

Performance of Cinchona Industrial Waste Ash and Pulverized Plastic Waste as Concrete Aggregate Materials for Production of Concrete Culvert

Omach Antony Owuonda*, Fundi Isaac Sanewu, Nyongesa Daniel Wekesa

Department of Civil, Construction and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya

Email: *tonyomach202@gmail.com

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Abstract

The global construction sector is undergoing a paradigm shift toward sustainable material utilization due to increasing environmental and resource constraints. In Kenya, culvert construction continues to rely heavily on conventional materials like cement and river sand, contributing to high carbon emissions and resource depletion. This study investigates the potential of incorporating Cinchona Industrial Waste Ash (CIW) and Pulverized Plastic Waste (PPW) as partial replacements for cement and sand, respectively. The objective was to optimize mix designs that achieve an acceptable balance between strength, durability, and workability. A total of 13 mix combinations were tested for compressive, tensile, and flexural strength, as well as water absorption and slump. CIW and PPW replacements ranged from 2% to 3.5%. The results revealed that the L₂ mix (2.5% PPW and 2.25% CIW) provided the best performance across all parameters. Theoretical validation was supported by the pozzolanic reactivity of CIW and the micro-filler effect of PPW, in line with BS EN testing standards. The study concludes that moderate dosages of CIW and PPW can enhance performance and sustainability of concrete used in culverts. It recommends wider adoption in Kenyan infrastructure projects, subject to further long-term durability studies under field conditions to confirm these promising laboratory results.

Keywords

Cinchona Industrial Waste Ash (CIW), Pulverized Plastic Waste (PPW), Sustainable Concrete, Partial Replacement, Culvert Construction, Pozzolanic Activity

1. Introduction

The global construction industry continues to grapple with escalating material costs and the environmental degradation associated with cement and aggregate production [1]. Cement manufacture alone contributes approximately 8% of global CO₂ [2] [3] emissions, releasing nearly 900 kg of CO₂ per ton of cement produced [4] [5]. Natural sand and coarse aggregate resources are being depleted at an unsustainable rate, with aggregate demand projected to increase by 59% by 2025. These concerns necessitate the exploration of sustainable alternatives that align with green engineering principles.

Industrial by-products such as Cinchona Industrial Waste Ash (CIWA), a residue from quinine extraction, exhibit significant pozzolanic properties [6]. Previous studies have shown that CIWA contains high levels of silica and lime, essential for enhancing concrete strength and durability [6]. In experimental investigations, replacement of cement with up to 70% CIWA yielded compressive strengths comparable to ordinary concrete blocks, while improving workability and reducing environmental impact.

The proliferation of plastic waste, expected to exceed 55 million tons annually by 2025, has created an urgent need for innovative recycling solutions [7]. Pulverized Plastic Waste (PPW), particularly when used as fine aggregate replacement, offers benefits such as reduced unit weight, improved thermal insulation, and enhanced durability against abrasion and water absorption.

Despite the proven pozzolanic potential of CIWA and the volumetric and insulation advantages of PPW, there is a notable gap in their combined application in concrete production. Existing studies have mostly focused on individual utilization of such wastes, with insufficient emphasis on their interaction, performance optimization, and suitability for structural elements like concrete culverts [6] [7]. The absence of design codes and performance benchmarks for such blended waste materials further inhibits their adoption in infrastructure projects.

This study seeks to synergize these two waste streams in sustainable concrete design. Specifically, it aims 1) to perform material characterization of CIWA and PPW for concrete culvert production, and 2) to investigate the physical and mechanical performance of concrete using optimum mixes of CIWA and PPW as partial replacements of cement and sand, respectively. The findings are expected to advance green concrete applications while addressing pressing waste management and material sustainability challenges.

