Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Cement replacement for lagoon-exposed concrete: a TOPSIS decision framework combining strength retention, water absorption, life-cycle carbon, embodied energy, and cost

Tobit Igba
Federal University of Agriculture
Solomon Oyebisi
sotech281.ola@gmail.com

University of the South Pacific

Research Article

Keywords:

Posted Date: November 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11607323/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Cement replacement for lagoon-exposed concrete: a TOPSIS decision framework combining strength retention, water absorption, life-cycle carbon, embodied energy, and cost

Tobit Igba[1], Solomon Oyebisi[2*]
[1]Civil Engineering Department, Federal University of Agriculture, Abeokuta, Nigeria
[2]Civil Engineering Department, University of the South Pacific, Suva, Fiji

[*]Correspondence: sotech281.ola@gmail.com

Abstract

The partial replacement of cement in concrete exposed to brackish water involves trade-offs between strength, durability, cost, and environmental impact. This study develops a transparent decision framework using TOPSIS to evaluate seven site-mixed 1:1.5:3 concretes from south-western Nigeria: a Portland limestone cement (PLC) control and mixtures containing 5, 10, or 15% cement replacement with waste ceramic tile powder or hydrated lime. Six criteria were considered: 90-day lagoon-exposed compressive strength, strength retention, water absorption, partial life-cycle global warming potential (GWP) covering the included production, construction and end-of-life stages, embodied energy, and cost based on 2026 Abeokuta prices. Rankings were examined under four weighting scenarios and 10,000 randomly generated weight combinations. Vector-normalised TOPSIS ranked the PLC control first under all four scenarios and in 70% of random simulations; COPRAS produced the same leading result. However, min–max TOPSIS, weighted sum and VIKOR ranked the 15% ceramic tile powder mixture first when carbon or cost was prioritised. Among the replacement mixtures, 5% hydrated lime performed best under equal and performance-led weighting and ranked first in 22% of simulations, supported by improved strength after lagoon exposure. The 15% ceramic tile powder mixture was favoured under carbon- and cost-led weighting but ranked first in only 6% of simulations. Despite reducing cost and GWP per cubic metre by 9% and 11%, respectively, it experienced a 42% reduction in lagoon-exposed strength. The findings demonstrate that single indicators can misrepresent overall suitability and that exposure-related performance should be considered alongside environmental and economic criteria when selecting cement replacements.

Keywords: Ceramic tile powder; embodied energy; global warming potential; hydrated lime; lagoon-exposed concrete; TOPSIS; sustainable concrete.

1 Introduction

Researchers have widely investigated partial replacement of Portland cement with supplementary cementitious materials and waste-derived powders to reduce the environmental burden of concrete production. Among these alternatives, waste ceramic tile powder has attracted interest because it offers a potential route for diverting construction waste from disposal while reducing demand for conventional cementitious materials. Its suitability, however, depends on its fineness, chemical composition, replacement level, and interaction with the cementitious matrix. Tanash et al. [1] reviewed the use of ceramic tile waste in cement-based composites and identified its potential contributions to mechanical performance, durability, and resource recovery. Experimental research has also investigated ceramic waste powder as a supplementary cementitious material, examining its effects on strength development, durability, and microstructure [2,3]. These findings support further

investigation of ceramic tile powder as a cement replacement, but they do not establish that every replacement level will provide an equivalent balance of engineering and sustainability benefits.

Selecting cement-replacement materials becomes more complex when concrete is intended for service in aggressive aqueous environments, where performance under conventional freshwater curing may not adequately represent behaviour under actual exposure conditions. Interactions between the exposure medium and the cementitious matrix can affect water absorption, deterioration, and the retention of mechanical strength. For concrete exposed to lagoon water, compressive strength after immersion, strength retention relative to freshwater-cured specimens, and water absorption offer complementary performance measures. However, these indicators capture distinct aspects of material behaviour and may favour different mixtures, underscoring the need for an integrated assessment when selecting suitable cement-replacement materials.

Environmental performance adds another dimension to material selection. Reducing cement content can lower the global warming potential (GWP) of concrete, but the magnitude of the benefit depends on the replacement material, its processing requirements, transportation, and the life-cycle stages included in the assessment. Knight et al. [4] demonstrated that the optimum replacement level for minimising environmental impacts while maintaining compressive strength depends on the supplementary cementitious material considered. Similarly, Olsson et al. [5] identified inconsistencies in life-cycle assessment (LCA) practices for cement and concrete, particularly regarding system boundaries, functional units, and the integration of material performance into environmental comparisons. These issues are especially relevant when comparing mixtures with different strengths and durability characteristics: a lower environmental burden per cubic metre does not necessarily imply better environmental performance for a given engineering function.

Economic considerations can further complicate the selection. Replacement material may reduce the cost of purchased cement but add processing, milling, transport, or handling expenses. Embodied energy may also vary independently of cost and GWP because the three indicators reflect different aspects of material production and supply. Consequently, selecting a mixture based on a single indicator can obscure important trade-offs among mechanical performance, durability, environmental impact, and affordability. An integrated assessment is therefore needed to transparently compare these competing objectives, rather than assuming that the mixture with the lowest cost or carbon footprint is necessarily the most suitable.

Multi-criteria decision analysis (MCDA) provides a structured way to evaluate alternatives against several criteria that may conflict. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives according to their relative closeness to a positive ideal solution and their separation from a negative ideal solution. Recent studies have applied TOPSIS to selecting sustainable concrete mixtures using mechanical, environmental, and economic indicators. For example, Najm et al. [6] evaluated self-compacting concrete mixtures incorporating alternative cementitious materials with respect to compressive strength, production cost, and GWP. Swathi and Vidjeapriya [7] used TOPSIS to optimise low-carbon binders for sustainable high-strength concrete. Mekky et al. [8] combined LCA and MCDA to evaluate the environmental and economic performance of concrete incorporating alum-sludge biochar. More recently, Silva et al. [9] integrated LCA and multi-criteria optimisation to compare recycled concrete mixtures using technical, environmental, and economic criteria. Collectively, these studies demonstrate the value of integrated decision frameworks in identifying trade-offs that may be overlooked when individual

indicators are assessed in isolation.

Despite these advances, applying MCDA to cement-replacement mixtures intended for aggressive lagoon environments needs further investigation. In particular, integrating exposure-conditioned compressive strength, strength retention, and water absorption with life-cycle global warming potential (GWP), estimated for the included production, construction, and end-of-life stages, embodied energy, and cost can provide a more context-specific basis for comparing alternatives. Decision-maker preferences also require attention. A mixture preferred under equal weighting may not remain preferable when mechanical performance, carbon reduction, or cost is prioritised. Evaluating predefined weighting scenarios alongside a large set of randomly sampled weights can therefore help distinguish consistently competitive mixtures from alternatives whose rankings depend on decision priorities. Such an analysis should therefore be interpreted as a test of ranking robustness under the assumed weighting distribution, rather than a prediction of actual stakeholder preferences.

This study develops and applies a TOPSIS-based decision framework to seven site-mixed concretes tested by the authors under freshwater and Lagos Lagoon exposure: a Portland limestone cement (PLC) control and six mixtures incorporating waste ceramic tile powder or hydrated lime at replacement levels of 5%, 10%, and 15% by mass of the original cement content. The study considers six criteria: 90-day compressive strength after lagoon immersion; the lagoon-to-freshwater strength retention ratio; water absorption after lagoon exposure; partial life-cycle indicators covering the included production, construction, and end-of-life stages; embodied energy; and material-related cost based on 2026 prices in Abeokuta, Nigeria. The study has four objectives: (i) to construct a decision matrix combining exposure-conditioned experimental performance with life-cycle and economic indicators; (ii) to rank the seven mixtures using TOPSIS under equal-weight, performance-led, carbon-led, and cost-led scenarios; (iii) to assess ranking robustness using 10,000 randomly generated criterion-weight vectors and calculate rank acceptability; and (iv) to identify the conditions under which a cement-replacement mixture may be preferred to the PLC control.

This research is innovative because it incorporates multi-criteria decision analysis, sustainability assessment, and experimental evaluation of concrete performance into a single decision-support system. While life-cycle carbon emissions and embodied energy address environmental sustainability, strength retention and water absorption assess mechanical performance and durability-related parameters. To ensure that the assessment also takes into account realistic economic factors, cost is taken into account. The TOPSIS methodology offers a clear and methodical way to rate potential materials based on how well they perform across these competing criteria.

By combining exposure-related performance with environmental and economic indicators, the framework aims to support more transparent selection of cement-replacement mixtures for concrete intended for coastal and lagoon environments. Instead of relying solely on specific mechanical, environmental, or financial indicators, the suggested method provides a comprehensive foundation for determining appropriate cement replacement solutions by considering these factors concurrently. The findings are expected to advance sustainable building materials by supporting well-informed decisions regarding durability, economic viability, cement replacement, and environmental impact reduction. Researchers, materials engineers, and practitioners seeking to balance competing performance needs when developing ecologically friendly concrete may also find the suggested decision framework helpful.

2 Materials and Methods

2.1 Decision framework

The proposed decision framework integrates experimentally measured performance and partial life-cycle indicators covering the included production, construction and end-of-life stages to evaluate the seven concrete mixtures and assess the robustness of their rankings (Fig. 1).

Stage 1: Construction of the decision matrix. Data were obtained from two sources. The first was an experimental programme conducted by the authors on the same seven mixtures (Section 2.2.1). It provided three performance criteria: 90-day compressive strength after immersion in Lagos Lagoon water, the lagoon-to-freshwater strength retention ratio, and water absorption after lagoon exposure. These results have not been published elsewhere; the full data set is given in Table S1. These data were combined with partial life-cycle indicators covering the included production, construction, and end-of-life stages: estimates of global warming potential (GWP), embodied energy, and cost based on 2026 prices in Abeokuta, Nigeria. The resulting decision matrix comprised seven concrete mixtures and six evaluation criteria. Compressive strength and strength retention were treated as benefit criteria, with higher values indicating better performance. Water absorption, GWP, embodied energy, and cost were treated as cost criteria, with lower values preferred.

Stage 2: Normalisation and ranking. Vector normalisation was applied to make criteria with different units and magnitudes comparable within the multi-criteria decision analysis. The normalised values were then weighted, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranked the mixtures by their relative closeness to the ideal and anti-ideal solutions. Four weighting scenarios were examined: equal-weight, performance-led, carbon-led, and cost-led. These scenarios allowed comparison of the preferred mixtures under different assumptions about the relative importance of mechanical performance, environmental impact, and economic cost.

Stage 3: Ranking robustness and acceptability. To assess the sensitivity of the rankings to criterion-weight selection, the analysis was repeated using 10,000 randomly generated weight vectors. For each mixture, rank acceptability was calculated as the proportion of simulations in which it attained each possible rank. This analysis distinguished mixtures that performed consistently across a broad range of weighting combinations from those whose ranking depended more strongly on particular decision priorities. A mixture that frequently achieved the first rank was considered a robust candidate under the assumed weight-sampling scheme, whereas one that ranked first only under a narrower set of weightings was considered a more conditional choice.

