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Sustainability assessments of ternary mixed concrete: A cradle-to-gate analysis

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ABSTRACT

The emissions of carbon dioxide into the atmosphere due to the rapid growth of construction activities and industrialization have raised global concerns on climate change. The indiscriminate disposal of agro-industrial wastes poses ecological challenges. Hence, this study aims to evaluate the sustainability of waste materials as constituents of concrete and to produce suitable cement substitutes to reduce energy consumption and carbon dioxide emissions. To achieve this goal, cement was partially replaced with waste wood ash (WWA, 5–15 wt%) and calcite powder (CP, 5–15 wt%) using a concrete mix ratio of 25 MPa. The samples were tested for slump and compressive strength. The embodied energy, global warming impact, and sustainability index of the concrete mixes were assessed using a cradle-to-gate analysis. The results showed an increase in compressive strength with increasing WWA and CP content in the ternary blends. The replacement of WWA (10 wt%) and CP (10 wt%) with cement showed the maximum compressive strength. The embodied energy and global warming potential of producing the ternary-mixed concrete decreased with increasing WWA and CP contents in the ternary mixes compared to the control concrete, resulting in high sustainability. The study's findings demonstrated that WWA and CP are environmentally friendly materials that can be used to produce sustainable concrete.

1. Introduction

In the building and construction sector, Portland cement (PC) is the main binder in the production of concrete. Its production uses 1.6 tonnes of raw materials, principally quartz and limestone, and emits 0.8 tonnes of carbon dioxide (CO_2) per tonne, accounting for 5–7% of global greenhouse gas emissions [1–5]. Additionally, it creates a variety of other damaging substances for the environment, including nitrogen oxides (NOx) and sulphur dioxide (SO_2), all of which contribute to global warming [6]. Reducing the greenhouse gas emissions, energy use, and utilization of resources connected with manufacture of cement is one of the industry's major difficulties. The most practical solution to these challenges is a partial replacement of PC with supplementary cementitious materials (SCMs) [1,3,6,7]. Because of this, professionals, academics, and researchers have developed creative solutions to reduce this problem by utilizing supplements in place of cement in some applications [8–13]. It is interesting to note that utilizing SCMs improves the qualities of concrete in addition to mitigating the negative economic and environmental challenges associated with the production and use of PC [10–13].

The residue powder left over after wood and wood products have been valorised is known as waste wood ash (WWA) [14,15]. The WWA by the burning of untreated wood are categorized as non-hazardous wastes by the European Waste Catalogue and Hazardous Residues List [16]. According to several studies on chemical compositions, WWA has calcium carbonate ($CaCO_3$), silicon oxide (SiO_2), and fairchildite ($K_2Ca(CO_3)_2$), which dictate its alkaline nature [17] and can have a good impact on the mineralogy of hydrated cement [18]. The effect of WWA on the strength properties of concrete was studied after 7 and 28 days by Chowdhury et al. [19]. Different water to cement ratios of different concrete mix proportions, such as 5–20% by weight, were used. The strength achieved was greater than the required target strength, according to the strength characteristics from the study [19]. Cheah and Ramli [20] investigated the use of WWA as a partial replacement for cement in the production of structural grade concrete and mortar. The results revealed that the long-term compressive strength increases with increasing WWA content in the mix. The pozzolanic activity of the

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Nomenclature

CA	Coarse aggregates
CO_2	Carbon dioxide
CP	Calcite powder
ECE	Embodied carbon dioxide emissions
EE	Embodied energy
FA	Fine aggregates
GhGE	Greenhouse gasses emissions
GWP	Global warming potential
ICE	Inventory of carbon and energy
LoI	Loss of ignition
MPa	Mega Pascal (a unit of compressive strength)
PLC	Portland limestone cement
SCM	Supplementary cementitious material
SI	Sustainability index
WWA	Waste wood ash

materials made of WWA is what causes the increase in strength. The C-S-H gel was generated by the reaction between the Portlandite and the amorphous silica in WWA, which strengthened it [20]. Udoeyo et al. [21] examined the possibility of using WWA at 5–30 wt% of PC in the production of concrete. The results indicated that the WWA particles, which served as filler material, decreased compressive strength. Loss in concrete strength was caused by a combination of factors, including a rise in surface area of WWA, an increase in the ash content, and a decrease in cement content.

