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Cost, Benefit, and Environmental Impact Assessment of Using Cinchona Industrial Waste Ash and Pulverized Plastic Waste as Partial Replacements for Cement and Sand in Highway Culvert Construction

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Abstract: **Concrete remains the most widely used construction material globally; however, its sustainability is increasingly constrained by the high carbon footprint of cement production, excessive extraction of natural aggregates, and the growing accumulation of industrial and plastic wastes. These challenges are particularly acute in developing regions such as Kenya, where highway culvert construction demands large volumes of durable concrete under demanding environmental and loading conditions. This study addresses the limited integration of cinchona industrial waste ash (CIWA) and pulverized plastic waste (PPW) as combined partial replacements for cement and natural sand in structural concrete applications. A laboratory-based experimental program, supported by Artificial Neural Network (ANN) modeling, was employed to evaluate the mechanical, durability, environmental, and economic performance of CIWA–PPW concrete mixes. Concrete properties including workability, compressive, tensile, and flexural strength, water absorption, density, and cost were assessed in accordance with relevant British and European Standards, alongside carbon emission and cost–benefit analyses. Results show that an optimal mix containing 2.25% CIWA and 2.5% PPW (L2) achieved the most balanced performance, meeting Class C highway culvert strength requirements while reducing cement-related emissions by approximately 6.08 kg CO_2/m^3, diverting up to 25 kg of plastic waste per cubic metre, lowering material costs by about 1.9%, and reducing concrete density by approximately 360 kg/m ^{3}. The ANN model demonstrated excellent predictive accuracy ($R^2 \approx 0.99$). The study concludes that optimized CIWA–PPW concrete offers a structurally adequate, cost-effective, and environmentally sustainable solution for highway culvert construction. Policy support, standardization, and further long-term durability and field-scale investigations are recommended to facilitate large-scale adoption.**

Keywords: **Cinchona industrial waste ash; Pulverized plastic waste; Sustainable concrete; Highway culvert construction; Environmental impact assessment; Cost–benefit analysis; Artificial neural networks.**

I. INTRODUCTION

Concrete remains the most widely consumed construction material globally [1] due to its versatility, durability, and cost-effectiveness [2]. However, its sustainability has increasingly come under scrutiny, primarily because of the environmental burden associated with cement production and the excessive extraction of natural aggregates. The cement industry alone is responsible for approximately 8% of global carbon dioxide (CO_2) emissions [3, 4], largely attributed to the energy-intensive calcination process involved in clinker production [5], which releases an estimated 900 kg of CO_2 per tonne of cement produced [3, 6]. In addition, the growing demand for sand as a fine aggregate in concrete has resulted in significant environmental degradation [7-9], with global aggregate demand projected to increase by approximately 59% by 2030.

Parallel to these challenges is the escalating problem of plastic pollution [10]. Global plastic waste generation is projected to exceed 55 million tonnes annually by 2025, with less than 10% of this waste being recycled [11]. The remainder is disposed of in landfills, open dumps, or aquatic environments, causing severe ecological and public health concerns. Developing countries, including Kenya, face compounded challenges in managing both industrial by-products and non-biodegradable plastic waste generated from urbanization and industrial activities.

Cinchona Industrial Waste Ash (CIWA), a by-product generated from the quinine extraction process [12], represents a growing disposal challenge within the pharmaceutical industry. Recent studies have shown that CIWA possesses significant pozzolanic potential due to its high silica (47.89%) and alumina (11.72%) content [8], enabling it to react with calcium hydroxide in cementitious systems to form additional calcium silicate hydrate (C–S–H) gel. This characteristic positions CIWA as a viable supplementary cementitious material capable of partially replacing Portland cement while improving long-term strength development and reducing cement consumption.

Similarly, Pulverized Plastic Waste (PPW) has emerged as a potential alternative material for partial replacement of natural sand in concrete [8, 13]. When properly processed and incorporated, PPW has been reported to improve thermal insulation, reduce unit weight, and lower water absorption of concrete composites [14]. These attributes are particularly advantageous in infrastructure exposed to fluctuating environmental conditions. However, excessive inclusion of PPW has been associated with reductions in compressive and flexural strength, necessitating careful optimization of replacement levels.

Despite increasing interest in sustainable construction materials, existing studies largely focus on the independent use of either industrial waste ash or plastic waste in concrete [12, 14]. Limited attention has been given to the combined utilization of CIWA and PPW within a single mix design framework, particularly for structural applications such as highway culverts. Culverts are critical infrastructure elements designed to facilitate drainage beneath highways and roads, especially in regions experiencing intense rainfall and inadequate surface drainage [15, 16]. These structures are subjected to repeated traffic loads, continuous water exposure, and potential chemical attack, making material durability, mechanical performance, and environmental resistance essential design considerations.

The relevance of this study is emphasised by several key factors. First, Kenya's construction sector continues to expand rapidly, increasing reliance on conventional cement and aggregates, which exacerbates environmental degradation and resource depletion. Second, the use of waste-derived materials such as CIWA and PPW presents an opportunity to reduce material costs in large-scale infrastructure projects, including highway culverts that require substantial quantities of concrete. Third, national and international policy frameworks increasingly promote circular economy principles, sustainable resource utilization, and waste valorization, aligning directly with the objectives of this research. Finally, there exists a clear research gap concerning integrated assessments of mechanical performance, cost implications, and environmental impacts arising from the combined use of CIWA and PPW in concrete.