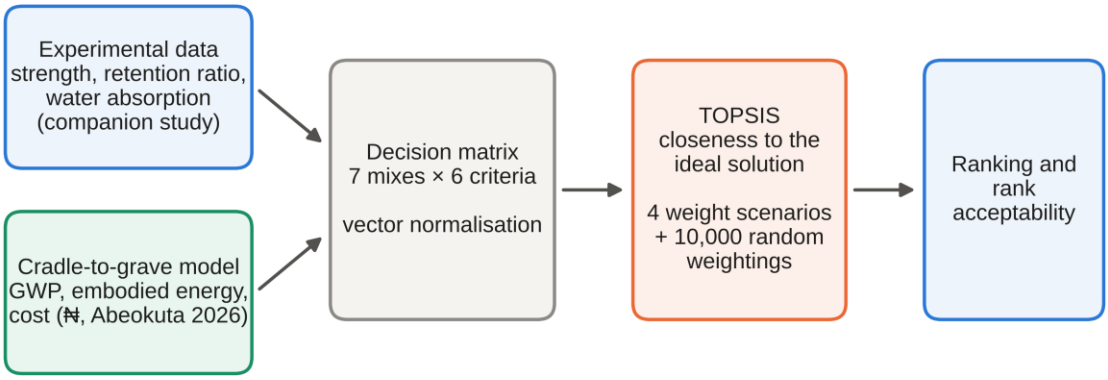


Fig. 1. Decision framework for TOPSIS-based ranking and robustness assessment of seven concrete mixtures using six performance, environmental, and economic criteria.

2.1.1 Life-cycle assessment boundary and assumptions.

The environmental assessment was conducted using a partial life-cycle boundary covering the included material production and supply processes, concrete production and construction activities, and end-of-life processes. The use stage (modules B1–B7) was excluded because the study did not model service-life-dependent maintenance, repair, replacement, or operational processes. End-of-life processes were assessed using the stated assumptions for demolition, crushing, recycling, and disposal, while potential benefits beyond the system boundary (Module D) were reported separately and not combined with the principal GWP result. Accordingly, the environmental results should be interpreted as comparative estimates for the specified system boundary rather than as complete cradle-to-grave impacts.

2.2 Alternatives and performance criteria

This study applies a TOPSIS-based decision framework to seven concrete mixtures evaluated experimentally under freshwater and Lagos Lagoon exposure conditions: a Portland limestone cement (PLC) control and six cement-replacement mixtures. Three mixtures (CT5, CT10, and CT15) incorporated waste ceramic tile powder (CT), while the remaining three (L5, L10, and L15) incorporated hydrated lime (L). The numerical suffixes denote the percentage of the original cement mass replaced by the respective material. Each replacement material was used separately at 5%, 10%, and 15% replacement levels; ceramic tile powder and hydrated lime were not combined in any mixture. All mixtures were prepared using a nominal mass proportion of 1:1.5:3, with the water content calculated as 0.55 times the remaining PLC mass.

2.2.1 Experimental programme

a. Materials

The binder used in this study was Portland limestone cement (PLC), classified as CEM II/A-L 42.5N. Hydrated lime was obtained from a building-materials vendor in Abeokuta, Nigeria, and subsequently pulverised in a milling workshop before use. Waste ceramic tiles were crushed and milled into powder using a hammer mill at the Department of Agricultural and Bio-resources Engineering, Federal University of Agriculture, Abeokuta, Nigeria. The resulting ceramic tile powder was passed through a 150 µm sieve, and only the fraction that passed was used in the concrete mixtures.

The fine aggregate consisted of sharp sand with a specific gravity of 2.50 and a fineness modulus of 2.64. The coarse aggregate was crushed granite with a specific gravity of 2.67 and a maximum particle size of 10 mm. Both aggregates were sourced from the Obada Oko area, Adigbe, Ogun State, Nigeria. The physical properties of the constituent materials were characterised in accordance with the relevant British and European standards. Potable water was used for concrete mixing.

b. Mix proportions

Seven concrete mixtures were investigated, comprising a Portland limestone cement control and six cement-replacement mixtures. The mixtures were prepared using a nominal mass proportion of 1:1.5:3. The control mixture contained 378 kg/m³ of PLC, with the constituent quantities determined using the absolute-volume method.

In the modified mixtures, 5%, 10%, or 15% of the original cement mass was replaced, separately, with waste ceramic tile powder (CT) or hydrated lime (L). The two replacement materials were not combined in any mixture. The resulting mixtures were designated CT5, CT10, CT15, L5, L10, and L15, where the numerical suffix represents the percentage of cement replaced by the respective material.

The mixing water was determined as 0.55 times the remaining PLC mass in each mixture. Consequently, the water-to-PLC ratio was maintained at 0.55, whereas the water-to-total-binder ratio decreased as the replacement level increased. The constituent quantities required to produce 1 m³ of concrete were calculated using the absolute-volume method and are presented in Table S1.

c. Specimens and curing

Concrete specimens (100 x 100 x 100 mm cubes) were prepared for compressive strength evaluation at 28 and 90 days under freshwater and Lagos Lagoon water-curing conditions. Following preparation, the specimens were subjected to the respective curing environments until the designated testing ages.

The freshwater-cured specimens served as the reference for evaluating the influence of lagoon-water exposure on compressive strength. The lagoon-water-cured specimens were immersed in Lagos Lagoon water to assess the development of the concrete mixtures under the investigated exposure conditions.

Three cube specimens were tested for each mixture, curing condition and testing age. Accordingly, the experimental programme comprised seven mixtures, two curing conditions, two testing ages and three replicate specimens, giving a total of 84 cubes for compressive-strength testing. An additional 84 cubes were tested for water absorption, covering seven mix proportions across two exposure media, two testing ages, and three replicates per condition.

d. Exposure water

Freshwater and Lagos Lagoon water were used as the two curing media. Water samples were analysed to determine their physicochemical characteristics. The lagoon water had a pH of 7.2, a chloride concentration of 48 mg/L, a sulphate concentration of 7 mg/L, total dissolved solids of 230 mg/L, and total hardness of 532 mg/L. The corresponding freshwater values were 7.2, 6, 2, 50, and 64 mg/L, respectively.

The relatively low chloride concentration in the sampled lagoon water, compared with typical seawater, indicates a mildly brackish exposure environment. However, the chemical characteristics of Lagos Lagoon water vary with location and season. Therefore, the reported values represent the water chemistry associated with the exposure conditions investigated in this study.

e. Tests

The compressive strength of the concrete mixtures was determined at 28 and 90 days after curing in freshwater and Lagos Lagoon water. The 28-day freshwater compressive strength served as the standard reference for assessing the performance of the replacement mixtures, while the 90-day lagoon-water strength was used to evaluate their performance under the investigated exposure condition. The workability of fresh concrete was measured using the slump test in accordance with BS EN 12350-2 [10]. Water absorption was tested in accordance with BS 1881-122 [11]. Compressive strength was determined in accordance with BS EN 12390-3 [12] after 28 and 90 days of curing in fresh water and lagoon water.

The reported compressive-strength values represent the mean of three cube specimens for each mixture, curing condition, and testing age. The results were subsequently used in the comparative economic and environmental assessment of the concrete mixtures.

Water absorption was determined after 28 and 90 days of curing in fresh water and Lagos Lagoon water, following the procedure of BS 1881-122 [11], using 100 mm cubes cast from the same batch as the compressive-strength specimens. The specimens were oven-dried at 105 ± 5 °C for 72 ± 2 h, cooled for 24 ± 0.5 h in a dry airtight vessel and weighed (M_{dry}). They were then immersed in water for 30 ± 0.5 min with at least 25 mm of water above the top surface, surface-dried and reweighed (M_{sat}). The mean of three cubes per mixture was used as the water-absorption criterion (Table 2; Table S1). Water absorption was calculated as illustrated in Eq. (1):

$$WA = \frac{M_{sat} - M_{dry}}{M_{dry}} \times 100 \quad (1)$$

where

M_{dry}: mass of the oven-dried specimen after cooling (g).

M_{sat}: mass of the specimen after the specified immersion and surface-drying procedure (g).

f. Strength retention ratio (SRR)

The influence of lagoon-water exposure on the compressive strength of each concrete mixture was evaluated using the strength retention ratio (SRR) in Eq. (2), defined as:

$$SRR_{90} = \frac{fc\ LW,90}{fc\ FW,90} \quad (2)$$

where:

SRR_{90} = 90-day Strength Retention Ratio;

$fc\ LW, 90$ = mean compressive strength of concrete cured in Lagos Lagoon water for 90 days (MPa);

$fc\ FW, 90$ = mean compressive strength of the corresponding concrete cured in freshwater for 90 days (MPa);

(c) denotes compressive strength, and the overbar indicates the mean value.

An SRR below unity indicates that compressive strength under lagoon-water curing was lower than under freshwater curing, whereas an SRR above unity indicates higher compressive strength under lagoon-water curing. An SRR equal to unity indicates that the mean compressive strengths under the two curing conditions were identical.

The analysis used treatment-mean values because it did not retain individual cube-level measurements. Consequently, the analysis could not quantify variability within each treatment or the uncertainty associated with the calculated strength retention ratios. This limitation should be considered when interpreting the comparative performance of the concrete mixtures.

Water was calculated as 0.55 times the mass of cement remaining after replacement, so the absolute water content fell from 208 kg/m³ in the control to 182 kg/m³ at 15% replacement, and the water-to-total-binder ratio fell from 0.55 to 0.47. The comparisons therefore represent the complete mixtures as proportioned by this rule; they do not isolate the effect of the replacement material at constant water content. All quantities were scaled to exactly 1 m³ with the absolute-volume yield of each mixture (specific gravities: cement 3.15, tile powder 2.60, lime 2.24, sand 2.50, granite 2.67; 2% air), which was 1–3% below 1 m³ for the replacement mixtures (Table S1).

The experimental results should be interpreted in the context of the available replication and exposure duration. For each mixture, the reported value represents the mean of three concrete cubes produced from a single batch. Accordingly, the specimens provide within-batch replication but do not constitute independent batch replicates. Furthermore, individual cube-level measurements were not retained; therefore, specimen-level variability could not be quantified or propagated through the TOPSIS analysis. The assessment is limited to 90 days of exposure to Lagos Lagoon water and does not establish long-term field durability. Water absorption is included as a comparative indicator of water transport and potential durability-related behaviour; however, it is not, on its own, sufficient to establish resistance to the range of chemical and physical deterioration mechanisms that may occur under lagoon exposure.