2. Literature Review

2.1. Theoretical Review

The use of alternative materials in concrete has gained momentum in recent years, particularly within the context of sustainability, material cost reduction, and environmental waste management. Among these alternatives, CIWA and PPW have emerged as promising candidates for partial replacement of cement and fine aggregates, respectively. A closer analysis of their individual effects presented in **Ta-**

ble 1 reveals both advantages and limitations, which, when combined, may produce a synergistic effect enhancing the overall performance of concrete. **Table 1** indicates that a joint utilization of CIWA and PPW addresses two pressing challenges in construction material science: the overdependence on virgin cement and aggregates, and the environmental burden of industrial and plastic waste. When properly formulated, this combination offers a technically feasible and environmentally responsible pathway toward sustainable concrete production.

Table 1. Theoretical framework upon which the two materials are proposed for the study.

Material	Positive Effects	Shortcomings	Expected Benefit When Combined
CIWA	Acts as a pozzolanic material due to high silica and lime content. - Enhances long-term strength and durability. Reduces cement content, lowering CO ₂ emissions.	May increase setting time beyond acceptable limits. - May reduce early strength. - Workability can be affected due to higher water demand.	PPW can improve workability by reducing density and increasing flow. PPW helps offset CIWA's extended setting time by contributing to faster placement.
PPW	Reduces unit weight of concrete. - Enhances thermal insulation. Improves abrasion resistance and reduces water absorption. Provides a recycling pathway for plastic waste.	Reduces compressive and flexural strength at high replacement ratios. Weak bonding with cement matrix due to hydrophobic nature. Increases porosity if not well graded.	CIWA contributes to densification of matrix via pozzolanic reaction, improving strength. CIWA improves interfacial bonding with plastic particles. Both reduce cost and environmental burden synergistically.
Combined CIWA + PPW	Sustainable use of both cement and sand substitutes. - Improved durability and eco-efficiency. Balanced mechanical performance with optimized mix design.	Requires careful optimization of mix ratios and water content.	Potential to produce lightweight, eco-friendly, durable concrete suitable for non-load and semi-structural applications such as culverts.

2.2. Existing Studies

Concrete faces two significant challenges: the environmental burden associated with cement production and the increasing scarcity of natural aggregates [8]. Cement production alone contributes to about 8% of global carbon dioxide emissions, primarily from the energy-intensive process of clinker formation [1]. Simultaneously, plastic waste pollution poses a severe ecological threat, with over 381 million tonnes generated annually and less than 10% being effectively recycled [9]. These issues have driven research efforts toward integrating alternative materials such as industrial ashes and plastic waste into concrete to promote sustainability, reduce cost, and conserve natural resources.

To address these problems, researchers have investigated various waste materials to partially replace cement and aggregates. CIWA has shown pozzolanic properties due to its high silica and lime content. Studies such as [6] explored CIWA as a cement substitute, aiming to lower clinker content and improve long-term strength. The methodology involved replacing cement in varying proportions (up

to 70%) and conducting standard tests such as compressive strength, water absorption, and slump flow. The findings revealed that up to 30% replacement maintained acceptable strength and durability parameters, while 10% - 20% showed optimal results for practical use. The study concluded that CIWA can effectively reduce cement consumption without compromising structural integrity.

Research PPW focused on mitigating the environmental impact of non-biodegradable plastics. [10] conducted a comparative study using regular and gamma-irradiated plastic waste as partial replacements for both cement and fine aggregates. The methodology involved incorporating PET plastics into concrete at varying proportions (up to 10%) and evaluating mechanical performance using compressive and tensile strength tests. The results showed that untreated plastic waste generally reduced compressive strength, whereas irradiated plastics improved bonding properties and slightly enhanced mechanical behavior, particularly when used in small amounts (1% - 5%). The study concluded that while plastics reduce the overall density and increase durability against chemical attacks, their inclusion beyond certain thresholds adversely affects strength unless treated or blended with pozzolanic materials.

