strengths (f_c) to examine the sustainability prospects relative to the concrete's strength performance [51,102,103]. Therefore, the S_i of the concrete mixes was determined via the relationship as illustrated in Eq. (11) [104].

$$S_i = \frac{GWP + GTP + (CO_{2i} \times EE)}{f_c} \tag{11}$$

where:

S_i = Sustainability index ($kgCO_2$-eq/m^3.MPa);
GWP = GWP = global warming potential ($kgCO_2$-eq/m^3);
GTP = global temperature potential ($kgCO_2$-eq/m^3);
EE = embodied energy (MJ-eq/m^3);
CO_{2i} = carbon dioxide intensity of the energy supply, taking as 0.050 $kgCO_2$/MJ [104];
f_c = 28-day compressive strength (MPa).

3.6. Economic index (E_i)

The broad utilization of any product as an alternative option in the construction and building industry depends upon its relative cost at the user level [103]. The economic index compares and relates the cost

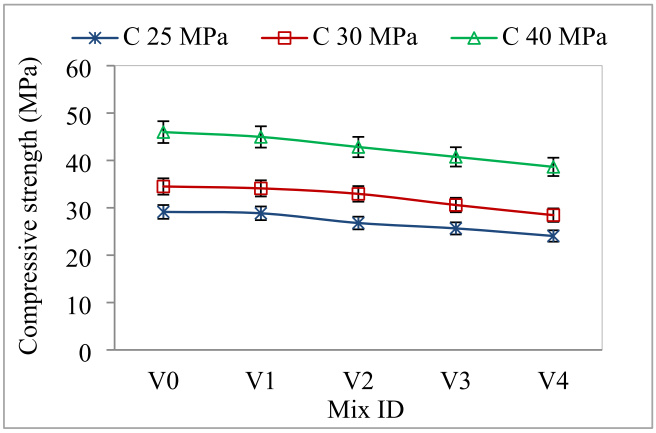


Fig. 5. Compressive strengths at 28 days of curing.

feasibility for each mix to its total production cost and 28-day compressive strength value [105]. The production cost for each blend is determined by the cost of the concrete constituents by their mix design proportions [102,105]. In this regard, the production cost was prepared for one cubic metre of concrete. Thus, the economic index was determined to assess the cost advantage of the concrete mix using Eq. (12) [101,102,105].

$$E_i = \frac{C_t}{f_c} \tag{12}$$

where:

E_i = economic index ($/m^3. MPa);

c_t = total cost of 1 m^3 of concrete (($/m^3);

f_c = 28-day compressive strength (MPa).

4. Results and discussion

4.1. Compressive strength

As indicated in Fig. 5, the results revealed a marginal decrease in strength with increasing VPA content in the mix at all concrete strength grades. The reason could be related to the passive rate of pozzolanic reaction between VPA and Portlandite ($Ca(OH)_2$) produced by the PLC hydration, retarding the strength development [73–75]. However, a 5–15 wt% of VPA substitution met the 28-day target strengths for all concrete strength grades. Therefore, a 15 wt% optimum replacement of PLC with VPA can be applied in the building and construction sector as reinforced concrete in structural elements and as special concrete and construction [69]. A 20 wt% of VPA substitution can be applied as plain and reinforced concretes for all concrete grade strengths [69]. Ultimately, this study only assessed the compressive strengths at 28 days of curing to evaluate the strength cost of attaining the sustainable and economic characteristics of VPA-cement-based concrete compared with PLCC.

4.2. Transportation impact

Subject to the details highlighted in Tables 3, 7, and 8, and Eq. (6), Fig. 6 (a)-(c) indicate the transport impacts of GTP (TiGTP), GWP (TiGWP), and embodied energy (TiEE) of each concrete constituent, respectively. The average transport distance of water was zero, resulting in zero transport impact. Therefore, no water inclusion. From Fig. 6 (a)-(c), it was also evident that transportation impacts of global temperature potential, global warming potential, and embodied energy decreased minimally with increasing VPA contents in the BCC mixes for all concrete grade strengths. This is mainly because the average transportation distance of VPA as SCM was about 73 % lesser than PLC. As VPA content in the mix increased from 5 to 20 wt%, the TiGTP, TiGWP, and TiEE reduced by approximately 3–4 % for all concrete grade strengths compared with PLCC. The reasons could be attributed to the fact that the required transportation for PLCC constituents per cubic metre was higher than BCC constituents [101]. Also, it supports O'Brien et al. [106] 's assertion that pozzolan (fly ash) would reduce the GHG emissions if utilized to replace PC as long as the transportation distance of fly ash is lesser than the transportation distance of PC of the same mix design. However, this inference disagrees with Sandanayake et al. [78], where fly ash fails to demonstrate a significant reduction in environmental impact because the transportation distance of fly ash is 50 % longer than cement.

As clearly indicated in Fig. 6 (a)-(c), coarse aggregate (CA) depicts the most significant contributor to transportation impact compared with other concrete constituents. It takes about 24, 79, and 96 % longer distances to transport CA to the concrete production site than PLC, VPA, and FA. According to Fernando et al. [18] and Robayo-Salazar et al. [81], these findings signify the importance of selecting locally available materials to reduce further the impacts of material transportation on GTP, GWP, and EE.