2.3 Environmental and cost criteria

Ceramic tile powder was modelled with the cut-off approach: discarded tiles were treated as waste, and no burden from the original tile manufacture was allocated to them. The system included road transport of the tiles over 20 km (0.0755 kg CO_2-eq/t·km) and hammer milling at 30 kWh/t. The mill ran on the university mains, which is supplied alternately by the national grid and a diesel standby generator. Milling electricity was therefore assigned 0.60 kg CO_2/kWh, between the grid factor (0.40 kg CO_2/kWh [13]) and that of the generator (0.80 kg CO_2/kWh, from 0.3 L/kWh × 2.66 kg CO_2/L). Using either bound changed the GWP of any mixture by less than 0.5 kg CO_2-eq/m³ and left the rankings in every scenario unchanged (Table S4). Milling cost and energy conservatively assume generator supply. Collection and sorting were excluded. These assumptions were applied identically to CT5, CT10 and CT15. Raising milling energy to 60 kWh/t and haul distance to 50 km together increased the GWP of CT15 by only 1.2 kg CO_2-eq/m³ (from 249.2 to 250.5), so its advantage over the control (278.8) stems from reduced cement content rather than from the processing assumptions. Allocating part of the original tile-manufacturing burden to waste would reduce this advantage; the cut-off rule therefore represents the most favourable case for the tile powder.

CO_2 uptake was calculated as the product of the carbonatable CaO in the cement and lime, multiplied by 44.01/56.08, where 44.01/56.08 is the molar ratio of CO_2 to CaO. The maximum degree of carbonation was set to 0.75. At end of life, 50% of the concrete was assumed to be crushed and reused, based on a Nigerian demolition-waste survey [14], and 50% landfilled; crushed and landfilled concrete were assumed to reach 10% and 2% of the maximum uptake, respectively. No uptake during service was included, and no time horizon beyond end-of-life processing was modelled. The same assumptions were applied to all mixtures.

The partial life-cycle GWP per cubic metre was estimated in accordance with the stated principles of ISO 14040/14044 and EN 15804 [15–17]. The functional unit was 1 m³ of concrete. The assessment included the specified material supply and production processes (A1–A3), transport to site (A4), site mixing and material losses (A5), and end-of-life processes (C1–C4), including the modelled carbonation uptake of demolished concrete. The use stage (B1–B7) was excluded because service-life-dependent maintenance, repair, replacement and in-service carbonation were not modelled. Module D was calculated separately and excluded from the principal GWP criterion. The results are therefore comparative estimates within this partial life-cycle boundary and should not be interpreted as complete cradle-to-grave impacts.

The inventory combined locally obtained material prices, published environmental and energy factors, experimentally determined material properties, and modelling assumptions. These inputs therefore differ in their data quality and geographical representativeness. Nigerian data were used where available; where local factors were unavailable, published international datasets or stated assumptions were adopted. The assumptions and their sources are identified in Supplementary Tables S2 and S3, while selected influential assumptions were examined through sensitivity analysis in Supplementary Table S4. The resulting environmental and cost indicators should be interpreted as comparative estimates for the stated location, prices, system boundary, and inventory assumptions.

It is reported separately in Table S4, at about −5.7 to −5.8 kg CO_2-eq/m³ for every mixture, alongside the module-by-module GWP results. Table S3 sets out the system boundary and indicates whether each input was measured, priced locally, or taken from the literature. Nigerian background data were used where available, including the cement production emissions intensity reported by the main domestic producer [18] and local survey data on demolition waste [14]. Hydrated-lime impacts were taken from a recent life-cycle assessment (LCA) [19]. Embodied energy per cubic meter was estimated using factors from previous Nigerian assessments [20,21], with the lime contribution from the Inventory of Carbon and Energy (ICE) database [22]; the stage-by-stage results are presented in Table S5.

The cost assessment included purchased materials, milling of waste ceramic tile powder and hydrated lime, site-mixer diesel consumption, and 3% allowance for site losses, based on 2026 prices in Abeokuta: cement, ₦15,000 per 50 kg bag; Hydrated lime, ₦28,000 per 25 kg bag; sharp sand, ₦137,800 per 20 t; granite, ₦572,400 per 30 t; and diesel, ₦1,856 per litre. The material-related cost per cubic metre was calculated by multiplying the quantity of each costed input by its unit price and summing the contributions: cement, lime, sand, granite, diesel for milling (tile powder and lime) and site mixing (0.5 L/m³), and a 3% allowance for site losses. Labour, formwork and water were excluded because the same casting procedure, moulds and water source were used for every mixture, and the water quantity differed by less than 30 kg/m³ between mixtures. The prices represent Abeokuta in 2026 and should be read as a location- and time-specific comparison. Itemised quantities, prices and costs are given in Tables S2 and S6. All material quantities and associated impacts and costs were normalised to exactly 1 m³ of concrete to account for the slightly lower yield of the cement-replacement mixtures.

2.4 TOPSIS

Four weighting scenarios were defined to reflect alternative priorities in concrete mixture selection (Table 1). The equal-weight scenario assigned the same importance to every criterion. The performance-led scenario placed greater weight on compressive

strength and strength retention, whereas the carbon-led scenario prioritised global warming potential (GWP) and embodied energy. The cost-led scenario placed greater emphasis on economic performance. These scenarios were intended to represent plausible decision priorities rather than fixed preferences shared by all structural engineers, sustainability practitioners, or contractors. Such multi-dimensional comparisons are consistent with recent applications of TOPSIS to sustainable concrete, in which mechanical, environmental, and economic indicators are evaluated together [6,23]. Because TOPSIS rankings can depend on the weighting and normalisation procedures adopted, the analysis also examined the sensitivity of the results to alternative criterion weights [23–25].

Table 1. Criteria, direction and weights in the four scenarios.

Criterion	Direction	Equal	Performance-led	Carbon-led	Cost-led
Strength, lagoon 90 d (MPa)	Benefit	0.167	0.30	0.10	0.10
Strength retention ratio (–)	Benefit	0.167	0.25	0.10	0.10
Water absorption, lagoon 90 d (%)	Cost	0.167	0.15	0.10	0.10
Life-cycle global warming potential (GWP) (kg CO_2-eq/m³)	Cost	0.167	0.10	0.40	0.15
Embodied energy (MJ/m³)	Cost	0.167	0.10	0.20	0.15
Cost (₦/m³)	Cost	0.167	0.10	0.10	0.40

For the decision matrix x_{ij} (mixture i, criterion j), each criterion was vector-normalised, as illustrated in Eqs. (3)-(7):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x^2{}_{ij}}} \quad (3)$$

The weighted normalised matrix was then calculated as:

$$v_{ij} = w_j r_{ij} \quad (4)$$

For each criterion, the positive and negative ideal solutions were determined according to whether the criterion is a benefit or a cost, and the distance of each alternative from both ideals was calculated as:

$$D_i^{+} = \sqrt{\sum_j (v_{ij} - v_j^{+})^2} \quad (5)$$

$$D_i^{-} = \sqrt{\sum_j (v_{ij} - v_j^{-})^2} \quad (6)$$

Finally, the closeness coefficient was calculated as:

$$C_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \quad (7)$$

Higher C_i indicates greater closeness to the positive ideal.

To assess ranking robustness beyond the four predefined scenarios, 10,000 weight vectors were sampled from a uniform distribution over the feasible weight space using a Dirichlet distribution with all concentration parameters set to one. Each vector contained non-negative criterion weights that summed to unity, allowing examination of a broad range of relative preferences without privileging any particular weighting pattern. TOPSIS was recalculated for each sampled vector, and rank acceptability was calculated as the proportion of simulations in which each mixture attained each rank. This probabilistic approach complements scenario-based sensitivity analysis by

showing not only the preferred mixture under specified assumptions, but also how frequently each mixture ranks highly across the sampled weighting space. Related work has used stochastic multicriteria acceptability analysis to examine the robustness of rankings under uncertainty in decision preferences [25]. The 10,000 weight vectors were sampled from a Dirichlet distribution with parameter vector $\alpha = (1, 1, 1, 1, 1, 1)$, i.e., uniformly over all non-negative weight vectors summing to one. The simulations were implemented in Python (v3.13.18) equipped with NumPy (v2.5.3) and SciPy (v1.18.1) libraries, using NumPy's default PCG64 generator with seed 20261024. Each vector was checked to be non-negative and to sum to one within 10^{-9}. For every vector, TOPSIS was recalculated with the same decision matrix, criterion directions and vector normalisation as in the predefined scenarios. Rank acceptability was calculated as the percentage of simulations in which each mixture attained each rank. No ties in Ci occurred in the 10,000 simulations; had they occurred, tied mixtures would have been ordered by their position in Table 3. The code (Supplementary Code TOPSIS.py), the 10,000 weight vectors (CSV), and a README are provided as Supplementary Data; running the code reproduces Fig. 6.

The four weighting scenarios were specified by the authors to examine how the ranking changes under different decision priorities; they are analytical assumptions rather than measured stakeholder preferences. Equal weighting assigns 1/6 to every criterion. The performance-led scenario allocates 0.70 in total to lagoon strength, strength retention, and absorption; the carbon-led scenario allocates 0.60 to GWP and embodied energy; and the cost-led scenario allocates 0.40 to cost. In each non-equal scenario, the remaining weight is spread so that no criterion receives zero weight. All weights are non-negative and sum to one.

2.5 Sensitivity to method

Vector-normalised TOPSIS was retained as the primary method. The analysis was repeated with (i) TOPSIS using linear min–max normalisation, with benefit and cost criteria oriented so that 1 is best; (ii) a weighted-sum model (WSM) on the same min–max scores; (iii) COPRAS, which uses sum normalisation and treats benefit and cost criteria separately; and (iv) VIKOR with $v = 0.5$. Each method was applied to the four scenarios and to the same 10,000 weight vectors.

A hierarchical weighting scheme was also tested, in which weights are first assigned to dimensions and then divided equally among the criteria within each dimension. Two groupings were examined: (A) mechanical performance (strength, R_f), durability (absorption), and environmental-economic burden (GWP, energy, cost); and (B) performance and durability (strength, Rf, absorption), environment (GWP, energy), and economics (cost). Each grouping was evaluated with equal dimension weights and with 10,000 vectors in which dimension and within-dimension weights were drawn from flat Dirichlet distributions (seed 20261028). The results of these comparisons are reported in Section 3.4 (Tables 6 and 7).

3 Results

3.1 Workability and compressive strength

The effect of a supplementary powder on slump is governed by its particle size, specific surface area, and replacement level, together with the overall mix proportions, which jointly determine the direction and extent of any change in workability [26]. Here, slump rose as the replacement level increased (Fig. 2a), despite a decline in the water-to-total-binder ratio. This decline arose because the mixing water was proportioned to the remaining Portland limestone cement (PLC) rather than to the total

binder content, so the improved slump cannot be explained by additional water relative to the binder. A more plausible explanation lies in altered particle packing and in the surface properties of the replacement powders, although neither was measured in this study. The improvement in workability was accompanied by a marked reduction in strength (Fig. 2b), with all replacement mixes developing 28-day compressive strengths approximately 12–15 MPa lower than the control. Ceramic tile powder and hydrated lime therefore increased slump under the mix-design conditions examined, which underlines the need to evaluate workability and compressive strength together when assessing the suitability of these materials for concrete.