Calcite powder (CP), which is produced through the carbonization process, is an abundant and a versatile industrial filler [22]. Calcite powder, also known as $CaCO_3$ powder, is an extremely fine-grained, white powder that can be used as a filler in concrete. This common element can be found naturally in substances like limestone, chalk, or marble. The three primary chemical components of calcite powder are silicon oxide (SiO_2, 1–2%), magnesium oxide (MgO), and $CaCO_3$ (around 93–97%) [23]. The powder can also be produced via the interaction of carbon dioxide and calcium hydroxide, and its fineness aids in the early hydration of cement. By employing CP as a partial cement replacement, CO_2 and NO_2 emissions from the manufacture of cement are reduced [23,25] Calcite powder acts as a cement alternative and enhances the strength and characteristics of the concrete, addressing environmental issues by minimizing the overuse of cement [24]. According to earlier studies, replacing 10–30% of the cement with calcite powder results in higher performance for both freshly-poured concrete and hardened concrete [23,25].

Building construction utilizes embodied energy and generates CO_2, both of which have detrimental effects on the environment. The majority of construction laws, rules, policies, codes, and standards demand that buildings adhere to specific environmental performance criteria since there is growing interest in sustainability [26]. Embodied energy is the total amount of energy used during all processes involved in producing a material [27,28]. The kind and quantity of construction materials used affect the embodied energy of a building. Utilizing locally produced materials also reduces the need for transportation, which lowers the embodied energy by lowering the fuel consumption [29]. Embodied carbon dioxide emission (ECE) is the total amount of greenhouse gases a product emits over the course of its entire life cycle. Additionally, it refers to the volume of carbon dioxide produced, transported, and used in the creation of building materials [27,28].

Despite numerous studies on the use of WWA and CP as cement substitutes in the manufacture of concrete, the ternary uses of cement, WA, and CP have not been examined. The sustainability index (SI) and embodied energy of calcite powder-infused WWA-cement-based concrete have also received little to no attention. This is the rationale behind this research.

This study evaluates the sustainability potentials of WWA and CP as cement alternatives in concrete production. Portland cement was replaced with WWA and CP at weights of 5%, 10%, and 15% each. The slump on the fresh samples was determined, and after the concrete had hardened for 28 days, compressive strength was determined, while EE, ECE, and the SI were evaluated. These findings offer a potential solution to the waste management issues in WWA and CP by lowering the energy consumption of high-embodied energy PC mixes and the CO_2 emissions associated with the production of clinker. The research findings would be helpful in identifying the fundamental components and prerequisites for effective minimization when analyzing the environmental potentials of CP-modified WWA cement concrete.

2. Methodology

2.1. Materials

As shown in Fig. 1, the cement and binders used in this investigation were obtained from Ota in the Nigerian state of Ogun. The WWA, as displayed in Fig. 1 (c), was sieved with a 45 µm BS to produce particles with a size like cement. Table 1 displays the oxide constituents of the binding materials used after examination via X-ray technology (Phillips PW-1800). It is clear from Table 1 that the oxide compositions of the CP utilized were comparable to those described in Ali et al. [23]. ASTM C618 [30] categorizes pozzolan as Class C and F pozzolan if the summation of silica (SiO_2), alumina (Al_2O_3), and ferrite (Fe_2O_3) is greater than 50%. However, the amount of calcium oxide (CaO) in the WWA utilized is less than 18%. In light of the classification, the WWA used in this study is categorized as class F pozzolan because the addition of SiO_2, Al_2O_3, and Fe_2O_3 is greater than 50%, while CaO is less than 18%, complying with ASTM C618 criteria [30]. In the same vein, the results of oxide compositions are consistent with earlier research [19–21], where silica, alumina, and ferrite of WWA were added up to more than 50%. The specific gravity (SG) and specific surface area (SSA) of binding materials used were determined using a clean Le Chatelier apparatus and kerosene [31]. This led to SGs for Portland limestone cement (PLC), CP, and WWA of 3.15, 2.74, and 2.55, respectively. Similar results were achieved for PLC, CP, and WWA, with SSAs of 375, 1426, and 1620 m^2/kg, respectively.