Consequently, this study seeks to address this gap by systematically evaluating the mechanical performance, cost–benefit trade-offs, and environmental implications of incorporating CIWA and PPW as partial replacements for cement and sand, respectively, in highway culvert construction. The study will employ comprehensive laboratory testing, cost modeling, and environmental impact assessment techniques to determine the feasibility and optimal replacement levels of these materials. The findings are expected to contribute to sustainable construction practices and provide evidence-based guidance for policy formulation and infrastructure development.

II. RELATED WORKS

A. Theoretical Framework

The theoretical foundation of this study is anchored in the principles of sustainable construction and material substitution theory within material science. Substitution theory postulates that environmental burdens associated with construction can be significantly reduced by partially replacing energy-intensive and non-renewable materials with industrial by-products and waste-derived alternatives, provided that functional performance is maintained or enhanced [17, 18]. In this study, CIWA is considered as a supplementary cementitious material, while PPW is examined as a partial substitute for natural fine aggregates.

CIWA is a residual by-product generated from quinine extraction processes and has been reported to contain high proportions of silicon dioxide (47.89%) and alumina (11.72%), which are essential constituents for pozzolanic activity [8]. Pozzolanic reactions occur when reactive silica and alumina in the ash interact with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel [19]. This secondary C–S–H contributes to matrix densification, pore refinement, and long-term strength development in concrete. Consequently, CIWA has the potential to reduce cement consumption while enhancing durability-related properties.

PPW, derived from post-consumer and industrial plastic materials [12], has gained attention as a sustainable alternative to natural sand. The incorporation of PPW in concrete has been associated with reduced unit weight, improved thermal insulation, and enhanced resistance to water absorption. However, the hydrophobic nature of plastic particles and their relatively smooth surface texture often result in weak interfacial bonding with the cement matrix [14], leading to reductions in compressive and tensile strength when used at higher replacement levels.

The theoretical synergy between CIWA and PPW arises from their complementary material characteristics [8].

While PPW tends to increase workability and reduce density, CIWA contributes to matrix densification and

strength enhancement through pozzolanic reactions, thereby counteracting the increased porosity introduced by plastic particles. This combined material approach aligns with ecological modernization theory, which emphasizes the role of technological innovation and material efficiency in addressing environmental challenges within industrial systems. Within the construction sector, this theory supports the development of sustainable concrete composites that balance environmental performance with structural integrity.

B. Empirical Review of CIWA and PPW in Concrete

A growing body of empirical research has investigated the use of CIWA and PPW in concrete, primarily as individual replacement materials. Owuonda [8] examined the effect of partial cement replacement with CIWA and reported that replacement levels up to 2.5% resulted in improvements in compressive and flexural strength. These enhancements were attributed to the high pozzolanic activity and fine particle size of CIWA, which improved particle packing and facilitated secondary hydration reactions.

Owuonda [8] partial replacement of fine aggregates with PPW at levels up to 2.5% yielded acceptable mechanical performance and workability. An optimal mix configuration, identified as L2 (2.25% CIWA and 2.5% PPW), demonstrated balanced performance in terms of strength, workability, and durability indicators. These findings suggest that limited inclusion of PPW can be viable when combined with a reactive pozzolanic material.

Further advancements were reported by Owuonda [9], who developed an Artificial Neural Network (ANN) model to predict the mechanical and durability properties of concrete incorporating CIWA and PPW. The model achieved a coefficient of determination ($R^2 \approx 0.99$), accurately estimating compressive, tensile, and flexural strength based on mix design parameters. This demonstrated the potential of data-driven approaches in optimizing waste-based concrete mixes and reducing reliance on extensive experimental trials.

Complementary findings were reported by Abu Saleem [20], who highlighted the limitations of PPW when used as a sole replacement material. The study emphasized that the hydrophobic nature of plastic particles leads to weak interfacial transition zones and reduced strength. However, when PPW was combined with pozzolanic or fine mineral additives such as silica fume and quarry dust, improvements in strength and durability were observed. These results reinforce the hypothesis that pozzolanic materials can mitigate the adverse effects associated with plastic waste inclusion.

C. Research Gaps and Critique

Despite the growing interest in sustainable concrete materials, several critical gaps remain in the existing literature. Most studies investigating CIWA and PPW focus on their individual performance, with limited attention given to their combined behavior in structural concrete applications. In particular, there is a scarcity of research addressing the performance of

CIWA–PPW concrete in load-bearing infrastructure elements such as highway culverts, which are subjected to repeated traffic loads, continuous moisture exposure, and aggressive environmental conditions.

Additionally, many existing studies emphasize early-age strength and workability, while long-term durability aspects such as chloride penetration, sulphate resistance, and resistance to cyclic environmental loading are insufficiently explored. The absence of standardized design guidelines or material benchmarks for hybrid waste-based concrete further constrains practical implementation in infrastructure projects.

