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Sustainability assessment of cement concrete modified with bagasse ash and calcite powder

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A B S T R A C T

The continued global expansion in the built environment has resulted in significant demand for cement as a building and construction material. However, carbon dioxide emissions from the cement manufacturing processes contribute significantly to global warming and climate change. This study evaluates the sustainability of cement concrete mixed with bagasse ash (BA) and calcite powder (CP). A binary mixture of BA (5–15%) and CP (5–15%) was used in a partial replacement level of cement using a 25 MPa concrete mix design. Slump was examined while compressive strengths were tested after 7–28 days of water curing. Embodied energy, embodied carbon dioxide emissions, and sustainability index of the mixed concrete were evaluated after 28 days using the carbon and energy inventory. The results showed a decrease in slump as the replacement of bagasse ash and calcite powder in the mixture increased. In addition, the compressive strength of the mixed concrete decreased slightly as the percentage replacement of BA and CP in the mix increased. However, at 15% BA and 15% CP replacement level, the ternary concrete mix attained the compressive strength of 25.53 MPa compared to 29.45 MPa obtained for the control sample after 28 days. In addition, the blended concrete resulted in lower embodied energy, embodied carbon dioxide emissions, and sustainability index than the control concrete, meaning that cement-based concrete modified with BA and CP is more sustainable than Portland cement concrete.

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1. Introduction

The turn of the 21st century has seen an upswing in urbanization and construction activity. As the world population grows, so does the demand for housing and infrastructure from the construction industry. Concrete is the second most consumed material in the world after water and forms the backbone of the construction industry [1]. Its properties such as strength, durability and adaptability make it the material of choice for many structures. However, the manufacturing process of Portland cement alone is energy-intensive, accounts for about 8% of global carbon dioxide (CO_2) emissions and contributes to climate change [2–4]. In addition, every 1 kg of cement production emits about 1 kg of CO_2 [5], with calcination and combustion processes accounting for 90% of the CO_2 [6]. Consequently, practitioners, researchers and scholars have found innovative ways to mitigate this global problem by using supplemental cementitious materials (SCMs) as a partial replacement of cement [7–10]. Interestingly, it has been reported that the use of SCMs is not only viable in terms of reducing the environmental and economic impacts associated with cement manufacture and use, but also improves the physical, mechanical and durability properties of concrete [7–10].

Bagasse is a dry, pulpy, fibrous waste made by extracting sugar juice from sugar cane. Bagasse ash (BA) is one of the agricultural by-products that comes from processing bagasse at around 700 °C [11] and has good pozzolanic properties. In addition, about 25–40 kg of BA is produced from one ton of bagasse [12]. According to statistical data from the Food and Agriculture Organization of the United Nations (FAOUN) [13], world sugar cane production was about 1.9 billion tons, of which 92 and 1.5 million tons were in Africa and Nigeria. Xu et al. [14] argued that an increase in demand for sugar and ethanol increases the production of sugarcane bagasse. However, most of the bagasse produced is often

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indiscriminately disposed of, resulting in environmental pollution. Various studies have partially replaced cement with BA in concrete production. The results showed about 5–10% of BA as the optimal replacement level for improved compressive strength [10,14,15], chemical resistance and drying shrinkage [14,15]. In the presence of superplasticizer, however, 20% by weight of BA can be used [15].

Calcite powder, on the other hand, is versatile industrial filler obtained through the carbonization process [16]. Calcite powder, also known as calcium carbonate ($CaCO_3$) powder is a very finely ground and white powder that can be used as filler in the manufacture of concrete. This substance is widespread and can be found naturally in sources such as limestone, chalk or marble. It consists of three main chemical compounds: $CaCO_3$ (approx. 93–97%), magnesium oxide (MgO, 1.5%) and silicon oxide (SiO_2, 1–2%) [17]. The reaction of carbon dioxide with calcium hydroxide can also give the powder and its fineness helps early hydration of cement. The use of calcite powder (CP) as a partial cement replacement reduces CO_2 and NO_2 emissions from cement production. Also, it consumes less energy, resulting in long-term sustainability of construction projects and improved environmental protection [17]. Additionally, the use of calcium powder as a filler improves the strength and properties of the concrete while also acting as a cement substitute, helping to address environmental concerns by reducing the overuse of cement [18]. From the point of view of previous studies, about 10–30% calcite powder has been specified as the optimal replacement amount for cement, resulting in better performance of fresh and hardened concrete [17,19]. Despite various studies on the application of bagasse ash and calcite powder as cement substitutes in concrete production, the combined applications of BA and CP have not been investigated, hence this study.