Similarly, [11] examined the use of mixed plastic waste as fine aggregate replacement. Their experimental design involved replacing sand in increments of 5%, up to 25%, and performing standard concrete tests. They found that up to 10% replacement improved water absorption resistance and shrinkage behavior, but strength parameters decreased beyond this point. They concluded that PPW could be used effectively in non-load-bearing concrete applications if properly proportioned.

Abu Saleem's work further emphasizes the need for proper mix optimization, as PPW has weak adhesion with the cement matrix due to its hydrophobic nature. However, it can be compensated by pozzolanic additives or mineral admixtures. In fact, combining pozzolanic materials like silica fume or CIWA with PPW could counteract the strength deficiencies by densifying the cementitious matrix and enhancing interfacial bonding.

[12] explored the use of plastic waste and Quarry Dust (QD) in producing eco-friendly paving blocks. Using gradation curves, the optimal mix of QD and ballast (B) with modified polymer was determined. Mechanical tests revealed that the blocks maintained structural integrity, with only minor strength reductions under acidic conditions. The findings support the material's suitability for outdoor use and highlight its potential for sustainable Non-Motorized Transport (NMT) infrastructure, promoting innovative solutions in urban development. [13] explored the combined sustainability and performance benefits of partially replacing coarse aggregate with varying proportions of plastic waste (0% - 12.5%). Using a 35 MPa control mix (slump 100 mm) designed to BS standards, physical tests (slump, density) and mechanical tests (compressive, flexural, tensile strength, ultrasonic) were conducted. Results showed minimal performance loss at 2.5% PW, but strength declined sharply beyond this threshold. The study concludes that small PW dos-

ages can yield eco-friendly concrete suitable for structural applications such as culverts.

[14] [15] explored their combined use as partial fine aggregate replacements in C-25 concrete to improve sustainability. Cement setting time, workability, and mechanical properties were tested after 7 and 28 days of curing. The optimal result was achieved with 10% replacement (3% WP, 7% WG) at a water-cement ratio of 0.4, yielding up to 12.55% higher compressive strength and 19.7% greater flexural strength, though splitting tensile strength decreased slightly. The study concluded that controlled WG/WP blends can enhance certain structural properties. The research successfully identifies a WG/WP mix that improves compressive and flexural strength while retaining acceptable workability. However, durability factors such as sulphate resistance, chloride penetration, and freeze-thaw performance were not assessed. Performance was measured only up to 28 days, limiting understanding of long-term behaviour. The study also did not explore chemical interactions between WG, WP, and the cement matrix.

[16] investigated the production of paver blocks by partially replacing sand with PET waste at 10% - 30% levels. Using a 1:2:3 cement-aggregate-sand ratio, 17 trials were designed via a Box-Behnken approach, testing different PET percentages, water-cement ratios (0.52 - 0.58), and curing periods (7 - 28 days). Results showed optimal performance at 10% PET and a water-cement ratio of 0.55, yielding 29.74 MPa compressive and 4.92 MPa flexural strength, with water absorption of 3.39% - 3.95%. The study concluded that PET-modified paver blocks are lighter and structurally suitable for prefabricated applications. The study's strength lies in its statistical optimization and multi-parameter testing, identifying 10% PET as optimal for strength and durability balance. However, it does not assess freeze-thaw performance, abrasion resistance, or long-term weathering. Furthermore, higher PET levels were quickly dismissed without exploring potential improvements through additives or surface treatments to enhance bonding with the cement matrix.