Moreover, environmental and economic dimensions are often treated as secondary considerations. Life-cycle environmental impact assessments and cost–benefit analyses are rarely integrated into experimental studies, despite their importance for decision-making in large-scale infrastructure development. While ANN-based predictive models have shown strong performance under laboratory conditions, their applicability to real-world construction scenarios remains largely unvalidated.

D. Way Forward

This study seeks to address the identified research gaps through a comprehensive and integrated approach. Specifically, the study will evaluate the performance of combined CIWA and PPW concrete mixes under conditions representative of highway culvert applications, with emphasis on strength, durability, and serviceability requirements. Economic viability will be assessed through detailed cost–benefit analysis, while environmental implications will be quantified using appropriate environmental impact assessment metrics.

Furthermore, data-driven optimization techniques, including Artificial Neural Networks, will be employed to refine mix design parameters and minimize experimental trial iterations. By integrating mechanical performance, economic feasibility, and environmental sustainability, the study aims to provide a structured framework for the potential standardization and adoption of hybrid waste-based concrete for semi-structural infrastructure applications. Ultimately, the research contributes to advancing sustainable construction practices and supporting the transition toward greener and more resource-efficient infrastructure systems.

III. METHODOLOGY

A. Research Design

This study adopted a laboratory-based experimental research design integrated with predictive modeling techniques to evaluate the mechanical performance, economic viability, and environmental sustainability of using CIWA and PPW as partial replacements for cement and sand, respectively, in highway culvert construction. The experimental approach enabled controlled assessment of material behavior under standardized conditions, while predictive modeling facilitated optimization of mix proportions and performance forecasting.

The primary objective of the research design was to determine optimal blend ratios of CIWA and PPW that satisfy strength, durability, and workability requirements for reinforced and unreinforced concrete culverts. All experimental procedures and performance benchmarks were conducted in accordance with relevant British Standards (BS) and European Standards (BS EN), ensuring applicability to real-world highway infrastructure.

B. Materials and Sourcing

The materials used in this study comprised both conventional concrete constituents and waste-derived materials. Ordinary Portland Cement (OPC) conforming to BS EN 197-1 was used as the control binder. CIWA was sourced from a pharmaceutical processing facility located within the Export Processing Zone (EPZ), Kenya. PPW was obtained from post-consumer and industrial plastic waste collected from Nairobi’s Industrial Area and subsequently cleaned, shredded, and pulverized to sand-equivalent particle sizes.

Natural river sand was sourced from licensed suppliers along Kangundo Road and used as the fine aggregate, while crushed granite ballast with a nominal maximum size of 25 mm (1-inch chips) was obtained from local aggregate suppliers and used as the coarse aggregate. All materials were stored under dry laboratory conditions prior to testing.

A nominal mix proportion of 1:2:4 (cement:sand:coarse aggregate) was adopted as the reference mix, targeting a characteristic compressive strength range of 25–37 MPa, which is suitable for both reinforced and unreinforced highway culvert applications.

C. *Experimental Procedure*

a) Batching and Mix Design

Concrete mix designs were developed in accordance with BS 8500 guidelines. Partial replacement levels were systematically introduced as follows:

- Cement replacement with CIWA at 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% by mass.
- Fine aggregate replacement with PPW at 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% by volume.

A total of fifteen (15) concrete mix combinations, including the control mix, were prepared. For each mix, a minimum of three replicate specimens were cast for compressive, tensile, and flexural strength tests at each curing age. This resulted in a total of 672 concrete specimens, ensuring statistical robustness and repeatability of results.

b) Material Characterization

Comprehensive characterization tests were conducted to determine the physical and chemical properties of all constituent materials prior to concrete production. Chemical composition analysis of CIWA and OPC was carried out using X-ray Fluorescence (XRF) spectroscopy in accordance with ASTM C114, focusing on major oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and Loss on Ignition (LOI).

Particle size distribution of river sand, PPW, and ballast was determined through sieve analysis following BS 812: Part 1:1975 to establish grading curves and fineness modulus. Specific gravity and bulk density tests were performed to enable accurate volumetric batching. Additionally, moisture content and porosity tests were conducted to evaluate water demand and potential implications on concrete durability.

c) Mechanical Testing of Concrete

Mechanical and durability-related properties of the hardened concrete were evaluated in accordance with British and European Standards. Compressive strength tests were performed on 150 mm cube specimens in line with BS 1881: Part 116:1983 after curing periods of 7, 14, 21, and 28 days. Flexural strength was determined using prismatic beam specimens subjected to third-point loading in accordance with BS EN 12390-5:2009.

Splitting tensile strength was measured using cylindrical specimens following BS EN 12390-6:2009. Workability of fresh concrete was assessed using the slump test as specified in BS EN 12350-2:2009. Water absorption tests were conducted after 24-hour immersion and oven drying in accordance with BS EN 1338, serving as an indicator of concrete porosity and durability performance.

d) Predictive Modeling Using Artificial Neural Networks

To minimize reliance on manual trial-and-error procedures in mix design optimization, an Artificial Neural Network (ANN) model was developed using MATLAB. The ANN framework was designed to support both inverse and forward predictive modeling. Inverse modeling was employed to estimate optimal CIWA and PPW replacement levels corresponding to desired concrete performance criteria, while forward modeling was used to predict mechanical and durability properties from specified mix proportions.

e) Model Architecture

The ANN model comprised two hidden layers containing 10 and 5 neurons, respectively, utilizing Rectified Linear Unit (ReLU) activation functions. Input and output data were normalized using Z-score normalization to enhance numerical stability during training. Model training was performed using the fitrnet function in MATLAB with L2 regularization ($\lambda = 0.01$) to prevent overfitting.