This paper assesses the sustainable prospects of BA and CP as cement substitutes in concrete manufacturing. To achieve this goal, cement was replaced by BA and CP at 5%, 10%, and 15% weight each. Slump was studied while compressive strength, embodied energy, embodied CO_2, and sustainability index were evaluated after 28 days of concrete hardening. The results found would help identify the underlying variables and conditions for impact reduction when considering the environmental prospects of cement concrete modified with bagasse ash and calcite powder.

2. Materials and methods

2.1. Materials

All materials used (42.5 R Portland lime cement [PLC], calcite powder, sugar cane bagasse and fine and coarse aggregates) were sourced in Ota, Ogun State, Nigeria. Sugar cane bagasse (Fig. 1a) was sun dried for 7 days to aid in the recycling process. It was then processed in the Covenant University Mechanical Foundry under closed conditions at a temperature of 700 °C to obtain bagasse ash (Fig. 1b). The ash was passed through the 90 µm BS sieve to obtain a particle size similar to cement. The chemical compositions of the cement and binders used are shown in Table 1, using X-ray equipment (Phillips PW-1800) for analysis. From Table 1 it can be seen that the CP used exhibited similar chemical compositions reported in Ali et al. [17]. In addition, according to ASTM C618 [20], the sum of silica, alumina and ferrite over 50% is classified as Class C and F pozzolan. However, the calcium oxide (CaO) content in BA used is below 18%. Therefore, based on the classification, the BA used in this study met the ASTM C618 specification [20] and is classified as class F pozzolan. The specific gravity (SG) and specific surface area (SSA) of cement and binders were determined using a clean Le Chatelier flask, stopper, and kerosene [21]. This resulted in a SG of 3.15, 2.22, and 2.74 for PLC, BA, and CP, respectively. Similarly, the SSA of 375, 675, and 1426 m^2/kg were obtained for PLC, BA, and CP, respectively.

Fine aggregate (sharp sand 4.5 mm in size) and coarse aggregate (granite 12.5 mm in size) were used in saturated dry conditions. The moisture and water content of the aggregates was determined according to BS 12620 [22] using the oven-dried method at 105 ± 5 °C. These gave 0.32 and 0.22% as moisture content for fine and coarse aggregates and 0.69 and 0.79% as water absorption for fine and coarse aggregates.

2.2. Experimental methods

ACI 211 [23] was used to design the mix quantities and the results are presented in Table 2. Cement was replaced with 5, 10 and 15 wt% of both BA and CP using grade 25 concrete targeting a concrete strength of 25 MPa after 28 days hardening. These proportions were assumed to investigate how the sufficient amount of calcium oxide in CP and silica in BA might affect the concrete properties. The components were prepared in accordance with BS 1881 [24]. The slump test, as shown in Fig. 2a, was carried out with a slump cone of 300 mm in height, 200 mm in bottom diameter and 100 mm in top diameter. A compressive strength test was also performed on the 150 mm^3 cubes. The fresh samples were compacted in three layers with a 16 mm diameter tamping rod and cured at 25 ± 3 °C and 65% relative humidity [25] for 7, 14 and 28 days (Fig. 2b and c).