Fine aggregates (FA) and coarse aggregates (CA) were also obtained locally and used in this study. The oven-dried technique at 105 ± 5 °C was used to determine the aggregates' moisture content and water absorption in accordance with BS 12620 [32]. According to these, the moisture content was 0.32% for FA and 0.22% for CA, and the water absorption was 0.69% for FA and 0.79% for CA. The particle size distribution for the binding materials and the aggregates used are shown in Figs. 2 and 3.

2.2. Experimental methods

The mix quantities were designed in accordance with ACI 211.1 [33], and the outcomes are shown in Table 2. The targeted slump was 25–50 mm and the water-to-cement ratio was 0.61 maximum. With grade 25 MPa concrete adopted, the compressive strength is expected to exhibit 25 MPa at 28 days of curing. Portland cement was replaced with 5–15 wt% of each WWA and CP. BS 1881 [34] was followed in the preparation of the components. A slump cone, as depicted in Fig. 4 (a), was used to examine the workability of the fresh samples of concrete. Using a tamping rod with a 16 mm diameter, fresh samples were compacted in three layers and then cured for 7, 14, and 28 days at 25 ± 3 °C and 65% relative humidity [35]. This is displayed in Fig. 4 (b). On the 150 mm × 150 mm × 150 mm cubes, a compressive strength test shown in Fig. 4 (c) was also carried out.

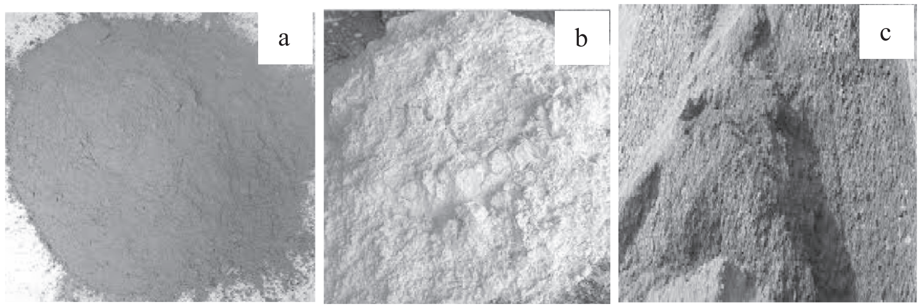


Fig. 1. (a) PLC; (b) CP; (c) WWA.

Table 1
Oxide compositions of binding materials used.

Oxide contents (%)	PLC	CP	WWA	ASTM C618 [30] Class F Class C
CaO	64.90	97.15	10.12	≤ 18 > 18
SiO_2	21.60	0.18	45.79	
Al_2O_3	5.85	0.02	20.55	
Fe_2O_3	2.78	0.01	4.48	
MgO	1.42	0.02	3.65	
SO_3	2.03	–	1.02	< 5 < 5
K_2O	0.72	–	3.75	
Na_2O	0.14	–	2.86	
P_2O_5	–	–	1.13	
LoI (800 °C)	1.38	0.26	5.87	< 6 < 6
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	-	70.82	> 50 > 50