On the other hand, the TiGTP, TiGWP, and TiEE increased with increasing concrete strength grades by about 7 and 5 % for C 25 and C 30 MPa concrete grades, respectively, compared with C 40 MPA concrete grade. These can be attributed to the fact that as concrete strength grades increase, binding materials (PLC and VPA) required for concrete production also increase [65], increasing the transportation impact.

Ultimately, it is noteworthy that the transportation distance of concrete constituents is interrelated with the distances of other components of specific concrete, inferring that transportation distance does not affect the relative quality of concrete [101]. However, it is expedient to express that the transportation effect depends on the local factors and varies significantly. This aligns with Sandanayake et al. [78], who deduced that different product locations would generate different results based on the transportation distance and available materials. Thus, the findings would help assess an in-depth investigation on selecting concrete constituents before their design and production for sustainable application and utilization.

4.3. Embodied energy (EE)

Fig. 7 presents the concretes' EE with references to Tables 3 and 4 and Eq. (8). The results revealed that BCC exhibited lesser EE than PLCC. The reasons could be attributed to the fact that the initial energy factor of VPA required for BCC production was 73 % lesser than PLC, indicating that VPA is a low EE construction material. As VPA content in the BCC mixes increased from 5 to 20 wt%, there was about 3–13 % reduction in cumulative embodied energy compared with PLCC mixes for all concrete strength grade levels. This performance supports previous studies' inference that low EE construction materials reduce the concrete's EE [45,48,86,107,108]. Abubakar et al. [45] saved about 3–12 % of EE by replacing OPC with 5–20 % corn cob ash (CCA) to produce blended cement concrete. In a related study, the cumulative energy demand was reduced by 3–5 % at 8–12 wt% replacement of OPC with ultrafine fly ash (UFFA), and 16–28 % at 40–60 wt% replacement of OPC with fly ash [109]. Similarly, about 8 and 21 % reduction in cumulative energy demand was obtained when OPC was replaced with 40 wt% of GGBFS-10 wt% of SF and 40 wt% of fly ash-10 wt% of SF, respectively [109].

Fig. 7 shows an increase in cumulative embodied energy with increasing concrete strength grade. It was evident from Table 3 that C 40 MPa concrete grade binders (PLC and VPA) increased approximately by 31 and 22 % compared with C 25 and C 30 MPa concrete grades, respectively. These increase the embodied energy coefficients of binders (PLC and VPA), increasing cumulative EE. Statistically, there was an approximately 27 and 19 % increase in cumulative EE for C 40 MPa concrete grades compared with C 25 and C 30 MPa grades. A similar trend was reported by Lovecchio et al. [109]. The C 40 MPa control