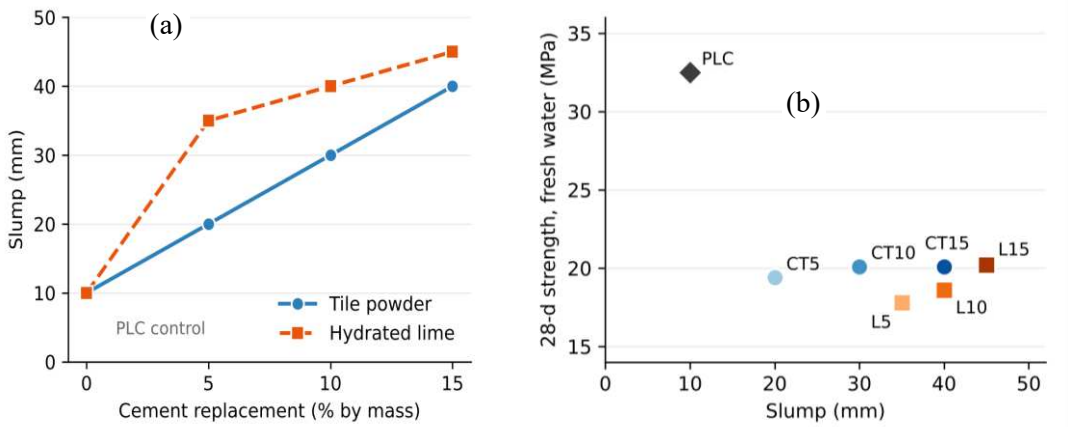


Fig. 2 Workability. (a) Slump against cement replacement. (b) 28-day strength (freshwater curing) versus slump; the PLC control yields the lowest slump and the highest strength.

Table 2 lists the measured compressive strengths, and Fig. 3 shows how they varied with mix, curing medium, and age. The PLC control reached 32.5 MPa at 28 days and 36.0 MPa at 90 days in fresh water. In Lagos Lagoon water, it reached 27.3 and 29.0 MPa. Lagoon exposure therefore reduced the control's strength by 16.0% at 28 days and 19.4% at 90 days, so the gap between the two curing media persisted and widened slightly with age.

All six replacement mixes were weaker than the control in both media and at both ages. At 28 days in fresh water, they reached 55–62% of the control strength. After immersion in lagoon water, the tile-powder mixes reached 56–62% of the control and the lime mixes 68–69%.

By comparison, the replacement level made little difference. In fresh water, the 28-day strengths of the tile-powder mixes ranged only from 19.4 to 20.1 MPa, a spread of about 3.5%. For tile powder, almost all of the strength loss therefore occurred between the control and the 5% mix, with little further change at 10% and 15%. The lime mixes did not weaken further as more lime was added: their 28-day freshwater strength rose slightly, from 17.8 MPa at 5% to 20.2 MPa at 15%. Unexpectedly, some mixes lost strength between 28 and 90 days. In fresh water, L10 fell from 18.6 to 15.2 MPa and L15 from 20.2 to 16.4 MPa (about 18–19%), and in lagoon water CT5, L10 and L15 fell by about 9%, 23% and 24%, respectively, while CT10 and CT15 remained essentially unchanged. Strength normally continues to rise with age, so these reductions are more likely to reflect the experimental conditions than a real loss of capacity. Hydrated lime is not pozzolanic on its own, and unconsumed calcium hydroxide may leach from the paste during prolonged immersion, increasing porosity at higher lime contents. Because each age was represented by three cubes from a single batch, specimen-to-specimen variability may also have contributed. These reductions

affect the 90-day lagoon strengths of L10 and L15 used in the decision matrix and should be confirmed with replicated batches and longer exposure periods. These dosage differences should be read with caution.

Water absorption increased between 28 and 90 days for every mix in both media, including the control, whose absorption rose from 3.1% to 3.6% in fresh water and to 4.5% in lagoon water (Table 2). Continued hydration typically refines the pore structure and reduces absorption, so this trend runs counter to expectations. Possible contributing factors include leaching of calcium hydroxide during immersion, microcracking induced by oven-drying at 105 °C before testing, and differences between specimens tested at the two ages, which came from a single batch per mix. The absorption values are therefore used here as comparative indicators between mixes at the same age and exposure, rather than as absolute measures of how durability develops over time.

Fig. 4 presents SEM micrographs of selected specimens acquired at 15 kV and 250× magnification, with a 200 µm scale bar in the original images. The CT15 specimen cured in lagoon water exhibits a relatively porous, fine-grained matrix containing a prominent rounded void several hundred micrometres across (Fig. 4a). In contrast, the PLC specimen subjected to freshwater curing exhibits a comparatively continuous matrix with fewer conspicuous voids (Fig. 4b), whereas the L5 specimen cured in lagoon water displays a granular matrix with visible microstructural features (Fig. 4c). Such differences in pore morphology and matrix continuity are relevant to understanding the behaviour of cementitious materials, as microstructural features, including pores and hydrated cement phases, influence their mechanical performance and transport properties [27,28].

Nevertheless, the present observations should be interpreted qualitatively because no quantitative porosity analysis or elemental mapping was performed, and each micrograph represents only a limited field of view. Consequently, the images provide supporting evidence of microstructural differences rather than definitive proof of a causal relationship between pore structure, strength, and water absorption. This cautious interpretation is consistent with recent research demonstrating the value of quantitative SEM image analysis for characterizing cementitious microstructures and relating their features to bulk material properties [28,29].

The microstructural analysis highlights key morphological features rather than providing a statistically representative assessment of each mixture. Because of the limited sampling area and specific fields of view, these observations are not used to quantify porosity or draw definitive conclusions about strength development mechanisms.

Earlier studies show that the effect of ceramic waste powder on compressive strength depends on its physicochemical properties, processing history, replacement level, and mix design [30]. Taher et al. [31] compared burnt and unburnt ceramic tile powders and found that performance varied with both powder type and dosage, with 10% replacement performing best in their study. Li et al. [32] reported that acceptable strength could be retained at up to 20% ceramic powder replacement. Tanash et al. [33], in their review, emphasised the role of waste characteristics and processing. Because those studies used different materials, replacement levels, and mix-design procedures, their results cannot be compared directly with the present findings.

The strength differences observed here cannot be attributed solely to cement replacement, for three reasons. First, the mixing water was set based on the remaining PLC content, so the water-to-total-binder ratio decreased with increasing replacement. Second, the control and replacement mixes were cast on different days, so any casting-

day effect cannot be separated from the effect of mix composition. Third, each treatment used three cubes from a single batch, which limits the assessment of variability within and between batches. The results therefore describe how these mixes performed under the specific proportions and casting conditions used, not the isolated effect of the replacement materials. Future studies should, where the research objective allows, keep the water-to-total-binder ratio constant, cast control and replacement mixes on the same day, and use independently replicated batches.

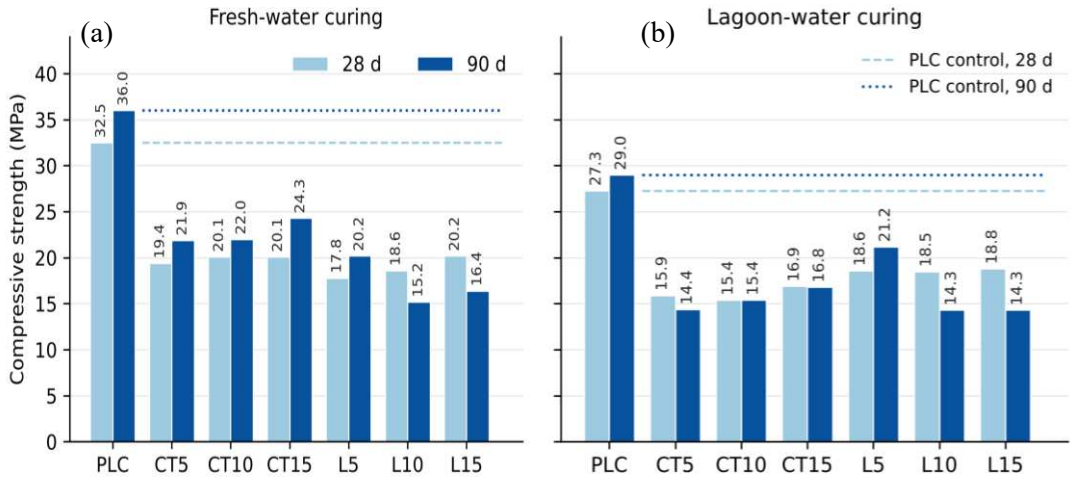


Fig. 3 Compressive strength at 28 and 90 days for (a) freshwater and (b) lagoon-water curing. Dashed and dotted lines mark the PLC control at 28 and 90 days. Each bar is the mean of three cubes.

Table 2. Slump, mean compressive strength, and water absorption of the concretes (strength and absorption: mean of three cubes).

Mix	Slump (mm)	Compressive strength (MPa)				Water absorption (%)			
		F 28 d	F 90 d	LW 28 d	LW 90 d	F 28 d	F 90 d	LW 28 d	LW 90 d
PLC	10	32.5	36.0	27.3	29.0	3.1	3.6	3.1	4.5
CT5	20	19.4	21.9	15.9	14.4	4.1	4.7	4.7	5.1
CT10	30	20.1	22.0	15.4	15.4	4.9	5.3	4.8	5.5
CT15	40	20.1	24.3	16.9	16.8	5.2	5.6	5.1	6.2
L5	35	17.8	20.2	18.6	21.2	4.3	4.9	4.9	5.3
L10	40	18.6	15.2	18.5	14.3	5.1	5.5	5.2	5.7
L15	45	20.2	16.4	18.8	14.3	5.4	5.9	5.6	6.6

F, freshwater curing; LW, lagoon-water curing. The water absorption of the control at 28 days is the same in both media (3.08 %).

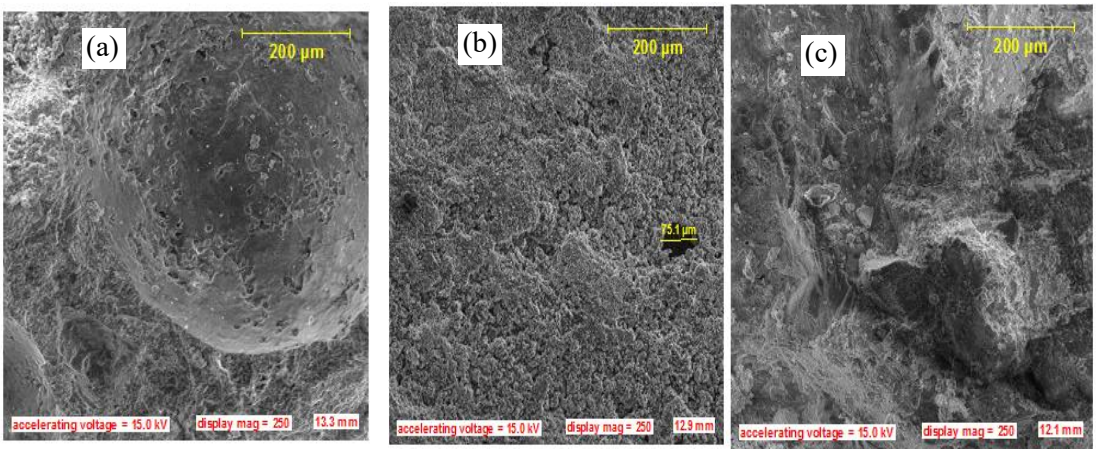


Fig. 4 SEM micrographs at 15 kV and 250× magnification (scale bar 200 µm). (a) CT15, lagoon-water curing; (b) PLC, freshwater curing; (c) L5, lagoon-water curing.