The literature indicates that both CIWA and PPW hold strong potential as sustainable alternatives in concrete production. CIWA enhances strength and durability through its pozzolanic activity, while PPW improves workability, reduces weight, and provides an environmentally responsible pathway for recycling plastic waste. However, CIWA can delay setting and reduce early strength, whereas excessive PPW content weakens the cement matrix. Combining these materials offers a promising route to balance such trade-offs, producing eco-efficient concrete for semi-structural applications such as culverts, blocks, and low-traffic pavements. Despite this potential, research to date has largely focused on each material in isolation, with minimal effort to optimize their combined use for culvert-grade concrete. Furthermore, few studies link comprehensive material characterization, encompassing fineness modulus, specific gravity, and oxide composition, with corresponding mechanical performance, leaving standardized grading and acceptance criteria for hybrid mixes underdeveloped. Critically, plastic waste incor-

poration beyond small fractions consistently impairs strength unless mitigated by treatments or reactive fines, and many prior works rely on broad dosage increments with limited durability assessments, potentially missing the narrow optimum range. The present study addresses these shortcomings by employing finely controlled low-dosage replacements and multi-property testing; nonetheless, long-term field durability, particularly under chloride ingress, sulphate attack, and freeze-thaw conditions, remains an area for further investigation.

3. Methodology

This study adopted an experimental laboratory-based design to evaluate the mechanical performance of concrete culvert blocks incorporating CIWA as partial cement replacement and PPW as partial sand replacement. The objective was to assess the optimal blend for structural and durability performance, with reference to highway culvert applications.

3.1. Materials and Sourcing

3.1.1. Materials

The key materials used included CIWA (sourced from Export Processing Zone (EPZ) Kenya), PPW (collected from Nairobi's Industrial Area), river sand, and ballast chips (sourced along Kangundo Road). Ballast of size 1 was used as coarse aggregate. The trial mix design followed the conventional 1:2:4 ratio, targeting a concrete compressive strength of 37 MPa in accordance with BS 8500.

3.1.2. Batching and Mix Design Considerations

The study complied with BS 5400 for load considerations and BS 8500 for concrete mix design. Emphasis was placed on achieving structural integrity under both dead and live loads, particularly HA or HB classifications for highway culverts. Reinforcement guidelines referenced BS 4449 and BS 8110, though the culverts in this study primarily focused on unreinforced mixes.

3.2. Material Characterization

Sieve Analysis followed BS 812: Part 1: 1975, using 1 kg samples for particle gradation. Specific Gravity and Bulk Density assessments were performed according to BS 812: Part 2: 1996, differentiating between loose and compacted aggregates. Water Absorption was measured following BS 812: Part 2: 1975, indicating porosity and potential durability of the concrete.

3.3. Mechanical Testing of Concrete Cubes

Compressive Strength tests were conducted using BS 1881: Part 116: 1983, where cubes were subjected to uniaxial loading to determine ultimate strength.

Flexural Strength testing, used to evaluate bending performance, was also part of the mechanical assessment, though no specific BS code was mentioned beyond standard practice.

Durability Assessments were based on water absorption, followed BS EN 1338,

involving 24-hour drying after immersion of blocks and calculating the weight difference to assess water ingress. This comprehensive methodology ensured that all experimental parameters were benchmarked against established standards, providing reliable data on the viability of CIWA and PPW in structural concrete applications for highway infrastructure.

4. Results and Findings

4.1. Physical Properties

4.1.1. Chemical Composition

The chemical composition of CIWA and Ordinary Portland Cement (OPC) was determined using X-ray Fluorescence (XRF) spectrometry in accordance with ASTM C114. Samples were oven-dried at $105 \pm 5^\circ\text{C}$ for 24 hours, ground to pass a $75\ \mu\text{m}$ sieve, and pressed into pellets with boric acid as a binder. Major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO) and minor constituents (Na_2O , K_2O , TiO_2 , P_2O_5 , MnO) were quantified, while Loss on Ignition (LOI) was determined separately by heating 1 g samples to 950°C for 2 hours to assess unburnt carbon and volatiles. Results, expressed as mass percentages corrected for LOI, provided the comparative profiles in **Table 2** for evaluating CIWA's pozzolanic potential and compatibility as a cement replacement.

Table 2. Comparison of chemical composition of Cinchona industrial waste and Portland cement.