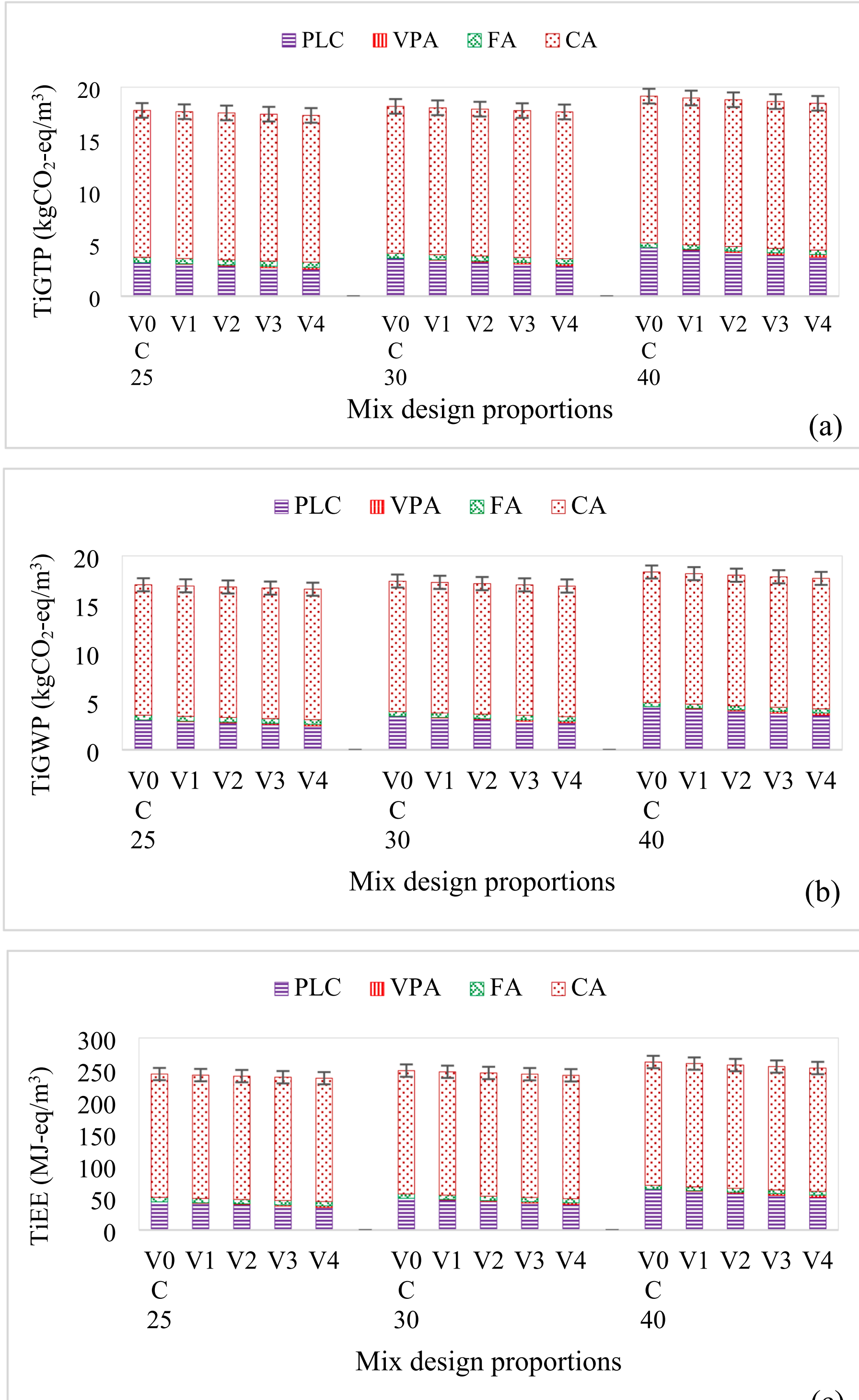


Fig. 6. Transportation impacts (a) global temperature potential, (b) global warming potential, and (c) embodied energy.

concrete grade yielded a 2256 MJ-eq/m3 than the C 30 MPa concrete grade, which exhibited a cumulative effect energy demand of 2088 MJ-eq/m^3, indicating about a 7 % increase. Also, the incorporation of 60 wt % of fly ash with OPC resulted in 1790 MJ-eq/m^3 of cumulative energy demand for C 40 MPa blended cement concrete grade compared with C 30 MPa blended cement concrete grade with 1592 MJ-eq/m^3, signifying an increase of about an 11 %.

Without compromising the compressive strength, the results presented herein clearly demonstrate that the energy lessening of cement-based concrete modified with VPA is attained at an optimum replacement of PLC with 15 wt% of VPA to compete favourably with PLCC counterpart. Therefore, BCC mixes should be carefully selected, proportioned, and designed to reduce their energy impacts, contributing to the sustainability of building materials.

4.4. Global warming potential (GWP)

Fig. 8 presents the GWP results with references to Tables 3 and 5 and

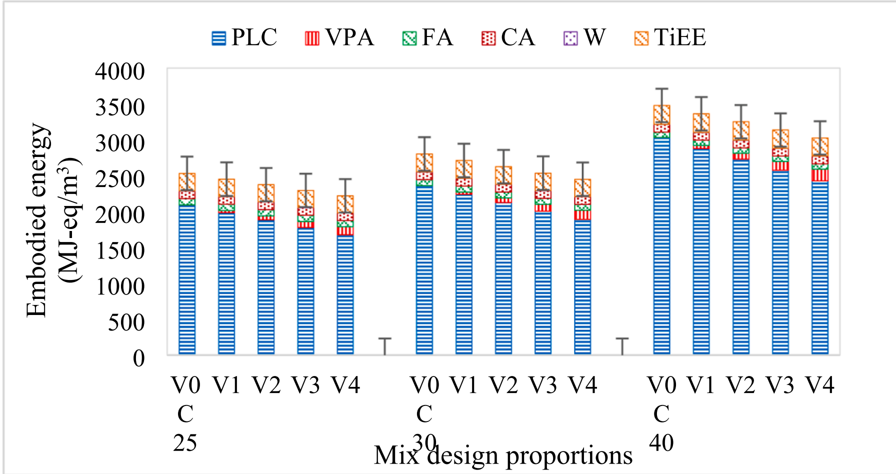


Fig. 7. The embodied energy of BCC and PLCC.

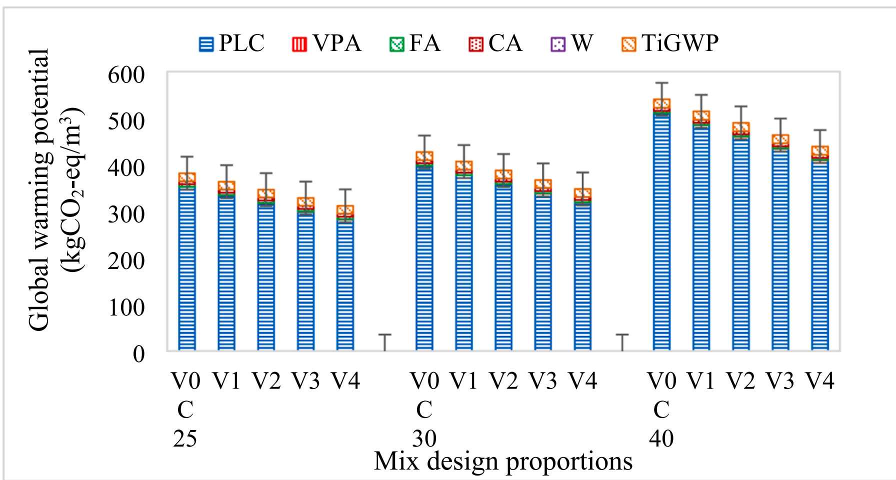


Fig. 8. Global warming potentials of BCC and PLCC.