3.2 Decision matrix

Fig. 5 and Table 3 present the decision matrix, with cell shading indicating each mixture's relative position between the minimum and maximum values for each criterion. The results reveal clear trade-offs, as no single mixture performed best across all six criteria. The PLC control achieved the highest 90-day compressive strength after lagoon exposure (29.0 MPa) and the lowest water absorption (4.5%), although its cost, global warming potential (GWP), and embodied energy were not the lowest. By contrast, CT15 recorded the lowest cost (₦130,958/m³), GWP (249 kg CO_2-eq/m³), and embodied energy (2,512 MJ/m³), but its lagoon-exposed compressive strength was considerably lower (16.8 MPa), and its water absorption was the second highest among the mixtures. L5 exhibited the highest strength retention ratio (1.05), the only value exceeding unity, indicating that its measured 90-day strength after lagoon exposure was slightly higher than its freshwater reference strength. However, this apparent advantage came with higher cost and GWP per cubic metre than the control. L10 and L15 performed comparatively poorly across most criteria, making them less competitive under the evaluated decision scenarios.

These results illustrate why environmental and economic indicators should not be interpreted independently of mechanical performance and durability. Recent reviews of concrete life-cycle assessment have highlighted the importance of incorporating performance-related measures when comparing mixtures with different binder compositions [5]. Similarly, Witte and Garg [34] showed that estimated GWP values can vary by assessment method and that carbon performance is more informative when interpreted alongside compressive strength. The close association observed among cost, GWP, and embodied energy in the present study is consistent with the substantial influence of binder composition on concrete's environmental burden. These associations are quantified in Table 4.

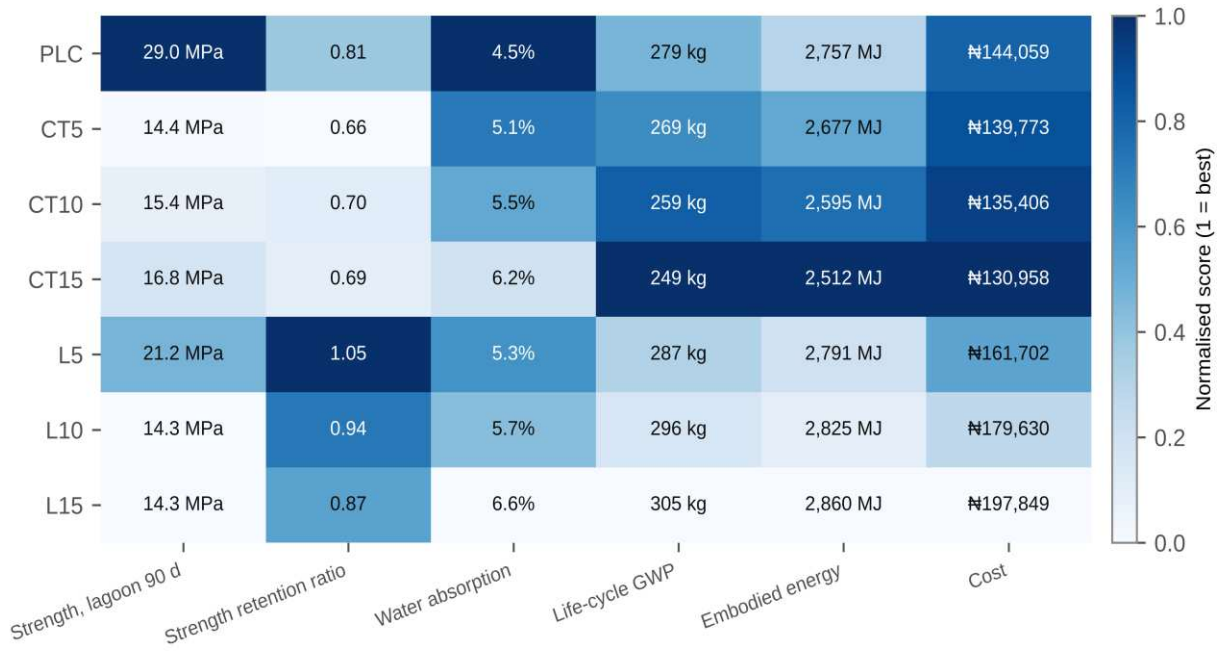


Fig. 5. Decision matrix. Cell values are the criterion values; shading shows each value's position between the worst (white) and best (dark) value of that criterion. GWP, embodied energy, and cost are per m³.

Table 3. Decision matrix of the seven mixtures. Strength and absorption are 90-day lagoon values; SRR (Eq. 2); GWP, embodied energy, and cost are per m³.

Mix	Strength (MPa) [+]	SRR (–) [+]	Absorption (%) [−]	GWP (kg CO_2-eq/m³) [−]	Energy (MJ/m³) [−]	Cost (₦/m³) [−]
PLC	29.0	0.806	4.5	278.8	2,757	144,059
CT5	14.4	0.658	5.1	269.1	2,677	139,773
CT10	15.4	0.700	5.5	259.3	2,595	135,406
CT15	16.8	0.691	6.2	249.2	2,512	130,958
L5	21.2	1.050	5.3	287.3	2,791	161,702
L10	14.3	0.941	5.7	295.9	2,825	179,630
L15	14.3	0.872	6.6	304.7	2,860	197,849

Table 4. Correlation between environmental-economic criteria (n = 7; exploratory).

Pair	Pearson r (p)	Spearman ρ
Cost – GWP	0.943 (0.001)	1.00
Cost – embodied energy	0.870 (0.011)	1.00
GWP – embodied energy	0.985 (< 0.001)	1.00

With only seven alternatives, these correlations are exploratory, but all three criteria ranked the mixtures identically. They are driven largely by the cement content and

therefore partly reward the same characteristic; because each receives a separate weight, their combined influence is larger than any single weight suggests. Under flat Dirichlet sampling, they received an average weight of 50%. Table 5 expresses the environmental and cost indicators per 90-day lagoon strength, relative to the control.

Table 5. Environmental and cost indicators per m³ and per MPa of 90-day lagoon strength (difference from the PLC control in brackets).

Mix	$f_{c,LW,90}$ (MPa)	GWP per m³	GWP per MPa	Energy per m³ (MJ)	Energy per MPa	Cost per m³ (₦)	Cost per MPa (₦)
PLC	29.0	278.8	9.61	2,757	95.1	144,059	4,968
CT5	14.4	269.1 (−3%)	18.69 (+94%)	2,677 (−3%)	185.9 (+96%)	139,773 (−3%)	9,706 (+95%)
CT10	15.4	259.3 (−7%)	16.84 (+75%)	2,595 (−6%)	168.5 (+77%)	135,406 (−6%)	8,793 (+77%)
CT15	16.8	249.2 (−11%)	14.83 (+54%)	2,512 (−9%)	149.5 (+57%)	130,958 (−9%)	7,795 (+57%)
L5	21.2	287.3 (+3%)	13.55 (+41%)	2,791 (+1%)	131.7 (+38%)	161,702 (+12%)	7,627 (+54%)
L10	14.3	295.9 (+6%)	20.69 (+115%)	2,825 (+2%)	197.6 (+108%)	179,630 (+25%)	12,562 (+153%)
L15	14.3	304.7 (+9%)	21.31 (+122%)	2,860 (+4%)	200.0 (+110%)	197,849 (+37%)	13,836 (+179%)

Per cubic metre, CT15 had 11% lower GWP and 9% lower cost than the control, but per MPa of lagoon strength its GWP, energy and cost were 54–57% higher. Every replacement mixture had higher carbon, energy, and cost per MPa than the control; the smallest penalty was for L5 (38–54%).

3.3 Rankings under the four scenarios

The TOPSIS results indicate that the Portland limestone cement (PLC) control consistently achieved the highest overall ranking across all four weighting scenarios, with closeness coefficients ranging from 0.65 to 0.77 (Fig. 6). However, the relative positions of the replacement mixtures varied according to the decision priorities, illustrating the influence of criterion weighting on multi-criteria evaluations of concrete sustainability. Recent studies applying TOPSIS and other multi-criteria decision-making methods to concrete mixture selection and low-carbon binder optimisation have reported similar sensitivity to weighting assumptions [7,35].

Under equal weighting, L5 ranked second (closeness coefficient = 0.57), followed by CT15 (0.38), CT10 (0.36), and CT5 (0.34). A similar ordering was observed under performance-led weighting, where L5 retained second place (0.56), while the ceramic tile powder mixtures ranked fourth or lower. This suggests that, when mechanical performance and durability-related indicators receive greater emphasis, the lower hydrated-lime replacement level provides a more favourable compromise among the evaluated criteria.

Under carbon-led weighting, CT15 moved to second place (0.53), marginally outperforming L5 (0.49) and CT10 (0.48). This shift indicates that increasing the importance assigned to environmental performance favoured the ceramic tile powder

mixtures, particularly CT15. Under cost-led weighting, the three tile-powder mixtures ranked second to fourth, with closeness coefficients ranging from 0.61 to 0.67, while L5 fell to fifth place. These results highlight the trade-off between performance-oriented selection and decisions that place greater emphasis on environmental and economic criteria, consistent with recent TOPSIS-based optimisation studies of low-carbon concrete binders [7].

L15 ranked last under equal, carbon-led, and cost-led weighting, but improved to fifth place under performance-led weighting. Overall, the results show that PLC control remained the preferred option within the four predefined scenarios, whereas the relative suitability of the replacement mixtures depended on the priorities assigned to strength, durability, environmental impact, and cost. This reinforces the value of evaluating concrete alternatives under multiple weighting scenarios rather than relying on a single set of criterion weights [35].