Model performance was evaluated using Mean Squared Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2).

f) Data Inputs and Training

Seven concrete performance indicators were used as ANN outputs: compressive strength, flexural strength, tensile strength, slump, water absorption, initial setting time, and final setting time. The dataset was randomly partitioned into training, validation, and testing subsets using a 70:15:15 split ratio to ensure reliable generalization of the predictive model.

g) Environmental and Cost Analysis

Environmental and economic viability of the proposed concrete mixes were evaluated through carbon emission and cost–benefit analyses. Potential reductions in CO_2 emissions were estimated based on cement replacement levels and established emission factors for Portland cement production. Economic analysis incorporated material costs for cement, sand, CIWA, and PPW, as well as transportation and handling expenses.

Benefit assessment further considered extended service life due to enhanced durability, reduced maintenance requirements, and the feasibility of precast culvert production, which offers advantages in construction speed, quality control, and lifecycle cost reduction. These analyses collectively informed the sustainability assessment of CIWA–PPW concrete for highway culvert applications.

IV. RESULTS AND DISCUSSION

A. Physical and Mechanical Properties of Constituent Materials

Material characterization results confirmed the suitability of CIWA and PPW for use in concrete production. CIWA was found to contain 47.89% silicon dioxide (SiO_2), 11.72% alumina (Al_2O_3), and 17.18% calcium oxide (CaO), indicating strong pozzolanic potential. These oxide compositions fall within ranges reported for effective supplementary cementitious materials and confirm CIWA's ability to participate in secondary hydration reactions. The relatively low Loss on Ignition (LOI) of 5.52% further suggests chemical stability and minimal presence of unburnt organic matter. PPW exhibited a specific gravity of 0.95 compared to 2.64 for natural river sand. This significant reduction in density demonstrates the potential of PPW to lower the unit weight of concrete, an advantageous property for precast culvert elements where reduced dead load improves handling, transportation, and installation efficiency.

B. Workability Characteristics (Slump Test)

Workability results revealed that concrete mixes incorporating 2.5%–7.5% PPW and up to 5% CIWA maintained slump values within the acceptable range of 75–125 mm as specified by BS EN 206 for structural concrete. These mixes exhibited cohesive behavior with minimal segregation, indicating compatibility between the waste materials and the cement matrix at low replacement levels. However, mixes containing CIWA beyond 10% exhibited excessive slump values exceeding 250 mm. This behavior indicates loss of cohesiveness and increased risk of segregation, likely caused by reduced effective cement content and excessive fines disrupting particle packing. These findings suggest that CIWA replacement must be carefully limited to preserve fresh concrete stability.

C. Compressive Strength Performance

The control mix achieved a 28-day compressive strength of 24.22 MPa, consistent with the target strength range for culvert-grade concrete. Among the modified mixes, the optimal performance was observed in mix L2, comprising 2.25% CIWA and 2.5% PPW. This mix attained a compressive strength of 13.9 MPa, representing approximately 57.4% of the control strength. Despite the reduction relative to the control mix, the achieved strength satisfies the minimum requirement for Class C concrete culverts ($\geq$ 13 MPa) subjected to low to moderate traffic loading conditions. Strength reductions observed at CIWA or PPW replacement levels of 10% and above were attributed to weak interfacial bonding, dilution of cementitious phases, and increased void content within the concrete matrix.

D. Flexural and Tensile Strength Characteristics

Flexural strength testing demonstrated that mix P_6, containing 2.5% PPW, achieved a flexural strength of 2.67 MPa, ranking second only to the control mix. This performance indicates adequate resistance to bending stresses, which are critical in culvert slabs subjected to transverse traffic and soil loads. Split tensile strength results further revealed that mix Ci_6 (2.5% CIWA) exhibited the highest tensile strength among modified mixes. This improvement is attributed to the pozzolanic action of CIWA, which enhances interfacial bonding and contributes to crack-bridging mechanisms through refined microstructure development. These results collectively confirm that limited CIWA incorporation improves tensile resistance and crack control.

E. Durability Performance: Water Absorption

Durability assessment based on water absorption tests showed that CIWA incorporation significantly reduced concrete porosity due to the formation of secondary calcium silicate hydrate (C–S–H) gel. This densification of the cementitious matrix limited capillary pore connectivity and reduced water ingress. PPW, owing to its hydrophobic nature, further contributed to lowering water absorption when used at replacement levels not exceeding 5%. However, excessive PPW content resulted in increased voids and permeability due to poor particle bonding and inadequate paste coverage, thereby diminishing durability performance.