Eq. (9). As shown in Fig. 8, the GWP results revealed that BCC exhibited a lesser GWP than PLCC for all concrete strength grades. The cumulative effects of various GHG emissions, which alter the atmospheric temperature, could be higher in PLCC than BCC mixes, hence this performance [81]. For PLCC, PLC is the only binder with the highest environmental impact, contributing approximately 92, 93, and 95 % for C 25, C 30, and C 40 MPa concrete grades, respectively. These generated about 353, 398, and 511 $kgCO_2$-eq per cubic metre of concrete for C 25, C 30, and C 40 MPa concrete grades. The reasons cannot be far-fetched: the high temperature (approximately 1450 °C) needed for the clinkerization process and the high amount of CO_2 emissions into the atmosphere during the chemical decomposition of limestone [81]. These findings confirm the previous studies where pozzolan (fly ash) and PLC contributed approximately 1 and 95 % to the cumulative GWP, respectively [18,45,56,81]. However, at 5–20 wt% of VPA substitution, about 0.04–0.20 % of GWP was contributed, yielding approximately 0.15–0.59, 0.17–0.67, and 0.22–0.86 $kgCO_2$-eq/m^3 of concrete for C 25, C 30, and C 40 concrete strength grades, respectively.

Relevant studies align with these results in that BCC exhibited lesser GWP values than PLCC. In this respect, Nath et al. [110] and Li et al. [111] noted the feasible reduction in GWP when fly ash, and waste basalt powder was replaced with OPC, respectively. Similar results were found by Lovecchio et al. [109], where the partial replacements of OPC with 8 wt% of UFFA, 12 wt% of UFFA, 40 wt% of fly ash, 60 wt% of fly ash, and 50 wt% of GGBFS reduced the cumulative GWP by 6.18, 9.17, 31.98, 47.97, and 33.02 %, respectively, compared with ordinary Portland cement concrete (OPCC). Robayo-Salazar et al. [81] reported a 44.7 % lesser GWP in natural volcanic pozzolan-GGBFS-based green concrete than OPCC. Despite these supporting studies, Lovecchio et al. [109] reported a contrary finding where the partial replacements of OPC with 2 wt% of nano-silica and 2 wt% of nano calcium carbonates yielded 12.58 % and 1.49 % increment in cumulative GWP compared with OPCC.

It was evident from Fig. 8 that the cumulative GWP increased as concrete grade increased from C 25 to C 40 MPa strengths. This increment could be related to the water-cement ratio, which is higher in C 25 and C 30 MPa grade strengths than in C 40 MPa grade strength, leading to the higher cement content in C 40 MPa than C 25 and 30 MPa grade strengths [65]. Consequently, binding contents (PLC and VPA) to the cumulative GWP increased, making C 40 MPa strength grade exhibits higher GWP than C 25 and C 30 MPa strength grades. As observed, C 40 MPa strength grade showed about 29 % and 21 % higher cumulative GWP than C 25 and C 30 MPa grade strengths. These results support the findings of Bianco et al. [112], where OPCC exhibited about 19 and 34 % increases in cumulative GWP. In comparison, fly ash-GGBFS-based green concrete (BCC) yielded approximately 14 and 32 % increase in cumulative GWP for C 40 and C 70 MPa strength grades, respectively, compared with C 30 MPa strength grade. Moreover, Yang et al. [113] reported approximately 37 and 43 % increase in cumulative GWP of PCC for C 40 and C 70 MPa strength grades, respectively, compared with C

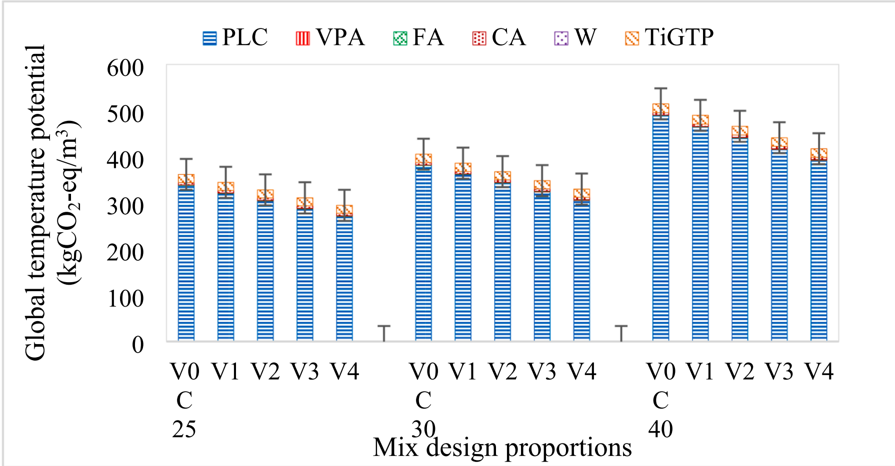


Fig. 9. Global temperature potentials of BCC and PLCC.