3. Sustainability assessments

The paper assesses the embodied energy (EE), embodied carbon dioxide (EC), and sustainability index (Si) of cement concrete modified with bagasse ash and calcite powder and compares it with control (cement) concrete. Through global warming potential (GWP), the greenhouse gasses such as CO_2, CH_4, NO_2 are converted into carbon dioxide equivalent (CO_2-eq) [26]. Thus, this study assumed embodied CO_2 as GWP. The functional units are m^3 per 25 MPa concrete, MJ-eq/m^3 for EE per cubic metre of concrete, kgCO_2-eq/m^3 for GWP per cubic metre of concrete, and kgCO_2-eq/m^3 for Si per cubic metre of concrete. The study boundary is cradle-to-gate, encompassing all input and output streams.

Fig. 1. (a) Sugar cane bagasse; (b) Sugar cane bagasse ash; (c) Calcite powder; (d) Portland limestone cement.

Table 1
Oxide compositions of cement and binders used.

Oxide composition (%)	PLC	CP	BA	ASTM C618 [20]	
				Class F	Class C
CaO	64.90	97.15	3.25	≤18	>18
SiO_2	21.60	0.18	76.29		
Al_2O_3	5.85	0.02	5.96		
Fe_2O_3	2.78	0.01	4.92		
MgO	1.42	0.02	1.12		
SO_3	2.03	–	0.85	<5	<5
K_2O	0.72	–	1.23		
Na_2O	0.14	–	0.35		
P_2O_5	–	–	0.20		
LOI, loss of ignition	1.38	0.26	5.33	<6	<6
$SiO_2 + Al_2O_3 + Fe_2O_3$	–	–	87.17	>50	>50

Table 2
Mix proportions.

Mix ID	Percentage replacement	Constituent materials (kg/m^3)					
		PLC	CP	BA	FA	CA	Water
S0	100% PLC	315	0.00	0.00	890	1042	190
S1	90% PLC + 5% BA + 5% CP	284	15.50	15.50	881	1042	190
S2	80% PLC + 10% BA + 10% CP	252	31.50	31.50	870	1042	190
S3	70% PLC + 15% BA + 15% CP	221	47.00	47.00	859	1042	190

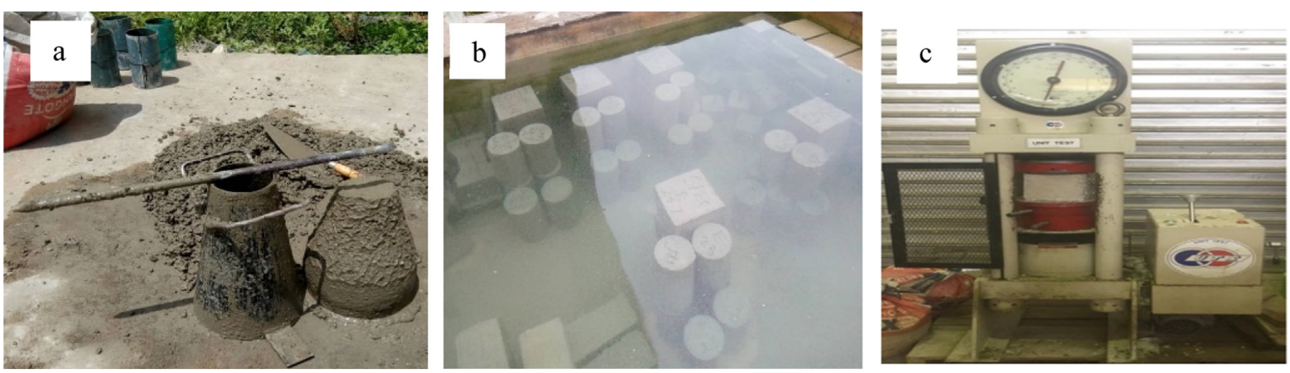

Fig. 2. (a) Slump test; (b) sample curing; (c) cube crushing.

3.1. Inventory data

The study applies the inventory of carbon and energy (ICE) to acquire datasets for these assessments. The inventory technique beats other methodologies in terms of accuracy and adaptability when applied to real-life case studies. It avoids the difficult approaches that require chemical equations by using energy and emission factors. The most commonly used additives in the manufacture of mixed cement concrete are agro-industrial by-products. Compared to other by-products, agro-industrial waste requires little energy for its production [26]. Table 3 therefore contains the embodied energy factor (EE_f) and global warming potential factor (GWP_f) for the components required to produce concrete.