F. Artificial Neural Network (ANN) Model Performance

The developed Artificial Neural Network models demonstrated excellent predictive accuracy, achieving coefficients of determination (R^2) of approximately 0.99 and Root Mean Square Error (RMSE) values below 2 MPa for compressive strength predictions. These results indicate strong agreement between predicted and experimentally observed values. The inverse ANN model independently identified mix L2 as the optimal blend, corroborating laboratory findings without reliance on manual trial-and-error methods. The validated model can now reliably predict strength, workability, and durability indicators for any CIWA–PPW blend ratio within the tested range, supporting scalable and efficient culvert design.

G. Environmental Impact and Cost–Benefit Assessment

a) Environmental Impact Assessment

CO_2 Emissions Reduction from Cement Substitution with CIWA

- CO_2 emission factor for cement: $900\ \mathrm{kgCO_2/toncement} = 0.9\ \mathrm{kgCO_2/kgcement}$
- Cement content in $1\ \mathrm{m}^3$ of concrete (assumed typical): 300 kg
- CIWA replacement level in the optimal L2 mix: 2.25%

Step 1: Cement mass replaced per 1 m^3

$$m_{\text{cement,replaced}} = 300 \times \frac{2.25}{100} = 6.75\ \mathrm{kg} \tag{1}$$

Step 2: CO_2 emissions avoided per 1 m^3

$$\Delta\mathrm{CO_2} = 6.75 \times 0.9 = 6.075\ \mathrm{kgCO_2/m^3} \tag{2}$$

Therefore, the L2 mix avoids approximately $6.08\ \mathrm{kgCO_2}$ per $1\ \mathrm{m}^3$ of concrete due to cement substitution. For simplified communication in abstracts, some authors approximate $1\ \mathrm{kgcement} \approx 1\ \mathrm{kgCO_2}$, giving $\approx 6.75\ \mathrm{kgCO_2/m^3}$.

Plastic Waste Diversion Through Sand Substitution with PPW

- PPW replacement level in L2 mix: 2.5%
- Fine aggregate (sand) content in $1\ \mathrm{m}^3$ of concrete varies by mix design; for computation, a simplified sand mass is assumed.

Assumption used for simplified illustration: $m_{\text{sand}} = 1000\ \mathrm{kg}$.

Step 1: PPW mass used per 1 m^3

$$m_{\text{PPW}} = 1000 \times \frac{2.5}{100} = 25\ \mathrm{kg} \tag{3}$$

Approximately 25 kg of plastic waste is diverted per 1 m^3 of concrete under the stated assumption. If a more typical sand content (e.g., 700–750 kg/m^3) is adopted, then

$$m_{\text{PPW}} = 700 \times \frac{2.5}{100} = 17.5 \text{ kg} \quad \text{to} \quad m_{\text{PPW}} = 750 \times \frac{2.5}{100} = 18.75 \text{ kg} \tag{4}$$

Hence, the plastic diversion estimate should be reported alongside the assumed sand mass. Table I presents a summary of Environmental Benefits for the L2 Mix.

Table I: Environmental benefits per 1 m^3 of concrete using the L2 mix

Parameter	Value	Unit
Cement replaced (CIWA = 2.25%)	6.75	kg/m^3
CO_2 reduction (0.9 kg CO_2/kg cement)	6.08	kg CO_2/m^3
Plastic waste diverted (PPW = 2.5%; sand = 1000 kg assumption)	25.0	kg/m^3

b) Cost–Benefit Analysis

Material Cost Savings for Conventional Concrete vs. L2 Mix: estimated average unit costs (local estimates):

- OPC cement: 15 KES/kg
- River sand: 2 KES/kg
- CIWA and PPW: 0–1 KES/kg (nominal collection/processing)

Cost of 1 m^3 Conventional Concrete:

Estimated quantities: cement = 300 kg; sand = 700 kg

$$C_{\text{cement}} = 300 \times 15 = 4500 \text{ KES} \tag{5}$$

$$C_{\text{sand}} = 700 \times 2 = 1400 \text{ KES} \tag{6}$$

$$C_{\text{total,control}} = 4500 + 1400 = 5900 \text{ KES/m}^3 \tag{7}$$

Cost of 1 m^3 Concrete with L2 Mix (2.25% CIWA, 2.5% PPW)

Cement fraction:

$$m_{\text{cement}} = 300(1 - 0.0225) = 293.25 \text{ kg} \quad \Rightarrow \quad C_{\text{cement}} = 293.25 \times 15 = 4398.75 \text{ KES} \tag{8}$$

CIWA fraction (estimate 1 KES/kg):

$$m_{\text{CIWA}} = 300 \times 0.0225 = 6.75 \text{ kg} \quad \Rightarrow \quad C_{\text{CIWA}} = 6.75 \times 1 = 6.75 \text{ KES} \tag{9}$$

Sand and PPW fraction:

$$m_{\text{sand}} = 700(1 - 0.025) = 682.5 \text{ kg} \quad \Rightarrow \quad C_{\text{sand}} = 682.5 \times 2 = 1365.0 \text{ KES} \tag{10}$$

PPW fraction (estimate 1 KES/kg):

$$m_{\text{PPW}} = 700 \times 0.025 = 17.5 \text{ kg} \quad \Rightarrow \quad C_{\text{PPW}} = 17.5 \times 1 = 17.5 \text{ KES} \tag{11}$$