24 MPa strength grades.

Andersson-Skold et al. [114] posited that global warming, rapid urbanization, and increasing needs for resources in cities would increase the risks of harsh weather conditions. However, GWP and other climate-associated hazards can be mitigated by using environmentally friendly and alternative building materials [115,116]. Consequently, it is evident from the results obtained herein that the production of cement-based concrete incorporated with VPA demonstrates a prospect for GWP reduction compared with Portland limestone cement concrete for C 25, C 30, and C 40 concrete grade strengths. Thus, this blended cement concrete can be applied in the building and construction sector, making cities and communities inclusive, safe, resilient, and sustainable and reducing the impact of climate change.

4.5. Global temperature potential (GTP)

Similar to global warming potentials, Fig. 9 presents the results of global temperature potentials using Tables 3 and 6 and Eq. (10). The results showed that BCC exhibited a lesser GTP than PLCC for all concrete grade strengths. The reason could be related to the fact that the absolute temperature required for the clinkerization process (1350–1450 °C) of PLCC binder (PLC) in response to GHGe pulse is higher than BCC constituent (VPA): VPA only requires a temperature of about 350 °C for its valorization. This assertion aligns with the report of Robayo-Salazar et al. [81], which inferred that GTP depends on the type and proportion of binders used for concrete production. The cumulative GTP, as shown in Fig. 9 for BCC mixes, varied from about 295–345 $kgCO_2$-eq/m^3, 330–386 $kgCO_2$-eq/m^3, and 418–490 $kgCO_2$-eq/m^3 compared with PLCC which yielded about 362, 405, and 515 $kgCO_2$-eq/m^3 for C 25, C 30, and C 40 concrete grade strengths, respectively. These results support the previous study where about 197 $kgCO_2$-eq/m^3 of GTP was reported for natural volcanic pozzolan-GGBFS-based green concrete compared with approximately 372 $kgCO_2$-eq/m^3 of GTP obtained for OPCC. The results obtained herein could not be further established due to the scarce literature on GTP of concrete, contributing germane knowledge to existing and further studies.

As evident in Fig. 9, at 5–20 wt% replacement of PLC with VPA, there was about 5–19 % of GTP saving for all concrete grade strengths (C 25, C 30, and C 40 MPa). The results affirm the global temperature saving potential of VPA when utilized as a supplementary cementitious material in the production of blended cement concrete. Similar to global warming potential results, Fig. 9 indicates an increase in cumulative GTP as concrete grade strength increased from C 25 to C 40 MPa due to the increase in binding materials with increasing concrete grade strength. Compared with C 25 and C 30 MPa grade strengths, C 40 MPa grade strength yielded about 30 and 21 % increases in cumulative GTP. Ultimately, the results established herein infer that cement-VPA-based concrete is an alternative concrete to PLCC, featuring environmentally

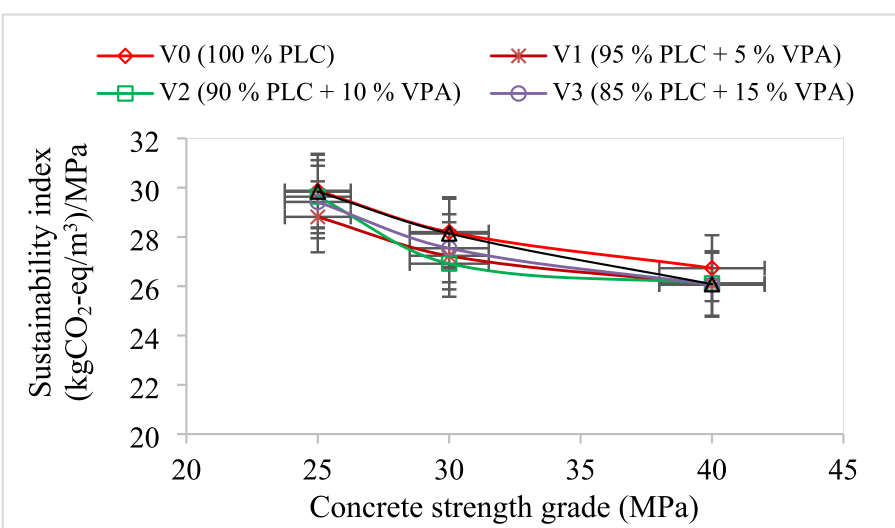


Fig. 10. Sustainability indexes of BCC and PLCC.

sustainable material which can be utilized in the building sector against global temperature warming.