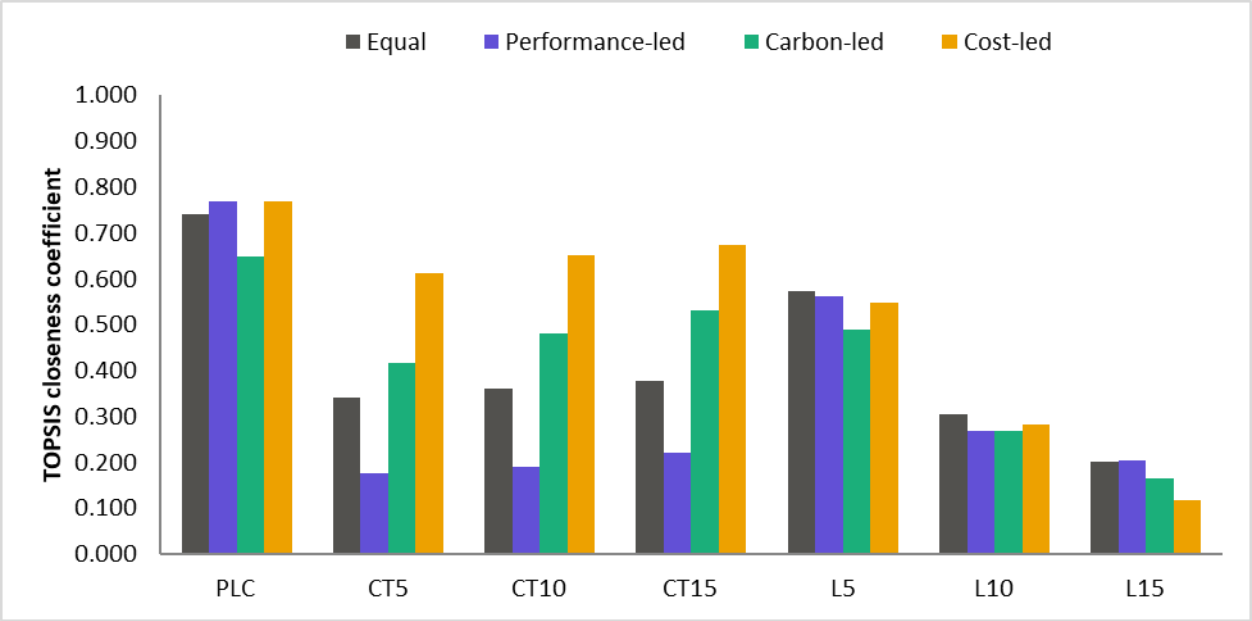


Fig. 6. TOPSIS closeness coefficients of the seven concretes under the four weighting scenarios of Table 1. Higher is better.

3.4 Robustness to the choice of weights

The robustness analysis based on 10,000 randomly generated weight vectors showed that the ranking of the concrete mixtures depended on the relative importance assigned to the six evaluation criteria (Fig. 7). The PLC control ranked first in 70.3% of simulations and appeared among the top two alternatives in 83.2% of cases, indicating that its leading position was maintained across a substantial proportion of the sampled weighting space. Among the replacement mixtures, L5 demonstrated the greatest overall competitiveness, ranking first in 21.8% of simulations and within the top two in 72.2%. By comparison, CT15 ranked first in 6.3% of cases and within the top two in 18.1% of cases, while the remaining mixtures rarely achieved the highest rank. This use of rank acceptability to examine the stability of multi-criteria rankings is consistent with robustness-oriented decision analysis, in which alternatives are assessed across a range of plausible criterion weights rather than under a single predefined weighting scheme [25].

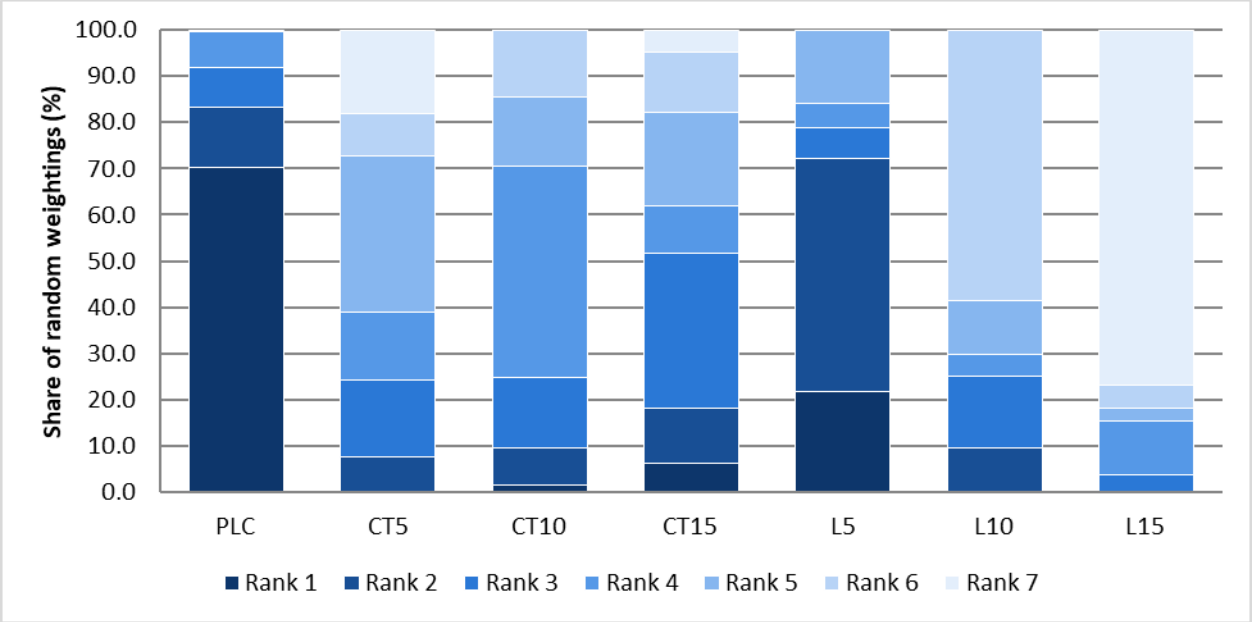


Fig. 7. Rank acceptability of the seven concrete mixtures based on 10,000 randomly generated criterion-weight vectors, expressed as the proportion of simulations in which each mixture attained each rank (rank 1 denotes the highest-ranked alternative).

An examination of the weight vectors associated with first-place rankings further clarified when each mixture was preferred. Simulations in which L5 ranked first assigned an average weight of approximately 0.36 to the strength retention ratio, around twice the equal-weight value of 0.167 for each of the six criteria. This indicates that L5 was particularly competitive when maintaining strength under lagoon exposure was prioritised relative to freshwater conditions. In contrast, simulations favouring CT15 assigned approximately 0.83 of the total weight collectively to global warming potential (GWP), embodied energy, and cost, while assigning only about 0.05 each to direct compressive strength and water absorption. Thus, CT15's first-place rankings were associated with weighting combinations that strongly prioritised environmental and economic performance over direct mechanical strength and water uptake. This preference-dependent behaviour is consistent with research applying TOPSIS to concrete mixture optimisation, where the preferred alternative reflects the balance between performance, environmental impact, and cost rather than superiority across every criterion [7].

The rankings under equal and performance-led weights were consistent across methods: PLC ranked first with every method, and L5 was the leading replacement under performance-led weights with every method. Under carbon-led and cost-led weights the result depended on the normalisation. Methods that preserve proportional differences between values (vector TOPSIS and COPRAS) kept PLC first, whereas methods that rescale each criterion to its own range (min–max TOPSIS, WSM and VIKOR) placed CT15 first. GWP and embodied energy differ by only 22% and 14% between the best and worst mixtures, whereas strength differs by a factor of two; range-based rescaling gives these small environmental differences the same span as the large strength differences. Table 6 compares the leading mixtures obtained with each MCDA method.

Table 6. First- and second-ranked mixtures by method and scenario, rank agreement with vector TOPSIS (Spearman ρ) and first-place share in 10,000 random weightings.

Method	Equal	Performance-led	Carbon-led	Cost-led	PLC / L5 / CT15 first (%)
TOPSIS, vector (reference)	PLC, L5	PLC, L5	PLC, CT15	PLC, CT15	70.3 / 21.8 / 6.3
COPRAS	PLC, L5 (1.00)	PLC, L5 (0.86)	PLC, CT15 (1.00)	PLC, CT15 (0.96)	76.6 / 15.6 / 7.6
TOPSIS, min–max	PLC, CT15 (0.89)	PLC, L5 (0.89)	CT15, CT10 (0.61)	CT15, CT10 (0.89)	44.2 / 17.2 / 32.8
WSM, min–max	PLC, CT15 (0.89)	PLC, L5 (0.61)	CT15, CT10 (0.75)	CT15, CT10 (0.89)	51.4 / 12.7 / 35.6
VIKOR (v = 0.5)	PLC, L5 (1.00)	PLC, L5 (0.61)	CT15, CT10 (0.61)	CT15, CT10 (0.89)	47.7 / 16.9 / 26.0

The hierarchical weights (Table 7) showed the same dependence on how the environmental-economic criteria were counted: when they formed a single dimension (grouping A), PLC ranked first in 77% of simulations, whereas when cost formed a separate dimension (grouping B), CT15 ranked first in 37% of simulations.

Table 7. Vector TOPSIS with hierarchical weights.

Grouping	Weights with equal dimensions (strength, R_f, absorption, GWP, energy, cost)	Rank with equal dimensions	First place in 10,000 (%) PLC / L5 / CT15
A	0.167, 0.167, 0.333, 0.111, 0.111, 0.111	PLC > L5 > CT5 > CT10 > L10 > CT15 > L15	77.1 / 17.1 / 3.6
B	0.111, 0.111, 0.111, 0.167, 0.167, 0.333	PLC > CT15 > CT10 > CT5 > L5 > L10 > L15	48.2 / 10.9 / 36.8

These findings should be interpreted as robustness within the sampled weight space, rather than as probabilities of actual stakeholder preferences. The random-weighting procedure identifies the proportion of sampled weight combinations under which each mixture achieves a given rank; it does not establish how frequently real decision-makers would adopt those preferences. Accordingly, CT15 should not be regarded as universally unsuitable for structural applications. Rather, selecting it requires careful consideration of the substantial reduction in lagoon-exposed compressive strength relative to the control and confirmation that the resulting concrete meets the relevant structural design requirements.

The robustness of the framework was examined with respect to both criterion weights and method. The random-weight simulations quantified rank acceptability under the stated weight distribution, and the additional analyses tested normalisation, a second and third MCDA method, hierarchical weighting and the correlation among the environmental-economic criteria. PLC and L5 were consistently preferred whenever performance received at least equal weight. When carbon or cost dominated, the choice between PLC and CT15 depended on whether small relative savings in carbon and cost were scaled to count as much as large relative losses in strength, a value

judgement that the decision-maker should make explicitly. These findings are specific to the seven mixtures, the selected criteria and the modelled exposure and life-cycle conditions.

4. Discussion

4.1 Implications of multi-criteria assessment for selecting cement replacement materials

The findings demonstrate the limitations of evaluating cement replacement materials using a single performance or sustainability indicator. When global warming potential (GWP), embodied energy, or cost is considered independently per cubic metre of concrete, CT15 emerges as the most favourable replacement among the mixtures investigated. However, this advantage shifts when the assessment incorporates structural performance and durability-related indicators. Under most of the weighting scenarios, CT15 ranks below both the PLC control and the 5% hydrated-lime mixture (L5). This distinction matters because reducing the environmental burden or cost of producing a unit volume of concrete does not necessarily make the resulting concrete a more resource-efficient structural material if it has substantially lower strength.