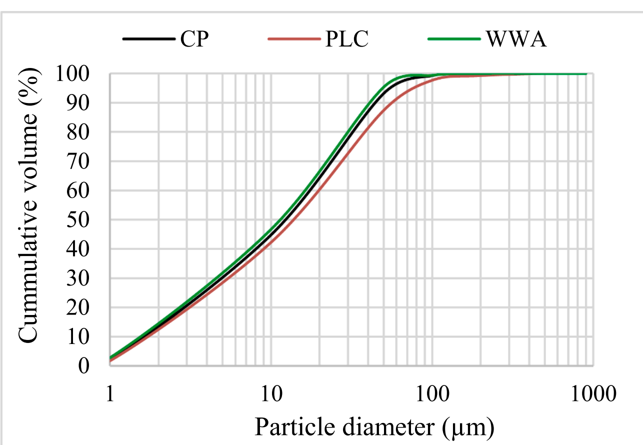
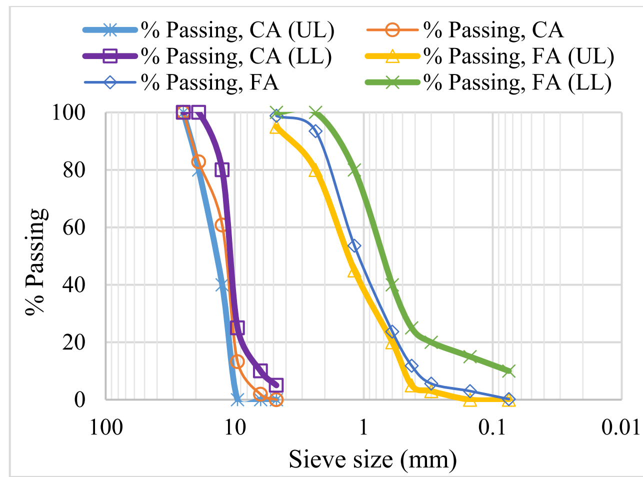


Fig. 2. Particle size distribution of WWA, CP, and PLC used.



UL is upper limit and LL is lower limit.

Fig. 3. Particle size distribution for FA and CA.

Table 2
Mix design quantities.

Mix identity	% replacement	Constituents (kg/m^3) PLC	CP	WWA	FA	CA	Water
M0	100% PLC	320	0.00	0.00	895	1036	192
M1	90% PLC + 5% WA + 5% CP	288	16	16	886	1036	192
M2	80% PLC + 10% WA + 10% CP	256	32	32	877	1036	192
M3	70% PLC + 15% WA + 15% CP	224	48	48	866	1036	192

3. Sustainability assessments

This research evaluates cement concrete modified with WWA and CP with reference to control samples in terms of EE, ECE, and SI. Carbon dioxide equivalent (CO_2-eq) is emitted from greenhouse gases including CO_2, CH_4, and NO_2 through the global warming potential (GWP) [27,28]. Consequently, this study used embodied CO_2 emissions as its GWP. The aforementioned functional units are taken into account: m^3 for 25 MPa concrete strength, MJ-eq/m^3 for EE, $kgCO_2$-eq/m^3 for GWP, and $kgCO_2$-eq/m^3 for SI. The investigation's scope encompasses all input and output streams from cradle-to-gate.

3.1. Data inventory

The inventory of carbon and energy (ICE) is used in the study to collect the data needed for these analyses. When used with real-world case studies, ICE outperforms other techniques when it comes to precision and versatility. Utilizing energy and emission variables allows one to sidestep the challenging methods that call for chemical equations. Due to their lower energy requirements compared to other byproducts, agro-industrial byproducts are the most often used additives in the manufacturing of blended concrete [27]. Waste materials are assumed to be completely free of EE and ECE [36–38], containing zero EE and ECE at the site of collection. However, the EE and GWP factors of WWA established in literature are 0.101 MJ/kg ash [39] and 0.006 $kgCO_2$-eq/kg ash [40]. Accordingly, Table 3 presents EE factor (EE_f) and GWP factor (GWP_f) required to produce the ternary mixed concrete (WWA-CP-PLC-based concrete).