Table 3
Energy and emission factors [26].

Material	EE_f (MJ-eq/kg)	GWP ($kgCO_2$-eq/kg)
PLC	5.50	0.95
CP	0.62	0.032
BA	0.24	0.01
Sand	0.081	0.0051
Granite	0.083	0.0052
Water	0.01	0.001

3.2. Impact evaluation

As stated above, the production of concrete consumes energy and emits carbon dioxide. Based on the study constraint (cradle-to-gate), the illustrations given in Eqs. (1) and (2) are used to assess the EE and GWP of the concrete produced per cubic meter [26,27]. The widespread use of concrete requires an assessment of its sustainable efficiency [27]. Thus, the sustainability index (Si) of the concrete mixes is illustrated in Eq. (3) [28,29]:

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

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

$$Si(kgCO_2 - eq/m^3.MPa) = \frac{GWP + (0.050 \times EE)}{28 - day\ compressive\ strength} \tag{3}$$

where w represents the weight of materials (kg).

4. Results and discussion

4.1. Slump

The workability of fresh concrete mix is assessed by setting test. Fig. 3 therefore shows the slump values for the fresh concrete mixtures. Accordingly, the control sample (100% Portland cement concrete, S0) gave the maximum slump. However, the slump of the fresh concrete mixes decreased with increasing BA and CP in the mix. Compared to the control sample, there were approximately 17, 50, and 58% reduction in the slump value when BA and CP increased from 5 to 15% in the blend. These results confirm previous studies in which the slump decreased with an increase in the replacement level of BA and CP by cement in concrete mixes [19,30]. The reasons can be attributed to the low SG and high SSA of BA and CP which increase binder volume for the same mass and decrease slump for the same water to binder ratio. However, the results contradict those of Ali et al. [17] where a replacement level of CP with cement resulted in an increase in slump. This may be related to CP's geological sources, processing techniques, chemical and mineral compositions.

4.2. Compressive strength

The compressive strength results are shown in Fig. 4. With the exception of the 15% replacement level, it can be seen from Fig. 4 that the partial replacement of cement by BA and CP at 5–10% resulted in higher compressive strength at ages 7 and 14 than control strength (S0). But after 28 days, the firmness decreased. Evidence for this early strength development can be seen in previous studies where the compressive strength of concrete modified with BA and CP increased after 7–14 days of curing, but after 28 days the strength decreased with increasing replacement levels of BA and CP [17,19,30]. The early strength development could be related to high amorphous silica in BA and filling effect of CP and high specific surface area of BA and CP. These stimulate the pozzolana and hydration reactions when there is an optimal water requirement and increase early strength [17,31]. In addition, the calcite filler reacts with the cement tricalcium aluminate (C3A), which reduces the cement–water compatibility and increases the early strength of the concrete [17]. Finally, from the results obtained here, it can be concluded that the replacement of cement with 10% BA and 10% CP meet the 25 MPa design strength and can be applied for structural purposes, while 15% can be used for mass concrete purposes.

4.3. Embodied energy (EE)

Fig. 5 illustrates the concrete's EE with reference to Tables 2 and 3 and Eq. (1). The results showed a decrease in EE with increasing BA and CP in the mixtures. Replacing cement with BA and CP at 5,

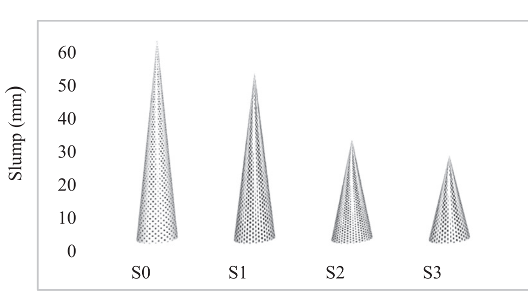

Fig. 3. Slump values of the fresh concrete mixtures.