In the present study, CT15 reduced cost and GWP per cubic metre by approximately 9% and 11%, respectively, relative to the control, but its 90-day compressive strength after lagoon exposure was approximately 42% lower. Consequently, the apparent environmental and economic benefits must be interpreted alongside the reduction in load-bearing capacity. This finding is consistent with research showing that the performance of ceramic waste powder as a cement replacement depends on replacement level, material characteristics, and the resulting mechanical and durability properties [1,3,36]. Although finely ground ceramic waste can improve particle packing and, where sufficient reactivity is present, support pozzolanic reactions, these effects do not guarantee that increasing the replacement percentage will maintain the reference concrete's strength.

The strength-normalised results reported in the present study further illustrate the importance of considering strength alongside environmental and economic indicators, in which all replacement mixtures had higher cost, embodied energy, and GWP per unit of compressive strength than the control. These results indicate that reducing the cement content was insufficient to offset the lower strength observed in the replacement mixtures. Strength-normalised indicators are therefore useful complements to volume-based indicators, particularly when comparing concrete mixtures intended to provide similar structural functions. Nevertheless, such ratios should not be interpreted in isolation: concrete selection must also consider durability, exposure conditions, design requirements, and service life. Recent concrete sustainability studies have used multi-criteria approaches to combine technical, environmental, and economic measures, avoiding reliance on a single indicator that may favour an alternative with important disadvantages elsewhere [7,37].

The TOPSIS analysis extends this comparison by examining the alternatives under several weighting scenarios rather than assuming a single, universally accepted trade-off between structural performance, environmental impact, and cost. The control ranked first across all four predefined scenarios, while the relative positions of the replacement mixtures changed when environmental or economic criteria were given greater weight. This distinction matters in practice, where clients, designers, contractors, and sustainability assessors may prioritise strength, durability, carbon emissions, and cost differently. The results do not imply that any single weighting scheme is universally correct; instead, they show how the preferred alternative varies with the adopted priorities. Similar applications of TOPSIS and related multi-criteria

methods have demonstrated the usefulness of integrating performance and sustainability criteria when selecting concrete mixtures [7,37].

4.2 Performance of the low-level hydrated-lime replacement

The relatively strong performance of L5 was mainly due to its strength-retention behaviour under lagoon exposure. It was the only mixture with a strength retention ratio greater than unity, and its 90-day lagoon-exposed compressive strength of 21.2 MPa was the highest among the replacement mixtures. This combination of strength retention and absolute strength helps explain why L5 ranked second under equal and performance-led weighting and remained competitive across the random-weight simulations. However, the strength retention ratio should be interpreted alongside the absolute compressive strength: a ratio above unity indicates that the measured strength under lagoon exposure exceeded the corresponding freshwater value, but it does not, by itself, establish long-term resistance to chemical deterioration.

The environmental and economic results present a different picture. According to the material inventory and 2026 local prices used in this study, hydrated lime had a higher embodied environmental burden than the cement it replaced and a substantially higher unit cost. Consequently, the improved ranking of L5 under performance-oriented weighting did not translate into an equivalent advantage under carbon-led or cost-led weighting. This illustrates the importance of distinguishing between a material's contribution to concrete performance and its overall suitability as a cement replacement. The present findings support further investigation of low-level hydrated-lime replacement, but replicated batches, longer exposure periods, and additional durability tests are needed before broader recommendations can be made.

4.3 Implications for improving ceramic tile powder concrete

For ceramic tile powder, the decision framework identifies a clear development objective: retain its environmental and cost advantages while improving its mechanical performance under lagoon exposure. CT15 ranked favourably when cost and environmental indicators received greater weight, but its substantial strength reduction limited its overall competitiveness when structural performance was weighted more heavily. Previous studies show that the effects of ceramic waste powder depend on its fineness, chemical composition, replacement level, and interaction with the remaining cementitious system. Tawfik et al. [3], for example, reported that increasing ceramic powder replacement could reduce strength relative to the control, while a combination of ceramic and brick powders produced more favourable properties than some single-powder mixtures. Recent reviews similarly identify the potential of finely processed ceramic waste as a supplementary cementitious material, while emphasising that performance improvements are not universal across replacement levels and concrete formulations [1].

These findings suggest that future mix development should prioritise optimising particle size, replacement percentage, water-to-binder ratio, and, where appropriate, the use of complementary supplementary cementitious materials. Such adjustments need to be verified experimentally, as improvements cannot be assumed. In particular, candidate mixtures should be assessed under both freshwater and lagoon exposures to distinguish gains in compressive strength from changes in strength retention and water absorption. The resulting data can then be incorporated into the existing decision matrix without changing the underlying selection framework. In this way, TOPSIS can support an iterative process in which improved mixtures are assessed against the same performance, environmental, and economic criteria, provided that the system boundaries, functional basis, and data quality remain consistent.

4.4 Methodological considerations and limitations

Several methodological choices could influence the rankings, and they were tested directly rather than assumed. First, cost, GWP, and embodied energy are closely related because all three are driven mainly by cement content. They ranked the mixtures identically (Spearman $\rho = 1.00$; Table 4), and together they received half of the nominal weight in both the equal-weight scenario and on average under flat Dirichlet sampling. To test whether this partial double counting drove the results, two hierarchical weighting schemes were applied, in which weights are assigned first to dimensions and then shared among their criteria (Table 7). When the three indicators formed a single environmental-economic dimension, the control ranked first in 77% of the simulations; when cost formed its own dimension, CT15 ranked first in 37% of the simulations. The ranking is therefore sensitive to how the environmental and economic dimensions are counted, a choice the decision-maker should make explicitly.

Second, TOPSIS rankings can depend on the normalisation and aggregation procedure, and adding or removing alternatives may cause rank reversal [38,39]. The analysis was therefore repeated with min–max normalised TOPSIS, a weighted-sum model, COPRAS and VIKOR (Table 6). Every method placed PLC first under equal and performance-led weights, and L5 was the leading replacement under performance-led weights across all methods. Under carbon-led and cost-led weights, methods that preserve proportional differences (vector TOPSIS and COPRAS) ranked PLC first, whereas range-based methods (min–max TOPSIS, weighted sum, and VIKOR) ranked CT15 first. The rankings therefore apply to the seven mixtures and six criteria assessed; adding mixtures or criteria could change the relative positions.

Third, water absorption is an indirect indicator of transport-related durability, not a complete measure of resistance to lagoon-induced deterioration. It does not quantify chloride ingress, sulphate attack, reinforcement corrosion, or long-term chemical degradation, and the 90-day exposure does not establish long-term service-life performance. Chloride penetration, sorptivity, mass change and longer-term strength development would provide a fuller durability assessment. Consequently, changes in lagoon-water chemistry during the exposure period were not captured, and the findings represent the specific water conditions measured at the beginning of the experiment.

Fourth, each experimental value is the mean of three cubes from a single batch per mixture. The mixtures were not all cast concurrently, individual cube results were not retained, and the lagoon water was characterised only at the start of immersion. Between-batch variability and measurement uncertainty could therefore not be quantified or propagated through the TOPSIS analysis, and small differences between alternatives should be interpreted with caution. Replicated batches, concurrent casting, reported dispersion, and repeated water sampling would strengthen future applications of the framework. The results are comparisons of the tested mixtures under the stated assumptions, not definitive rankings of ceramic tile powder and hydrated lime as material classes.

The unexpected reductions in strength and increases in water absorption between 28 and 90 days for some mixes (Section 3.1) underline this limitation.

The decision framework is also conditional on the selected alternatives, criteria, system boundary and weighting procedures. The rankings should therefore be interpreted as a comparative assessment of the seven mixtures investigated rather than as a universal recommendation for cement-replacement materials. Changes in material sources, local prices, environmental inventory factors, exposure conditions or decision-maker priorities may alter the resulting rankings. The framework is intended to support transparent comparison under specified conditions, and its application to other locations or concrete systems would require updated experimental and inventory data.

5 Conclusions

This study developed and applied a TOPSIS-based multi-criteria decision framework to evaluate the suitability of ceramic tile powder and hydrated lime as partial cement replacements in concrete exposed to Lagos Lagoon water. By integrating 90-day compressive strength under lagoon exposure, strength retention, water absorption, life-cycle global warming potential (GWP), estimated for the included production, construction, and end-of-life stages, embodied energy, and cost, the framework provides a more comprehensive basis for comparing concrete mixtures than assessments based on individual environmental, economic, or mechanical indicators. The principal conclusions are as follows.

1. The Portland limestone cement (PLC) control was the most consistently preferred mixture. It ranked first under all four predefined weighting scenarios and in 70.3% of the 10,000 randomly generated weight combinations. This consistency indicates that, among the seven mixtures evaluated, the control offered the most balanced overall performance across the selected structural, durability-related, environmental, and economic criteria. This result held for every method tested under equal and performance-led weights. When carbon or cost was emphasised, or when cost was weighted as a separate dimension, the leading mixture depended on the method, and CT15 became the preferred option under range-based normalisation.

2. Low-level hydrated-lime replacement was the strongest alternative to the control. The L5 mixture ranked first in 21.8% of the random-weight simulations and within the top two in 72.2% of cases. Its comparatively favourable ranking was associated with a 90-day lagoon-exposed compressive strength of 21.2 MPa and a strength retention ratio greater than unity. However, its higher cost and environmental burden limited its competitiveness when economic and environmental criteria received greater weight.

3. The principal advantage of CT15 was its environmental and economic profile per unit volume, rather than its overall performance. It achieved the lowest cost, GWP, and embodied energy among the mixtures, but its lagoon-exposed compressive strength was approximately 42% below that of the control. Although CT15 became more competitive under carbon-led and cost-led weighting, it ranked first in only 6.3% of the random-weight simulations. Its selection should therefore depend on whether the associated strength reduction is compatible with the intended application and applicable structural requirements.

4. The preferred replacement depended on the decision priorities. The variation in rankings across the four weighting scenarios and the 10,000 random-weight simulations demonstrates that no replacement mixture was universally optimal across the selected criteria. L5 was favoured when performance, particularly strength retention, received greater importance, whereas CT15 gained an advantage when environmental and economic indicators dominated. The random-weight results quantify robustness within the sampled weighting space; they should not be interpreted as probabilities of actual stakeholder preferences.

5. Exposure-adjusted performance should be integrated into sustainability assessments of cement replacement materials. Comparing cost, GWP, or embodied energy per cubic metre alone can favour mixtures whose lower material-related burdens are accompanied by substantial strength reductions under aggressive exposure. Combining these indicators with exposure-specific strength, strength retention, and water absorption provides a more informative basis for material selection, particularly where environmental and economic benefits must be balanced against engineering performance.