Oxide	Cinchona Industrial Waste Ash (% by weight)	Ordinary Portland Cement (% by weight)	Function in Cementitious Systems
SiO_2 (Silicon Dioxide)	47.89%	21.19%	Key pozzolanic material. Reacts with $\text{Ca}(\text{OH})_2$ to form strength-giving C-S-H gel.
Al_2O_3 (Aluminum Oxide)	11.72%	5.37%	Enhances early strength; forms calcium aluminates aiding in setting and strength.
Fe_2O_3 (Ferric Oxide)	10.12%	3.95%	Contributes to ferrite phases, minor strength contribution, affects color.
CaO (Calcium Oxide)	17.18%	63.41%	Primary binding oxide; hydrates to form C-H and C-S-H, major strength contributor.
MgO (Magnesium Oxide)	5.04%	1.44%	Affects volume stability and long-term durability when within safe limits.
$\text{Na}_2\text{O} + \text{K}_2\text{O}$ (Alkalis)	2.15%	0.68%	Must be controlled to minimize alkali-silica reaction (ASR) risks.
TiO_2 (Titanium Dioxide)	0.76%	Not typically reported	Minor effect; may influence reflectance or whiteness.
P_2O_5 (Phosphorus Pentoxide)	0.40%	Not typically reported	Generally inert or slightly retarding.
MnO (Manganese Oxide)	0.12%	Not typically reported	Inert at low concentrations.
LOI (Loss on Ignition)	5.52%	3.15%	Indicates unburnt material or organics; lower values imply better stability.

Source: (Researcher, 2025).

Table 2 indicates that CIWA has high levels of silicon dioxide (47.89%) and

aluminum oxide (11.72%), key indicators of pozzolanic activity crucial for strength development in concrete. With calcium oxide at 17.18%, CIWA shows potential as a partial cement replacement. A low loss on ignition (5.52%) indicates minimal unburned carbon, supporting chemical stability. Other compounds, including MgO and alkalis, are within safe limits, minimizing durability risks.

4.1.2. Sieve Analysis

Sieve analysis was performed on river sand, PPW, and ballast in accordance with BS 812: Part 1:1975 to establish particle size distribution profiles. This analysis underpins the design of well-graded aggregate blends, which improve packing density, reduce voids, and minimize the demand for excess cement paste. Incorporating such grading control is particularly important when introducing alternative materials like PPW and CIWA, whose physical characteristics may differ from conventional aggregates. The fineness modulus (FM), calculated from the gradation results (**Table 3**), provided a quantitative basis for modifying aggregate proportions, ensuring that partial replacement with these industrial by-products did not compromise compliance with standard grading limits, structural performance, or durability.

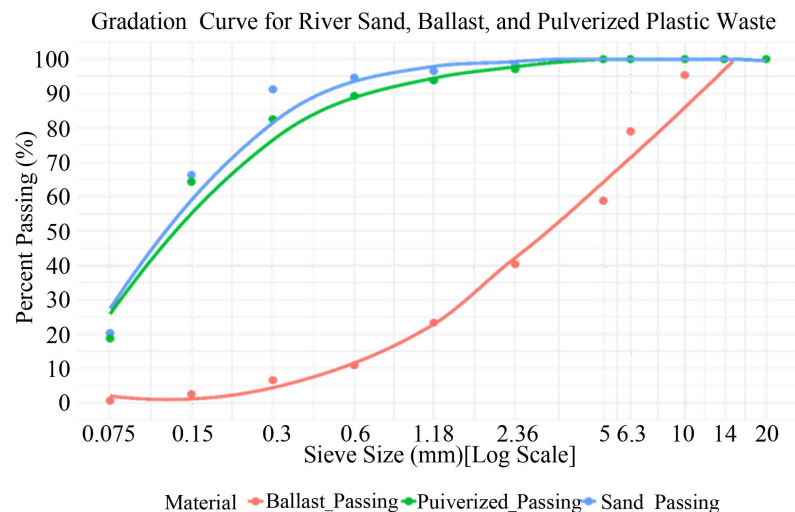
Table 3. Summary of sieve analysis results for constituent aggregates.