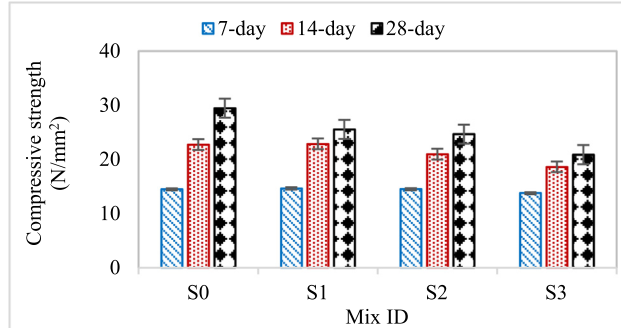

Fig. 4. Compressive strength.

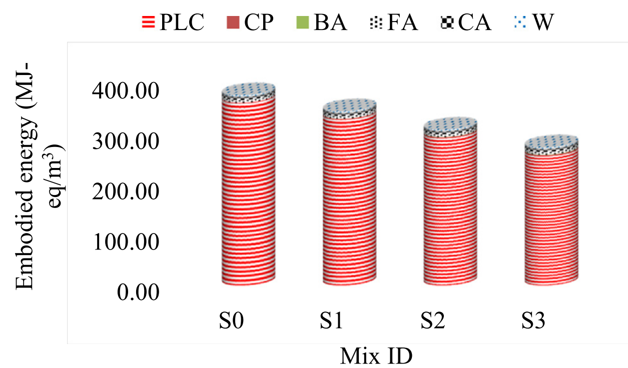

Fig. 5. The EE of concrete mixes.

10, and 15 wt%, respectively, reduced the EE of the concrete by 7.54, 16.23, and 24.58%, respectively, compared to the EE of the control concrete. A possible explanation for these results can be attributed to the embodied energy factors (EE_f) of the concrete components shown in Table 3. It was observed that the EE_f of PLC was approximately 89 and 96% higher than that of CP and BA, indicating that CP and BA are low EE building and construction materials. The effectiveness of BA and CP as low EE additives was illustrated in relevant studies where shea nut shell ash (SNSA) and corncob ash (CCA) reduced the EE of the concrete produced by 3–13% as their percentage replacement with cement ranged from 0 to 20% by weight [29,32]. Finally, these results demonstrate, without compromising the compressive strength, that the reduction of embodied energy of cement concrete modified with bagasse ash and calcite powder is feasible with an optimal replacement of cement with 10% BA and 10% CP.

4.4. Global warming potential (GWP)

Based on the mixture and factor details presented in Tables 2 and 3 and the relationship given in Eq. (2), the GWP results of concrete production per cubic meter are shown in Fig. 6. The results showed a decrease in GWP as the percentage replacement of PLC by BA and CP in the blend increased. The maximum GWP of the control concrete (S0) was 376.07 kgCO_2-eq per cubic metre of its manufacture. Thus, compared to this control, there was a reduction of 8.43, 18.10, and 27.43% in the mixed concrete at 5–15 wt% replacement levels of PLC with BA and CP. The incremental effects of various greenhouse gas emissions that adjust atmospheric temperature are more likely for cement than for pozzolana or additive [29], hence these results. Similarly, as shown in Table 3, the emissivity of PLC was 96.63 and 98.95% higher than that of CP and BA. These agree with previous studies that the emission factor for PLC was 95% greater than for SNSA [29] and CCA [32]. The adverse

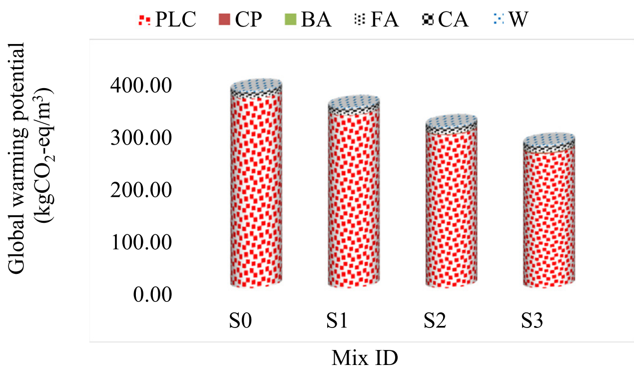

Fig. 6. The GWP of concrete mixes.

effects of global warming result in ozone depletion and harsh weather conditions. Obviously, these findings are significant in that both CP and BA can be used as cement substitutes in construction at a maximum of 10% each to create safe, sustainable, resilient and inclusive communities.