4.6. Sustainability index (S_i)

Fig. 10 shows the sustainability indexes for BCC and PLCC, applying the relationship illustrated in Eq. (11). The results signified that BCC yielded a lesser sustainability index than PLCC, indicating that BCC is more sustainable than PLCC [51,104]. The sustainability index of BCC at 5–20 wt% of VPA incorporation yielded about 28–29 kgCO_2-eq/m^3.MPa, 26–28 kgCO_2-eq/m^3.MPa, and 26 kgCO_2-eq/m^3.MPa compared with PLCC with a sustainability index of approximately 30, 28, and 27 kgCO_2-eq/m^3.MPa for C 25, C 30, and C 40 concrete strength grades, respectively. The reasons could be attributed to the relatively lesser compressive strength to the lesser embodied energy, global warming potential, and global temperature potential exhibited by BCC than PLCC. Although, beyond 15 wt% replacement of PLC with VPA, BCC mixes attained a similar sustainability index with PLCC mixes, signifying an optimum replacement of 15 wt% PLC with VPA is recommended. These results support the findings of Rahla et al. [117], which reported an improvement in the concrete's sustainability incorporated with SCMs (GGBFS, fly ash, and SF). At 30–40 wt% of GGBFS, 5–10 wt% of SF, and 10–20 wt% of fly ash, there were about 0.73–0.82, 0.61–0.67, and 0.51–0.52 sustainability scores, respectively, compared to the control concrete (100 wt% of OPC) with a 0.51 sustainability score. Moreover, Ashish [21] and Braganca et al. [118] noted that utilizing SCMs as OPC's partial replacement reduces the quantity of cement needed to produce concrete, enhancing the concrete's sustainability while maintaining or even improving its mechanical and durability properties. As a result of VPA's prospect of reducing the energy demand and global warming and temperature impacts of concrete production, its incorporation, as evident in Fig. 10, reduced the sustainability index of concrete produced, offering a sustainable benefit. This affirms the findings of Adesina [51], where the green concrete incorporated with a SCM (GGBFS) yielded approximately 57 % of Si, lesser than PCC.

Fig. 10 indicates a decrease in sustainability index with increasing concrete grade strengths, inferring that the higher the concrete grade strength, the more sustainable the concrete. At 0–20 wt% replacement of PLC with VPA, as shown in Fig. 10, there was about 6–9 % and 10–13 % reduction in Si for C 30 and C 40 concrete grade strengths, respectively, compared with C 25 MPa grade strength. Although, C 25 MPa grade exhibited lesser environmental impacts (EE, GWP, and GTP) than C 30 and C 40 MPa grades. However, C 30 and C 40 MPa grade strengths' compressive strengths were 15–19 % and 36–42 % higher than C 25 MPa grade strength, respectively, at 0–20 wt% of VPA substitution. Thus, the sustainability index is reduced at higher environmental impacts than higher strengths.

The efficient utilization of building materials is often assessed by different environmental evaluation indexes to ensure building sustainability [119]. It is expedient to state that an optimum of 15 wt% of VPA incorporation in the BCC mixes exhibited a lesser sustainability index than PLCC for all concrete strength grade levels, having met the recommended target strength. Ultimately, this sustainability index assessment makes it possible to deduce that the utilization of VPA for BCC production enables a more sustainable concrete output for structural applications than PLCC without compromising the strength performances. In addition, a 20 wt% of VPA substitution, having met the strength requirements for mass concreting purposes [65,67], is recommended for non-load bearing application.

4.7. Economic index (Ei)

The economic index of concrete depends on the current price/cost of raw materials and the corresponding 28-day compressive strength [102,105]. The market exchange policy affects the cost of raw materials [102]. Thus, determining the effective concrete cost requires the constituent quantities based on the mix design proportions, as highlighted in Table 3. To this end, Table 9 presents the current price of concrete constituents used during the assessment of this study. The cost analysis of each component, including material, processing, and transportation costs, was based on the local scenario (Nigerian context) and converted to the United States dollar ($) for wide and broad acceptability. Consequently, the total cost of constituents needed to produce one cubic metre of GPC and PLCC is presented in Table 10 regarding the mix design proportions indicated in Table 3.

Table 9
The current cost of each concrete constituent[a].

Constituent	Processing cost ($/kg)	Material cost ($/kg)	Transportation cost ($/kg)	Total cost ($/kg)
PLC	–	0.204	0.0097	0.214
VPA	0.068	–	0.005	0.073
FA	–	0.0071	0.0015	0.0086
CA	–	0.0120	0.013	0.0250
W	–	0.0024	–	0.0024

[a]Nigerian national naira (₦) at the conversion rate of ₦ 411.95 per. US dollar ($) for December 2021.

Table 10
The total cost of constituents needed for 1 m^3 of BCC and PLCC.