Sieve Size (mm)	Sand Passing	Ballast Passing	Pulverized Passing
20	100	100	100
14	100	100	100
10	100	95.38	100
6.3	100	78.96	100
5	100	58.78	100
2.36	98.2	40.32	97.1
1.18	96.5	23.28	93.8
0.6	94.6	10.92	89.3
0.3	91.2	6.56	82.5
0.15	66.3	2.47	64.3
0.075	20.3	0.62	18.7
Pan	1.6	0	1.1
FM	2.33	6.83	2.54

Source: (Researcher, 2025).

Table 3 shows that the sand used in the study has a fineness modulus (FM) of 2.33, aligning with ASTM C33's acceptable range of 2.3 to 3.1 for fine aggregates. This moderately fine gradation supports good workability and finish, though its lower-bound value may slightly increase water demand. PPW records an FM of 2.54, also within the ASTM range, indicating a slightly coarser gradation than sand. This could enhance particle packing and reduce paste demand, making

PPW a suitable partial sand substitute. The ballast used as coarse aggregate has an FM of 6.83, within the typical 6.5 - 8.0 range, ensuring structural strength and stability. Additionally, compliance with fines content requirements is crucial. Excess fines, above 4% for uncrushed gravel sand or 9% - 16% for crushed rock, can impair workability and increase shrinkage. Therefore, sand and PPW must be checked against these thresholds, with corrective measures like washing or blending applied if necessary. These gradation profiles support the suitability of CIWA and PPW in culvert concrete applications. The gradation curve for the sieve analysis presented in **Table 3** is presented in **Figure 1**.



Source: (Researcher, 2025).

Figure 1. Gradation curves for aggregate constituent materials.

Figure 1 illustrates the particle size distribution curves for sand, PPW, and ballast, supporting the material characterization objective of evaluating the suitability of PPW and CIW in culvert concrete. The curves for sand and PPW show smooth, S-shaped profiles typical of well-graded fine aggregates. PPW closely mirrors the sand distribution, particularly between 0.075 mm and 2.36 mm, confirming its slightly coarser gradation (FM = 2.54 vs. 2.33) and supporting its potential as a partial sand replacement. The ballast curve, steeper and shifted toward larger sizes (FM = 6.83), reflects coarse aggregate gradation ideal for load-bearing strength. The distinct gradation profiles collectively support an optimal mix design that enhances packing density, reduces voids, and improves strength and durability, key for infrastructure like culverts subjected to dynamic loads and environmental exposure.

4.1.3. Specific Gravity

Specific gravity is a vital factor in concrete mix design, influencing the accuracy of volume batching and the overall mass-to-volume balance of materials. It is defined as the ratio of a material's density to that of water. In this study, the specific gravity of PPW, CIWA, and river sand was determined to evaluate their suitability

as partial substitutes for cement and fine aggregates. These values are essential for calculating mix proportions and ensuring that the modified concrete maintains structural integrity, making them crucial for culvert construction applications. The results are presented in **Table 4**.

Table 4. Summary of specific gravity of concrete constituent materials.

Material	Specific Gravity (g/cm ³)
River Sand	2.64
Cinchona Industrial Waste Ash (CIWA)	2.14
Pulverized Plastic Waste (PPW)	0.95

Source: (Researcher, 2025).

Table 4 shows that the specific gravity results of river sand have a typical value of 2.64, consistent with standard fine aggregates. CIWA has a lower specific gravity of 2.14, indicating it is lighter than ordinary Portland cement and beneficial for reducing concrete density and embodied energy. PPW, with a specific gravity of 0.95, is significantly lighter, reflecting its polymeric nature. This makes it ideal for reducing the self-weight of concrete culverts, especially in precast applications, though it requires mix adjustments for volumetric balance and performance.