3.2. Impact assessment

As was previously noted, CO_2 is generated during the production of concrete. Equations (1) and (2) are engaged to determine the concrete's EE and GWP based on the research's boundary (cradle-to-gate) [27,28].

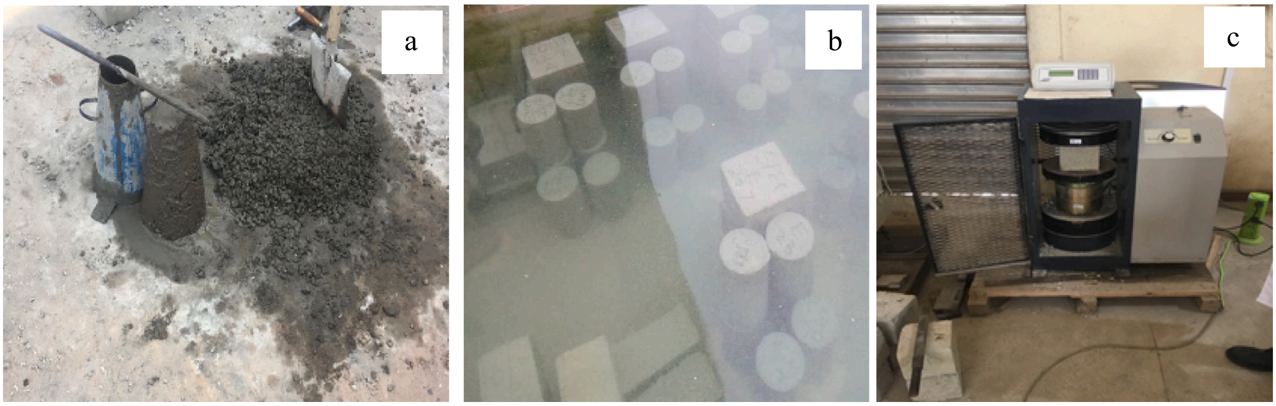


Fig. 4. (a) Workability test; (b) immersion of specimens in a water tank; (c) compressive strength test.

Table 3
Energy and emission factors.

Material	EE_f (MJ-eq/kg)	GWP_f ($kgCO_2$-eq/kg)	Reference
PLC	55×10^{-1}	95×10^{-2}	[27,28]
CP	62×10^{-2}	32×10^{-3}	[27,28]
WWA	10.1×10^{-2}	6×10^{-3}	[39,40]
FA	81×10^{-3}	51×10^{-4}	[27,28]
CA	83×10^{-3}	52×10^{-4}	[27,28]
Water	1×10^{-2}	1×10^{-3}	[27,28]

Given how frequently concrete is used, its sustainability must be considered [28]. As a result, Eq. (3) [29,41,42] provides an illustration of the concrete's SI.

$$EE\left(MJ-_{eq}/m^3\right) = (1+0.22)\sum_{i=1}^{n}\left(w \times EE_f\right) \quad (1)$$

$$GWP\left(kgCO_2 - eq/m^3\right) = (1+0.19)\sum_{i=1}^{n}\left(w \times GWP_f\right) \quad (2)$$

$$SI\left(kgCO_2 - eq/m^3.MPa\right) = \frac{GWP + (0.050 \times EE)}{28dayscompressivestrength} \quad (3)$$

where w signifies materials' weight (kg).