Concrete grade	Mix ID	PLC	VPA	FA	CA	W	Total cost ($/m^3)
C 25	V0	66.77	0.00	7.61	26.13	0.46	100.96
	V1	63.34	1.17	7.58	26.13	0.46	98.67
	V2	60.13	2.26	7.54	26.13	0.46	96.52
	V3	56.71	3.43	7.51	26.13	0.46	94.23
	V4	53.50	4.53	7.47	26.13	0.46	92.08
C 30	V0	75.33	0.00	7.31	26.13	0.46	109.22
	V1	71.48	1.31	7.27	26.13	0.46	106.64
	V2	67.84	2.56	7.23	26.13	0.46	104.21
	V3	63.99	3.87	7.19	26.13	0.46	101.63
	V4	60.35	5.11	7.16	26.13	0.46	99.19
C 40	V0	96.73	0.00	6.55	26.13	0.46	129.86
	V1	91.81	1.68	6.50	26.13	0.46	126.57
	V2	87.10	3.29	6.46	26.13	0.46	123.42
	V3	82.18	4.96	6.41	26.13	0.46	120.13
	V4	77.47	6.57	6.36	26.13	0.46	116.98

Table 10 shows a minimal cost reduction with increasing VPA content per cubic metre of the concrete mix. At 5–20 wt% of VPA substitution, there was about 2–9 %, 3–9 %, and 3–10 % decrease in total cost per cubic metre of BCC production for C 25, C 30, and C 40 concrete strength grades, respectively, compared with PLCC production of the same concrete strength grades. This performance is mainly due to the material and transportation costs of PLC, which are approximately 66 % higher than VPA. These results affirm the findings of a similar study where the incorporation of fly ash and SF for green concrete production resulted in about 11–18 % of cost reduction [101]. Besides, Fernando et al. [18] reported that about 10 % replacement of fly ash with RHA resulted in about a 3 % reduction in the total cost of producing green concrete per cubic metre.

The Portland limestone cement, as evident from Table 10, contributed about 58–66 %, 61–69 %, and 66–75 % to the total cost of producing PLCC compared with VPA, which contributed about 1–6 % to the cumulative price of having BCC per cubic metre for all concrete strength grades, respectively. These corroborate the findings of Fernando et al. [18], which stated that Portland cement accounts for 53 % of the total cost of PCC production, while rice husk ash and fly ash contribute about 5–8 % to the initial total cost. In the same vein, Shwekat and Wu [120] found that PLC and calcite powder contributed about 43 and 6 %, respectively, to the production of masonry units per square metre. On the other hand, fine aggregates were responsible for 8, 7, and 5 % total cost of the concrete production, while coarse aggregates contributed about 26–28 %, 24–26 %, and 20–22 % to the cumulative price of

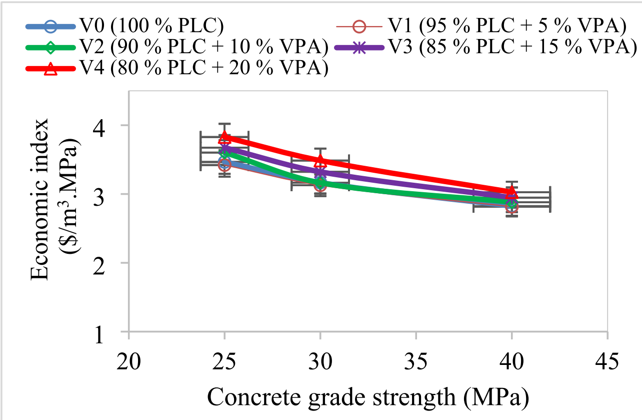


Fig. 11. Economic index of BCC and PLCC.

producing C 25, C 30, and C 40 concrete grade strengths per cubic metre, respectively. These results align with the previous study in that fine, and coarse aggregates were responsible for about 10 and 18 % of the initial total costs of producing green concrete per cubic metre, respectively [121]. Furthermore, water contributed 0.45–0.50 %, 0.42–0.46 %, and 0.35–0.39 % to the total cost of producing C 25, C 30, and C 40 concrete grade strengths per cubic metre, respectively. These results are contrary to the previous study where water was responsible for about 11 % of green cement production cost per cubic metre. The water used for the study herein possessed zero transport impact and was free, hence responsible for the low-cost contribution.

It was also clear from Table 10 that the concrete production cost per cubic metre increased with increasing strength grades. The reason could be related to the higher contents of PLC and VPA with increasing concrete strength grades. Compared with C 25 MPa strength grade per cubic metre, there was about 7–8 % and 21–22 % increase in production cost for C 30 and C 40 MPa strength grades, respectively. Nonetheless, the price changes due to each concrete constituent's processing and transportation costs and geographical context [18]. Therefore, Fig. 11 presents the economic index of BCC and PLCC, applying the relationship illustrated in Eq. (12).

In Fig. 11, BCC exhibited a lesser economic index at 5–10 % wt. % of VPA incorporation than PLCC (100 wt% of PLC) for all concrete grade strength levels, signifying that BCC is more economically efficient than PLCC [102,103,105]. However, at 15–20 wt% substitution of PLC with VPA, there was about 4–10 %, 5–10 %, and 2–7 % increase in the economic index for C 25, C 30, and C 40 concrete strength grades, respectively, compared with PLCC at 100 wt% PLC. The marginal decrease in compressive strength with increasing VPA content in the BCC mixes at all levels of concrete grade strengths could be responsible for these results.