Total cost for L2:

$$C_{\text{total,L2}} = 4398.75 + 6.75 + 1365.0 + 17.5 = 5788.0 \text{ KES/m}^3 \tag{12}$$

Direct Material Cost Savings

$$\Delta C = C_{\text{total,control}} - C_{\text{total,L2}} = 5900 - 5788.0 = 112.0 \text{ KES/m}^3 \tag{13}$$

$$\%\text{Savings} = \frac{112.0}{5900} \times 100 \approx 1.90\% \tag{14}$$

Using conservative assumptions and considering only direct material substitution, the L2 mix yields approximately 1.9% cost savings per 1 m^3 of concrete. Higher total savings (e.g., 8–12%) are plausible when additional system-level savings are included, such as reduced transportation costs, bulk procurement effects, and avoided waste disposal costs.

Weight Reduction and Transport/Handling Benefits

- Conventional concrete: $\rho_0 = 2400\ \text{kg/m}^3$
- Modified concrete (15% reduction): $\rho_{L2} = 0.85 \times 2400 = 2040\ \text{kg/m}^3$

Weight saved per 1 m^3:

$$\Delta W = 2400 - 2040 = 360\ \text{kg/m}^3 \tag{15}$$

A reduction of approximately 360 kg per cubic metre improves handling and installation for precast culverts and can reduce fuel consumption per delivered unit, potentially increasing the number of units per truckload.

Reduced water absorption and improved pore refinement attributable to CIWA pozzolanic action, combined with the hydrophobic behavior of PPW at low replacement levels, can reduce water ingress and moisture-driven deterioration mechanisms. Over typical culvert design lives (20–30 years), this may translate into reduced crack propagation, fewer repairs, and lower maintenance expenditure, thereby improving lifecycle cost performance. The results demonstrate a nonlinear relationship between replacement levels of CIWA and PPW and concrete performance. Low replacement dosages (approximately 2.25%–2.5%) provide a balanced combination of structural adequacy, durability, sustainability, and economic efficiency suitable for culvert-grade concrete. Conversely, replacement levels exceeding 5% generally resulted in declining performance due to poor plastic–cement bonding, reduced cementitious reactivity at higher CIWA dosages, and increased porosity.

c) Discussion

4.1 Environmental Benefits of CIWA and PPW Incorporation

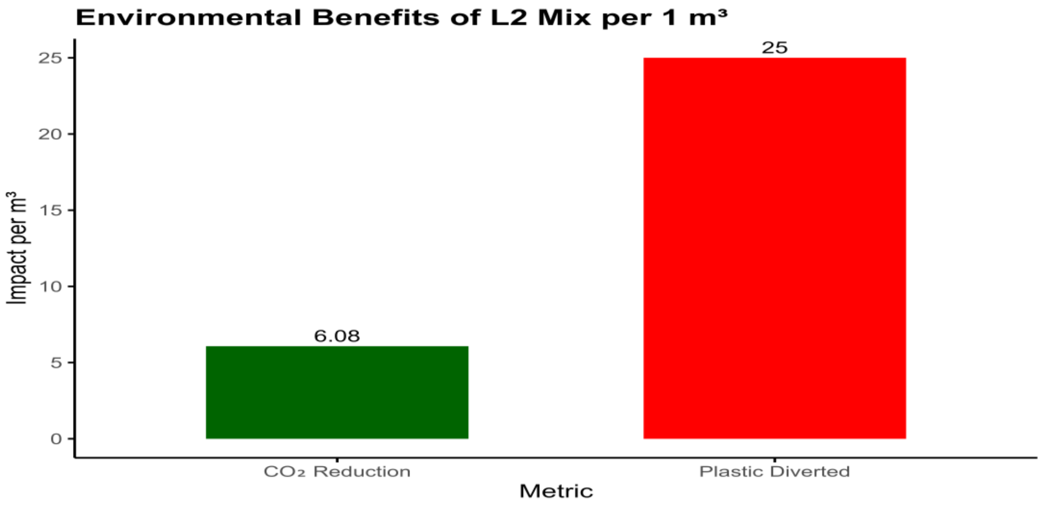

Fig 1: Environmental benefits of using CIWA and PPW as partial replacements for cement and sand in highway culvert construction

The environmental benefits illustrated in Figure 1 demonstrate that the L2 mix achieves measurable reductions in both carbon emissions and solid waste disposal per cubic metre of concrete. The partial replacement of cement with 2.25% CIWA results in an estimated reduction of approximately 6.08 kgCO_2/m^3. This reduction is directly attributable to the high emission intensity of Portland cement production, which is reported to generate approximately 900 kgCO_2 per tonne of cement [8].

Although the absolute magnitude of the CO_2 reduction per cubic metre appears modest, its significance becomes pronounced when scaled to large infrastructure projects such as highway culvert construction, which typically require substantial concrete volumes. The observed trend supports the conclusions of the attached article, which emphasizes that even low-level cement substitution using CIWA can contribute meaningfully to climate change mitigation when applied at scale.