4.5. Sustainability index (Si)

Referring to Eq. (3), Fig. 7 gives the Si of the concrete mixes. The results showed a slight 1.84% reduction in Si at 10 wt% replacement level of cement with BA and CP. The lower the concrete Si, the more sustainable the concrete [28,29]. Thus, concrete made with 10% by weight replacement of cement with BA and CP (S2) is more sustainable than the control concrete (S0). However, at 5 and 15 wt% substitution of BA and CP for cement, the Si increased slightly by 5.52 and 3.22%, respectively. The results are inconsistent with previous studies [29,32], but there may be a number of reasons for this. The magnitude of the environmental impact of concrete production and its 28-day compressive strength may cause the inconsistency. Although Oyebisi et al. [29] found a reduction in Si at higher environmental potentials than at higher compressive strength. Overall, considering the lower environmental impacts (EE and GWP) already established for cement concrete modified with bagasse ash and calcite powder, it can be concluded that CP and BA are sustainable building materials and can be used as a substitute for cement with a maximum of 10% by weight of cement while maintaining the design strength of 25 MPa.

5. Conclusions

This research evaluated the environmental impact and sustainability index of cement concrete modified with bagasse ash and calcite powder using carbon and energy data. In addition, experimental work was carried out to determine the compressive strength of the concrete mixes. Then the following conclusions are drawn:

BA and CP can be used as cement substitutes with maximum 10 wt% each for ternary mix concrete. At 5–15 wt% of BA and CP substitution, EE decreased by 8–25%. Global warming potential of cement concrete modified with bagasse ash and calcite powder concrete reduced by 8–28% with 5–15 wt% substitution of BA and CP. At 10% by weight replacement of cement with BA and CP, CP-modified BA cement concrete is more sustainable than conventional concrete.

One implication of this study is the feasibility of CP and BA as sustainable building materials. The results provide insights for alleviating the environmental impact of Portland cement production. The generalizability of these findings is subject to certain limitations. Notwithstanding these limitations, further studies need to be conducted to determine the transport and economic impacts of these concrete materials and ensure a cradle-to-site analysis.

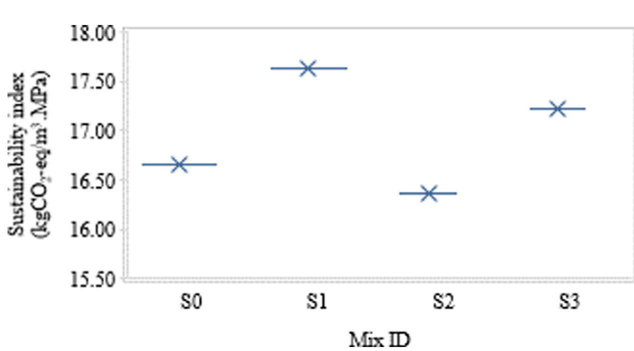

Fig. 7. Sustainability index of concrete mixes.

CRediT authorship contribution statement

Solomon Oyebisi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Software, Supervision, Writing – review & editing. **Festus Olutoge:** Funding acquisition, Resources, Validation, Writing – review & editing. **Akeem Raheem:** Validation, Writing – review & editing. **Daniel Dike:** Funding acquisition, Methodology, Resources, Validation, Writing – original draft. **Faithfulness Bankole:** Funding acquisition, Methodology, Resources, Validation, Writing – original draft.

Data availability

The data used are described in the article

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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