As indicated in Fig. 11, the economic index decreased as concrete grade strengths increased due to the higher compressive strength with increasing concrete grade strengths. Compared with C 25 MPa strength grade, there was about 9–13 % and 18–21 % reduction in the economic index for C 30 and C 40 MPa strength grades, respectively. This infers that C 40 MPa strength grade is more economically efficient than C 30 MPa strength grade, and in turn, C 30 exhibits higher economic efficiency than C 25 MPa strength grade. As a result of these findings and compared with PLCC, cement-based concrete's economic prospects incorporated with VPA are viable at an optimum replacement of PLC with 10 wt% of VPA.

4.8. Relationship between GTP and GWP

Fig. 12 presents the linear relationship between the GTP and GWP of cement-based concrete modified with VPA. Considering the correlation's goodness of fit, the coefficient of determination (R^2), as shown in Fig. 12, signified that the model was 100 % fit to predict the relationship between the GTP and GWP of BCC. The model equation presented herein (Fig. 12) would have been validated using the previous findings, but scarce literature on the relationship between GTP and GWP of GPC hampers this process. Thus, this developed equation is novel in cement-based concrete modified with supplementary cementitious material and can be applied in predicting global temperature potential once the global warming potential is known. Moreover, the relationship was modelled based on the mix design proportions, varying from C 25 to C 40 concrete grade strengths. However, the coefficient of determination (R^2) may vary due to the transportation distance of concrete constituents, types and methods of mix design quantities, and local scenario effects.

5. Conclusions

This study assessed the sustainability of cement-based concrete incorporated with Vitellaria Paradoxa ash (BCC) via the inventory of carbon and energy and relevant literature within the confine of cradle-to-site analysis. Furthermore, experimental laboratory works and statistical analysis were engaged, and the results were compared with the

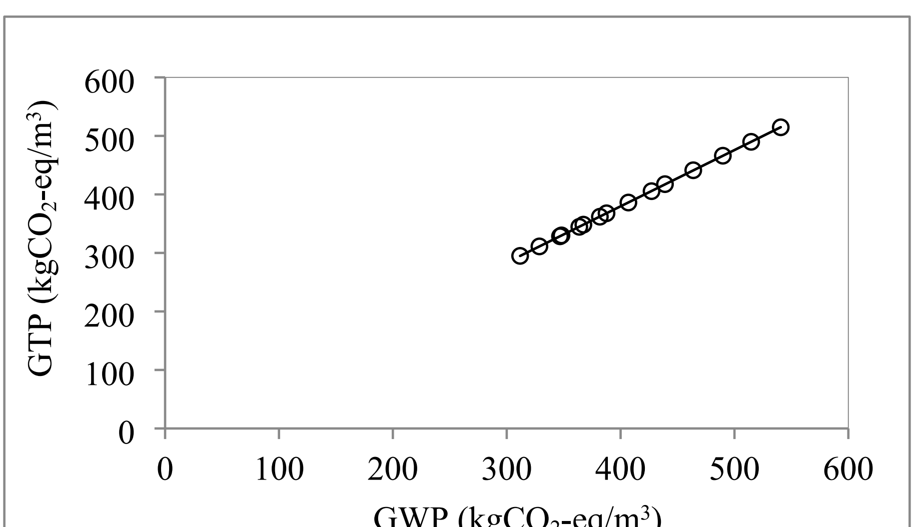


Fig. 12. Relationship between GTP and GWP of BCC.

Portland limestone cement concrete (PLCC). Consequently, the study concluded that BCC exhibited an approximately 3 % decrease in the cumulative EE to every 5 wt% of VPA substitution compared with PLCC mixes for all concrete grade strengths. Moreover, there was about a 5 % saving in cumulative GTP and GWP at every 5 wt% of VPA substitution for BCC compared with PLCC for all concrete grade strengths. At 5–20 wt % of VPA substitution, BCC yielded about 1–5 % of Si and 1–2 % of Ei lesser than PLCC.

Reducing environmental impacts can be attained by offsetting the conventional binder (PLC) to a sustainable binder (VPA). Thus, this study offers great prospects for cement-based concrete incorporated with VPA to reduce PLCC production's global warming and temperature impacts. It also provides significant potential for energy-saving and economic efficiency. However, this research recognizes variability as a considerable potential based on the specific mix design quantity and source and transportation of concrete constituents. Moreover, the cost challenges of PLC could be reduced by utilizing, for example, less expensive and environmentally friendly binders, which can exhibit similar performances as PLC. In addition, the transport distance required to obtain coarse aggregates could be optimized. Ultimately, the findings would help attain a cleaner environment and sustainable production in the construction and building sector.

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.

Acknowledgements

The authors would like to thank the Deanship of Scientific Research at Umm Al-Qura University for supporting this work by Grant Code: (22UQU4290255DSR06).

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