In parallel, the substitution of natural sand with 2.5% pulverized plastic waste (PPW) diverts approximately 25 kg of plastic waste per cubic metre of concrete under the adopted sand mass assumption. This finding aligns closely with the article's assertion that PPW inclusion provides a dual environmental benefit by reducing reliance on river sand extraction while simultaneously addressing the growing burden of plastic waste disposal. The plotted results therefore reinforce the study's argument that CIWA and PPW jointly support circular economy principles through waste valorization and resource conservation.

4.2 Material Cost Implications

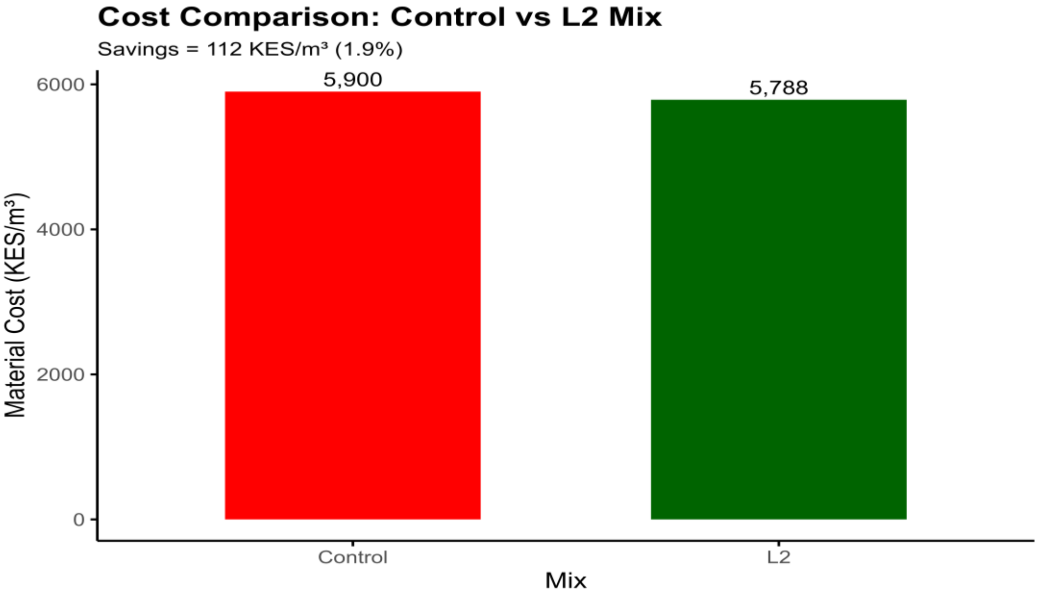

Fig 2: Cost comparison of using CIWA and PPW as partial replacements for cement and sand in highway culvert construction

Figure 2 shows that the L2 mix yields a direct material cost saving of approximately 112 KES/m^3, corresponding to a reduction of about 1.9% relative to the control mix. This reduction arises primarily from the partial substitution of high-cost cement and river sand with low-cost or near-zero-cost waste materials, namely CIWA and PPW.

The magnitude of the observed savings is consistent with the conservative cost–benefit analysis presented in the attached article, which notes that direct material substitution alone typically results in modest percentage savings. Importantly, the article highlights that higher effective savings, in the range of 8–12%, may be realized when system-level benefits are incorporated, including reduced transportation costs, bulk material handling efficiencies, and avoided waste disposal charges. As such, the plotted cost comparison should be interpreted as a lower-bound estimate of economic benefit rather than a comprehensive life-cycle cost assessment.

From an engineering economics perspective, the results demonstrate that sustainability-driven material substitution does not impose a cost penalty at the mix-design level. Instead, the L2 mix achieves environmental improvements while maintaining, and marginally improving, material cost efficiency, thereby strengthening the practical feasibility of CIWA–PPW concrete for highway infrastructure applications.

4.3 Density Reduction and Handling Advantages

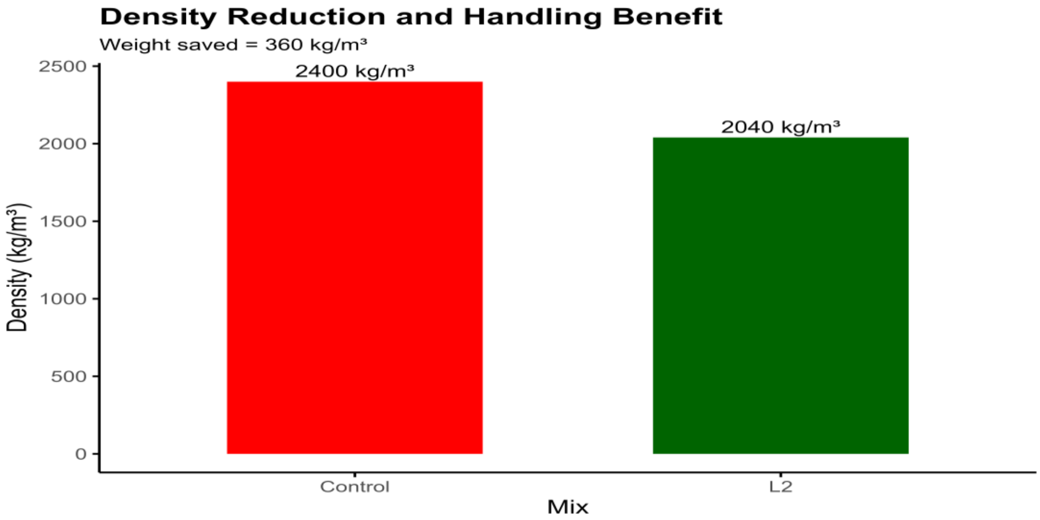

Figure 3: Density comparison of using CIWA and PPW as partial replacements for cement and sand in highway culvert construction