4.1.4. Bulk Density

Bulk density, which measures the mass per unit volume including voids, affects concrete's compaction, stability, and strength.

Table 5. Summary of bulk density of concrete constituent materials.

Material	Bulk Density (kg/m ³)
River Sand	1740
CIWA	1120
PPW	610

Source: (Researcher, 2025).

Table 5 shows river sand with the highest bulk density at 1740 kg/m³, reflecting its compactable nature. CIWA and PPW have significantly lower values of 1120 kg/m³ and 610 kg/m³, respectively. These lighter densities suggest that both materials can reduce the overall weight of concrete. However, CIWA may slightly impact strength if not properly proportioned, while PPW may increase void content, requiring careful mix design to maintain durability in culvert applications.

4.1.5. Moisture Content

Moisture content affects the water-cement ratio, influencing concrete's workability and strength.

Table 6. Summary of moisture content of concrete constituent materials.

Material	Moisture Content (%)
River Sand	2.81
CIWA	1.42
PPW	0.92

Source: (Researcher, 2025).

Table 6 shows river sand with a moisture content of 2.81%, CIWA at 1.42%, and PPW at 0.92%. The lower moisture absorption of CIWA and PPW allows for better control of the mix's water content, reducing the risk of excessive water that could weaken the concrete. Additionally, their reduced moisture content enhances dimensional stability, minimizing shrinkage and cracking, key qualities for durable concrete culverts exposed to fluctuating environmental moisture conditions.

4.1.6. Porosity

Porosity, which influences a material's permeability, durability, and strength, is critical in assessing concrete performance.

Table 7. Summary of moisture content of concrete constituent materials.

Material	Porosity (%)
River Sand	35.7
CIWA	47.7
PPW	36.0

Source: (Researcher, 2025).

Table 7 shows CIWA with the highest porosity at 47.7%, followed by PPW at 36.0% and river sand at 35.7%. CIWA's elevated porosity, typical of ash-based materials, may increase water absorption and affect compaction but supports long-term strength through pozzolanic reactions. PPW, though slightly more porous than sand, remains suitable due to its non-absorbent thermoplastic nature. However, its use requires careful mix design to manage water demand and ensure adequate compaction for durable culvert construction.

4.2. Mechanical and Physical Properties of Fresh and Hardened Concrete for Production of Highway Culverts

4.2.1. Preliminary Test

The preliminary tests constituted 14 batches with a control; hence, a total of 15 batches were generated based on **Table 8**.

Table 8. The baseline for the preliminary batching.

Batch	Base ratio	Source	Variable
	PPW		
5%			
10%	1:1.5:3	[11]	PPW
15%			

Continued

CIW			
5%			
10%	1:1.5:3	[4]	CIW
15%			

Source: (Researcher, 2025).

A total of 672 samples were cast for detailed laboratory tests. These initial mix designs are presented in **Table 9**.

Table 9. Preliminary batching based on **Table 8**, but with based mix design of 1:1:2.

Sample	Percent Replacement
Control	No replacement
Pure PPW	100% replacement of sand
<i>Pure Cinchona</i>	100% <i>replacement of sand</i>
P_1	5% of PPW with sand
P_2	10% of PPW with sand
P_3	15% of PPW with sand
P_4	12.5% of PPW with sand
P_5	7.5% of PPW with sand
P_6	2.5% of PPW with sand
Ci_1	5% of Ci with cement
Ci_2	10% of Ci with cement
Ci_3	15% of Ci with cement
Ci_4	12.5% of Ci with cement
Ci_5	7.5% of Ci with cement
Ci_6	2.5% of Ci with cement