Overall, the findings support the use of multi-criteria decision analysis as a transparent approach to identifying trade-offs when selecting cement replacement materials for lagoon-exposed concrete. Within the limits of the seven mixtures, experimental dataset, six criteria, and weighting procedures examined, the PLC control remained the most robust overall choice, while L5 and CT15 represented conditional alternatives for performance-oriented and environmental-economic priorities, respectively. Further validation using replicated batches, longer exposure periods, and additional durability indicators is required before extending these rankings to broader material classes or long-term service conditions.

Declarations

Funding. The authors received no specific funding for this work.

Competing interests. The authors declare that they have no competing interests.

Author contributions. Tobit Igba conceptualised the study, developed the research methodology, and led the manuscript preparation. Solomon Oyebisi contributed to data collection, while both authors contributed to data analysis, software-based evaluation, interpretation of the results, and critical revision of the manuscript. Both authors reviewed and approved the final manuscript.

Data availability. The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request

Ethics approval. Not applicable.

Use of AI tools. The authors confirm that no AI tools or AI-assisted technologies were used in the preparation or creation of this manuscript.

References

[1] A.O. Tanash, K. Muthusamy, A.M.A. Budiea, M.A. Fauzi, G. Jokhio, R. Jose, A review on the utilization of ceramic tile waste as cement and aggregates replacement in cement-based composite and a bibliometric assessment, Clean. Eng. Technol. 17 (2023) 100699. https://doi.org/10.1016/j.clet.2023.100699.

[2] X. Chen, D. Zhang, S. Cheng, X. Xu, C. Zhao, X. Wang, Q. Wu, X. Bai, Sustainable reuse of ceramic waste powder as a supplementary cementitious material in recycled aggregate concrete: Mechanical properties, durability and microstructure assessment, Journal of Building Engineering 52 (2022) 104418. https://doi.org/10.1016/j.jobe.2022.104418.

[3] T.A. Tawfik, A. Sičáková, E. Kuzielová, Š. Kušnír, A. Eštoková, M. Bálintová, N. Junáková, Sustainable reuse of waste ceramic tiles powder and waste brick powder as a replacement for cement on green high strength concrete properties, Innovative Infrastructure Solutions 9 (2024) 166. https://doi.org/10.1007/s41062-024-01498-2.

[4] K.A. Knight, P.R. Cunningham, S.A. Miller, Optimizing supplementary cementitious material replacement to minimize the environmental impacts of concrete, Cem. Concr. Compos. 139 (2023) 105049. https://doi.org/10.1016/j.cemconcomp.2023.105049.

[5] J.A. Olsson, S.A. Miller, J.D. Kneifel, A review of current practice for life cycle assessment of cement and concrete, Resour. Conserv. Recycl. 206 (2024) 107619. https://doi.org/10.1016/j.resconrec.2024.107619.

[6] O.F. Najm, O.A. Mohamed, E. Sami Hijah, Efficiency of self-compacting concrete made with variable sustainable cementitious materials: A TOPSIS algorithm approach, Mater. Today Proc. (2024). https://doi.org/10.1016/j.matpr.2024.04.073.

[7] B. Swathi, R. Vidjeapriya, A multi-criterial optimization of low-carbon binders for a sustainable high-strength concrete using TOPSIS, Constr. Build. Mater. 425 (2024) 135992. https://doi.org/10.1016/j.conbuildmat.2024.135992.

[8] K.M. Mekky, M.G. Ibrahim, K. Sharobim, M. Fujii, M. Nasr, Evaluating environmental and economic benefits of using biochar in concrete: A life cycle assessment and multi-criteria decision-making framework, Case Studies in Construction Materials 21 (2024) e03712. https://doi.org/10.1016/j.cscm.2024.e03712.
[9] L.S. Silva, K. Figueiredo, M.K. Najjar, C.M. Stolz, A.N. Haddad, M. Amario, Life cycle assessment and multi-criteria optimization of recycled concrete mixes: A case study in Rio de Janeiro, Brazil, Constr. Build. Mater. 502 (2025) 144467. https://doi.org/10.1016/j.conbuildmat.2025.144467.
[10] EN 12350-2, Testing fresh concrete—Part 2: Slump test, , BSI, London, , 2009.
[11] B. 1881-122: British Standards Institution, Water absorption, , BSI, , 2011.
[12] B.E. 12390-3: British Standards Institution, Compressive strength, , BSI, , 2019.
[13] International Energy Agency (IEA), Emissions Factors 2025, IEA, Paris, 2025. https://www.iea.org/data-and-statistics/data-product/emissions-factors-2025.
[14] H.C.O. Unegbu, D.S. Yawas, Optimizing construction and demolition waste management in Nigeria: challenges, regulatory frameworks, and policy solutions, Discover Civil Engineering 1 (2024) 141. https://doi.org/10.1007/s44290-024-00142-3.
[15] ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines, International Organization for Standardization, Geneva, 2006.
[16] ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework, International Organization for Standardization, Geneva, 2006.
[17] CEN, EN 15804:2012+A2:2019, Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products, European Committee for Standardization, Brussels, 2019.
[18] Dangote Cement Plc. (2025). Dangote Cement Plc annual report and accounts 2024. Lagos, Nigeria: Dangote Cement Plc.
[19] A. Laveglia, L. Sambataro, N. Ukrainczyk, N. De Belie, E. Koenders, Hydrated lime life-cycle assessment: Current and future scenarios in four EU countries, J. Clean. Prod. 369 (2022) 133224. https://doi.org/10.1016/j.jclepro.2022.133224.
[20] S. Oyebisi, F. Olutoge, I. Oyaotuderekumor, F. Bankole, H. Owamah, U. Mazino, Effects of cashew nutshell ash on the thermal and sustainability properties of cement concrete, Heliyon 8 (2022) e11593. https://doi.org/10.1016/j.heliyon.2022.e11593.
[21] S. Oyebisi, F. Olutoge, P. Kathirvel, I. Oyaotuderekumor, D. Lawanson, J. Nwani, A. Ede, R. Kaze, Sustainability assessment of geopolymer concrete synthesized by slag and corncob ash, Case Studies in Construction Materials 17 (2022) e01665. https://doi.org/10.1016/j.cscm.2022.e01665.
[22] Hammond, G., Jones, C., Lowrie, F., & Tse, P. (2011). Embodied carbon: The Inventory of Carbon and Energy (ICE). Building Services Research and Information Association (BSRIA).
[23] S. Rawat, H. Cui, Y. Xie, Y. Guo, C.K. Lee, Y. Zhang, An improved framework for multi-objective optimization of cementitious composites using Taguchi-TOPSIS approach, Expert Syst. Appl. 272 (2025) 126732. https://doi.org/10.1016/j.eswa.2025.126732.
[24] R. Susmaga, I. Szczęch, D. Brzezinski, Towards explainable TOPSIS: Visual insights into the effects of weights and aggregations on rankings, Appl. Soft Comput. 153 (2024) 111279. https://doi.org/10.1016/j.asoc.2024.111279.
[25] S. Corrente, M. Tasiou, A robust TOPSIS method for decision making problems with hierarchical and non-monotonic criteria, Expert Syst. Appl. 214 (2023) 119045. https://doi.org/10.1016/j.eswa.2022.119045.
[26] P.H. Joshi, D.N. Parekh, Valorization of ceramic waste powder as cementitious blend in self-compacting concrete – A review, Mater. Today Proc. 77 (2023) 1007–1015. https://doi.org/10.1016/j.matpr.2023.01.068.
[27] S.S. Bangaru, C. Wang, X. Zhou, M. Hassan, Scanning electron microscopy (SEM) image segmentation for microstructure analysis of concrete using U-net convolutional neural network, Autom. Constr. 144 (2022) 104602. https://doi.org/10.1016/j.autcon.2022.104602.
[28] Y. Li, Y. Ma, K.H. Tan, H. Qian, T. Liu, Microstructure-informed deep learning model for accurate prediction of multiple concrete properties, Journal of Building Engineering 98 (2024) 111339. https://doi.org/10.1016/j.jobe.2024.111339.

[29] H. Qian, Y. Li, J. Yang, L. Xie, K.H. Tan, Segmentation and analysis of cement particles in cement paste with deep learning, Cem. Concr. Compos. 136 (2023) 104819. https://doi.org/10.1016/j.cemconcomp.2022.104819.
[30] P. Jain, R. Gupta, S. Chaudhary, A literature review on the effect of using ceramic waste as supplementary cementitious material in cement composites on workability and compressive strength, Mater. Today Proc. 65 (2022) 871–876. https://doi.org/10.1016/j.matpr.2022.03.453.
[31] M.J. Taher, E.H. Abed, M.S. Hashim, Using ceramic waste tile powder as a sustainable and eco-friendly partial cement replacement in concrete production, Mater. Today Proc. (2023). https://doi.org/10.1016/j.matpr.2023.04.060.
[32] L. Li, P. Joseph, X. Zhang, L. Zhang, A study of some relevant properties of concrete incorporating waste ceramic powder as a cement replacement agent, Journal of Building Engineering 87 (2024) 109106. https://doi.org/10.1016/j.jobe.2024.109106.
[33] A.O. Tanash, K. Muthusamy, F. Mat Yahaya, M.A. Ismail, Potential of recycled powder from clay Brick, sanitary Ware, and concrete waste as a cement substitute for Concrete: An overview, Constr. Build. Mater. 401 (2023) 132760. https://doi.org/10.1016/j.conbuildmat.2023.132760.
[34] A. Witte, N. Garg, Quantifying the global warming potential of low carbon concrete mixes: Comparison of existing life cycle analysis tools, Case Studies in Construction Materials 20 (2024) e02832. https://doi.org/10.1016/j.cscm.2023.e02832.
[35] C. Moro, Comparative Analysis of Multi-Criteria Decision Making and Life Cycle Assessment Methods for Sustainable Evaluation of Concrete Mixtures, Sustainability 15 (2023) 12746. https://doi.org/10.3390/su151712746.
[36] J.O. Ikotun, P.O. Adedeji, A.J. Babafemi, A Comprehensive Review on the Performance of Low-Carbon Ceramic Waste Powder as Cement Replacement Material in Concrete, Applied Sciences 15 (2025) 6037. https://doi.org/10.3390/app15116037.
[37] M. Shmlls, M. Abed, J. Fořt, T. Horvath, D. Bozsaky, Towards closed-loop concrete recycling: Life cycle assessment and multi-criteria analysis, J. Clean. Prod. 410 (2023) 137179. https://doi.org/10.1016/j.jclepro.2023.137179.
[38] J. Więckowski, R. Król, J. Wątróbski, Towards robust results in Multi-Criteria Decision Analysis: ranking reversal free methods case study, Procedia Comput. Sci. 207 (2022) 4584–4592. https://doi.org/10.1016/j.procs.2022.09.522.
[39] H.-J. Shyur, H.-S. Shih, Resolving Rank Reversal in TOPSIS: A Comprehensive Analysis of Distance Metrics and Normalization Methods, Informatica (2024) 837–858. https://doi.org/10.15388/24-INFOR576.