4. Results and discussion

4.1. Slump

Fig. 5 presents the workability of the fresh concrete mixes. As shown in Fig. 5, even though the water-binder ratio of the concrete mixes was kept constant at 0.600, the gradual addition of PLC substitution with WWA and CP from 5 to 15% of the total binder weight caused the slump value of the concrete mixes to gradually decrease by 7–57 mm in comparison to the control concrete mix without WWA and CP. Similar patterns in the reduction of fresh concrete's slumps are reported by Udoeyo et al. [21] and Elinwa and Mahmood [43]. In both cases, the partial replacement of cement with WWA from a local timbre and bakery led to a decrease in the fresh concrete's slump in comparison to the control concrete mix. The WWA's tendency to function more as a filler than a binder in the matrix may be the cause of this development. As a result, there is more ash in the concrete mix, which increases the surface area that can be bonded using the same amount of PLC as the control [21]. The use of CP in the manufacturing of concrete did, however, result in a decrease in the water content of the concrete mix, as demonstrated by Lertwattanaruk et al. [44] and Ali et al. [23]. These could be due to the finer CP particle, which disperses the cement matrix and releases more paste to lubricate aggregates and improve workability [23].

4.2. Compressive strength

Fig. 6 shows the findings of the compressive strengths of samples of hardened concrete. With the exception of 15% WWA + 15% CP (M3), it is evident from Fig. 4 that the addition of more WWA and CP increased the concrete's early strengths (7 and 14 days). At a later age (28 days), however, the strength decreased as WWA and CP in the mixes rose in comparison to the control sample. Early strength increased by around 2–4% with a 5–10% substitution of PLC with WWA and CP, but it decreased by about 11–13% at later age. The partial replacement of WWA and CP in the manufacturing of concrete resulted in an early

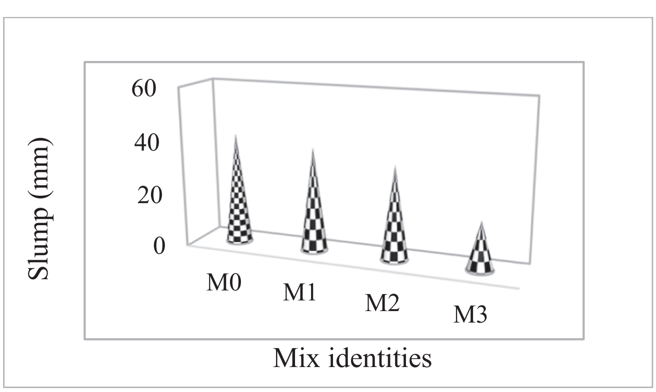


Fig. 5. Slump results.

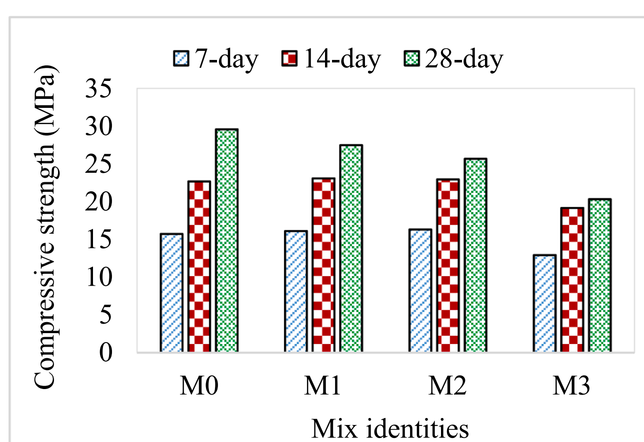


Fig. 6. Compressive strength.

strength improvement, but the strength dropped at a later age compared to the concrete sample without WWA and CP, according to similar trends observed in pertinent studies [21,23,43]. The reaction of CP ($CaCO_3$) with C_3A phase of PLC, which produces better cement particles and complete hydration at the ideal water requirement for high early strength accomplishment, may be the cause of this tendency [23]. Additionally, high amorphous silica and specific surface area of WWA may be associated to the early strength development, boosting the pozzolanic reaction at the ideal water requirement and raising early strength [21,43]. Rollakanti et al. [15] investigated the mechanical properties of concrete by partially replacing of cement with wood ash and fine seashell powder. The results showed the maximum compressive strength at 10% replacement of PC with wood ash and seashell powder, attaining 15.26% more than the compressive strength obtained for conventional concrete at the same age. Overall, substituting cement with 10% WWA and 10% CP satisfies the design strength criteria of 25 MPa and is suitable for structural use, while 15% is suitable for mass concrete.