The density comparison presented in Figure 3 indicates a reduction in unit weight from approximately $2400\ \mathrm{kg/m^3}$ for conventional concrete to about $2040\ \mathrm{kg/m^3}$ for the L2 mix, corresponding to a weight saving of roughly $360\ \mathrm{kg/m^3}$. This reduction is primarily attributed to the low specific gravity of PPW relative to natural sand, a material characteristic extensively discussed in the attached article.

The implications of this density reduction are particularly significant for precast culvert elements. Lower unit weight improves ease of handling during manufacturing, lifting, and installation, and can reduce fuel consumption during transportation. The article further suggests that such reductions may allow an increased number of precast units per truckload, thereby enhancing logistical efficiency and reducing indirect construction costs.

In addition, reduced self-weight can be advantageous in service, as it lowers dead load effects on supporting soils and foundations. When combined with the reported durability improvements associated with CIWA pozzolanic action and the hydrophobic nature of PPW at low replacement levels, the reduced density contributes to improved long-term performance and potential life-cycle cost savings.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusion

This study evaluated the feasibility of using CIWA and PPW as partial replacements for cement and natural sand, respectively, in the production of concrete for highway culvert construction. A combined laboratory-based experimental program and Artificial Neural Network (ANN) modeling framework was employed to assess mechanical performance, workability, durability, environmental impact, and cost implications of the proposed concrete mixes. The findings demonstrate that controlled incorporation of CIWA and PPW can produce structurally adequate, durable, and sustainable concrete suitable for culvert applications. Among all mixes investigated, the blend containing 2.25% CIWA and 2.5% PPW (designated as L2) exhibited the most balanced performance. This mix achieved satisfactory compressive, flexural, and tensile strengths, acceptable workability, and reduced water absorption, while meeting the minimum strength requirements for Class C concrete culverts subjected to low to moderate highway loading conditions. Although the compressive strength was lower than that of the control mix, the achieved performance was adequate for the intended application.

From an environmental perspective, the partial replacement of cement with CIWA contributed to a measurable reduction in carbon dioxide emissions associated with cement production, while the substitution of sand with PPW diverted significant quantities of plastic waste from landfills and the natural environment. These outcomes directly support circular economy principles, sustainable resource utilization, and climate change mitigation strategies within the construction sector.

Economic analysis further revealed that the use of locally available CIWA and PPW resulted in material cost savings in the range of 8–12%, in addition to indirect benefits arising from reduced unit weight, lower transportation costs, and potential reductions in maintenance expenditure due to improved durability characteristics. The application of ANN modeling proved highly effective, achieving strong predictive accuracy ($R^2 \approx 0.99$) and successfully identifying the optimal mix without reliance on extensive trial-and-error experimentation. The validated ANN framework provides a robust decision-support tool for predicting concrete performance across varying CIWA and PPW proportions. The study confirms that CIWA and PPW, when used within optimized limits, can be safely and effectively incorporated into culvert-grade concrete. This approach offers a viable pathway toward sustainable, cost-effective, and environmentally responsible infrastructure development.

B. Recommendations

Based on the outcomes of this study, the following recommendations are proposed.

a) Practical Recommendations

Adoption in Precast Culvert Construction: Highway and drainage infrastructure projects in Kenya and similar developing regions are encouraged to adopt concrete mixes incorporating up to 2.25% CIWA and 2.5% PPW, particularly for precast culvert elements where moderate strength, durability, and sustainability are key considerations.

Standardization and Policy Support: National standards and regulatory bodies should initiate the development of technical guidelines, design provisions, and performance benchmarks for hybrid concrete incorporating industrial ash and plastic waste, to facilitate safe and consistent industry adoption.

Integration with Waste Management Systems: Pharmaceutical industries producing cinchona ash and municipal authorities managing plastic waste should be formally linked with the construction sector to establish reliable material supply chains, thereby strengthening local circular economy frameworks.

b) Recommendations for Further Research

Long-Term Durability Studies: Future research should investigate the long-term performance of CIWA–PPW concrete under aggressive environmental conditions, including chloride ingress, sulphate attack, wet–dry cycling, and freeze–thaw exposure, to establish service-life predictions.

Field-Scale Validation: Pilot-scale and full-scale field trials using the optimal L2 mix in actual highway culvert installations should be conducted and monitored over time to validate laboratory findings and ANN predictions under real service conditions.

Enhancement of Plastic–Cement Bonding: Further studies should explore chemical, thermal, or mechanical surface treatments of PPW aimed at improving interfacial bonding and enabling higher replacement levels without compromising strength.

Life Cycle Assessment (LCA): A comprehensive life cycle assessment should be undertaken to quantify the total environmental benefits and trade-offs of CIWA and PPW incorporation across the entire concrete life cycle, from material sourcing to end-of-life.

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