4.3. Embodied energy (EE)

Referencing Tables 2 and 3 as well as Eq. (1), Fig. 7 shows the EE of the concrete mixtures per cubic metre. The findings revealed that when WWA and CP in the combinations increased, EE decreased. In comparison to the EE of the control concrete, the EE of the concrete was lowered by 8.60, 17.20, and 25.81%, respectively, by substituting WWA and CP for PLC at 5, 10, and 15 wt%. The factors of embodied energy of the concrete elements displayed in Table 3 may provide one explanation for these outcomes. As evidence that CP and WWA are low EE materials, PLC's EE_f was 89 and 98% greater than that of CP and WWA, respectively. The success of WWA and CP as low EE materials was demonstrated in pertinent study, where bagasse ash (BA) and CP decreased the EE of the concrete's manufacture by around 8–25% while replacing cement at a rate of 5–15% by weight [29]. Finally, these findings show that With the optimal substitution of PLC with 10% WWA and CP each, the embodied energy of WWA-CP-PLC-based concrete can be reduced without compromising compressive strength.

4.4. Global warming potential (GWP)

The findings of the GWP of concrete mixes are displayed in Fig. 8 and are based on the mix proportions, factor variables, and illustration provided in Eq. (2) as well as Tables 2 and 3. The outcomes showed that the manufacture of control concrete (M0) had a total GWP of 373.83 $kgCO_2\text{-eq/m}^3$. However, as the percentage substitution of PLC by WWA and CP increased from 5, 10, and 15% each, the GWP of the concrete mixes decreased by 9.50, 19.00, and 28.50%, respectively. These results are due to the fact that cement is more likely to experience the cumulative effects of different GhGE that alter the temperature of the air than pozzolana or an additive [42]. The emissivity of PLC was also 96.63 and 99.37% greater than that of CP and WWA, as indicated in Table 3. These support earlier investigations that found that PLC had an emission factor that was 95% higher than that of sheanut shell ash (SNSA) [42], 96% higher than that of corn cob ash (CCA) [36], and 98% higher than that of BA [29]. Ozone depletion and extreme weather are two consequences of global warming. These results are obviously important since they show that CP and WWA can both be used as cement substitutes in construction at an optimum of 10% each in order to create inclusive, durable, and secure societies.

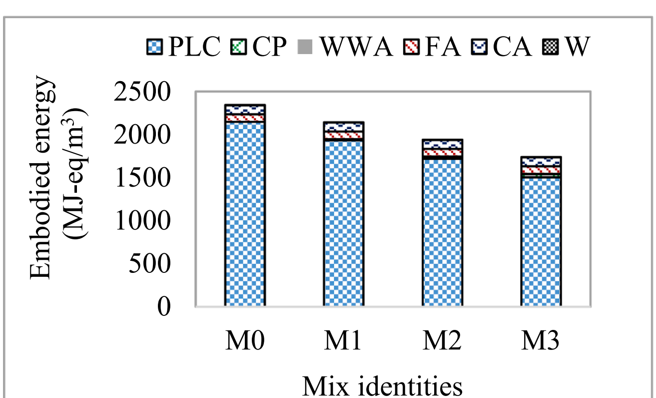


Fig. 7. Results of embodied energy of concrete mixtures.

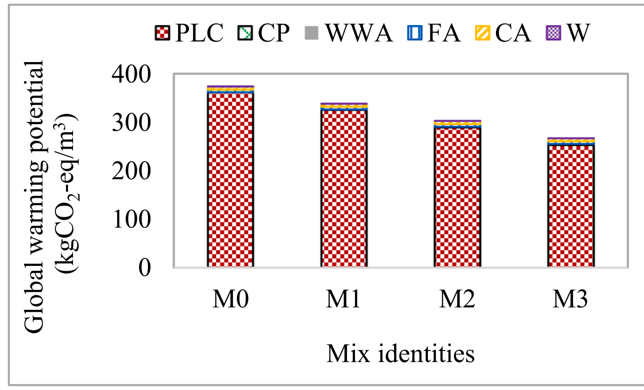


Fig. 8. GWP of concrete mixtures.

4.5. Sustainability index (SI)

According to Eq. (3), Fig. 9 provides concrete's index in connection to the outcomes shown in Figs. 7 and 8. The results indicated a control concrete production (M0) with SI of 16.60 $kgCO_2\text{-eq/m}^3$. The index was reduced by 2.40 and 6.16% with 5 and 10 wt% replacement of PLC by WWA and CP, respectively. However, at a 15% substitution of PLC with WWA and CP, the SI was slightly increased by 1.25%. At low SI, concrete is more sustainable [41,42]. As a result, concrete produced by replacing PLC with WWA and CP at 5 and 10% by weight is more environmentally friendly than control concrete (M0). These findings support relevant research where BA and SSNA were used in place of cement to lessen the environmental impact of the concrete by lowering the SI, making it more sustainable than concrete without BA and SNSA [29,42]. Overall, it can be asserted that CP and WWA are green building materials that can be used in place of cement up to 10 wt%.

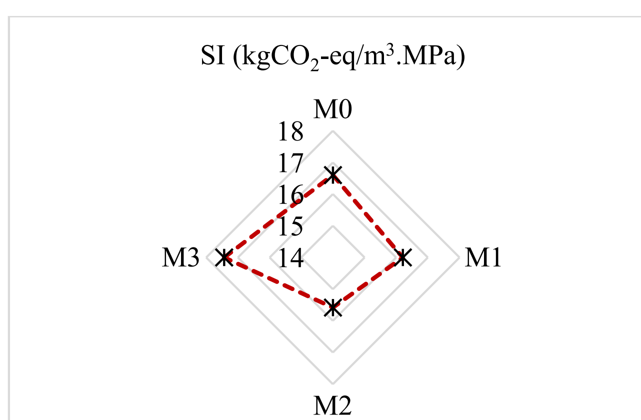


Fig. 9. SI of concrete mixes produced.

5. Conclusions

Using carbon and energy data as well as findings from other pertinent studies, this study assessed the sustainability of ternary mixed concrete incorprated cement, WWA and CP. Through experimental testing, the strength of the concrete produced was also established. The inferences that follow are then drawn:

For ternary mix concrete, up to 10% each, WWA and CP can be utilized as alternatives to cement. The embodied energy fell by 8–25% at 5–15 wt% of WWA and CP replacement. With a 5–15% substitution, the GWP of WWA-CP-PLC-based concrete reduces by 10–29%. The ternary mixed concrete (WWA-CP-PLC-based concrete) is around 3–7% more sustainable than the control concrete at a 5–10 wt% replacement of PLC with WWA and CP.

The viability of CP and WWA as sustainable building materials is one implication of this study. The findings offer suggestions for reducing the environmental impacts of producing Portland cement. There are restrictions on how broadly these results can be applied. Despite these drawbacks, further research must be done to assess the transport and economic effects of these materials and to guarantee a cradle-to-site examination.

CRediT authorship contribution statement

Solomon Oyebisi: . **Festus Olutoge:** Resources, Writing – review & editing. **Anthony Ede:** Visualization, Writing – review & editing. **Bankole Faithfulness:** . **Hilary Owamah:** Visualization, Writing – review & editing. **Daniel Dike:** Investigation, Resources.

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.

Data availability

All data used are included in the manuscript

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