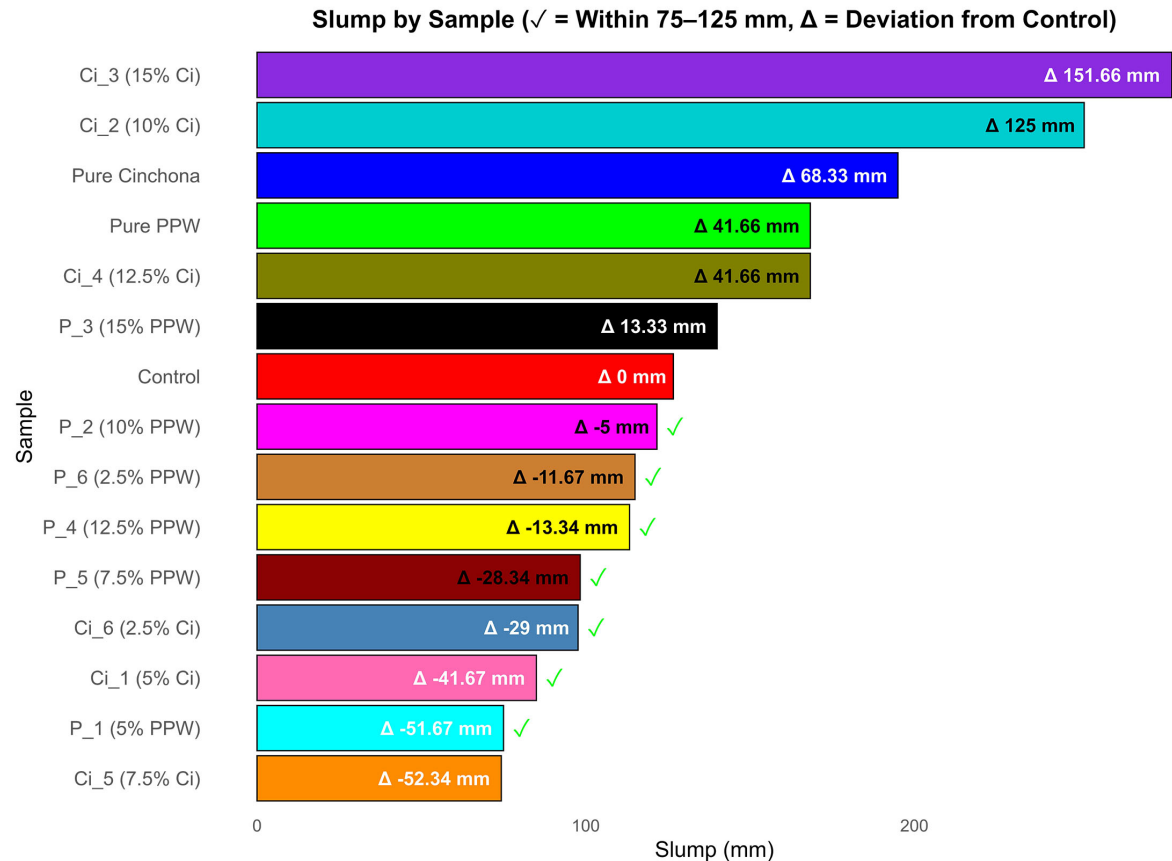
Source: (Researcher, 2025).

Table 9 reveals that, beyond the initial objective of using CIWA as a partial cement replacement, a 100% substitution of sand with CIWA was tested to evaluate its standalone performance. This unexpected yet purposeful trial aligned with the broader goal of optimizing waste material utilization in concrete. It provided valuable insights into CIWA's physical and mechanical behavior, helping to define its material boundaries. The results served as a benchmark for assessing performance relative to pure PPW mixes and supported the identification of optimal blend ratios by highlighting CIWA's role in enhancing strength and durability.

4.2.2. Slump

The slump test was conducted to assess the workability and consistency of fresh concrete and the results are presented in **Figure 2**. A water cement ratio of 0.55 was used to attain a homogeneous mix for all the samples. This was done since

scope of the experiment did not focus on water cement variation.



Source: (Researcher, 2025).

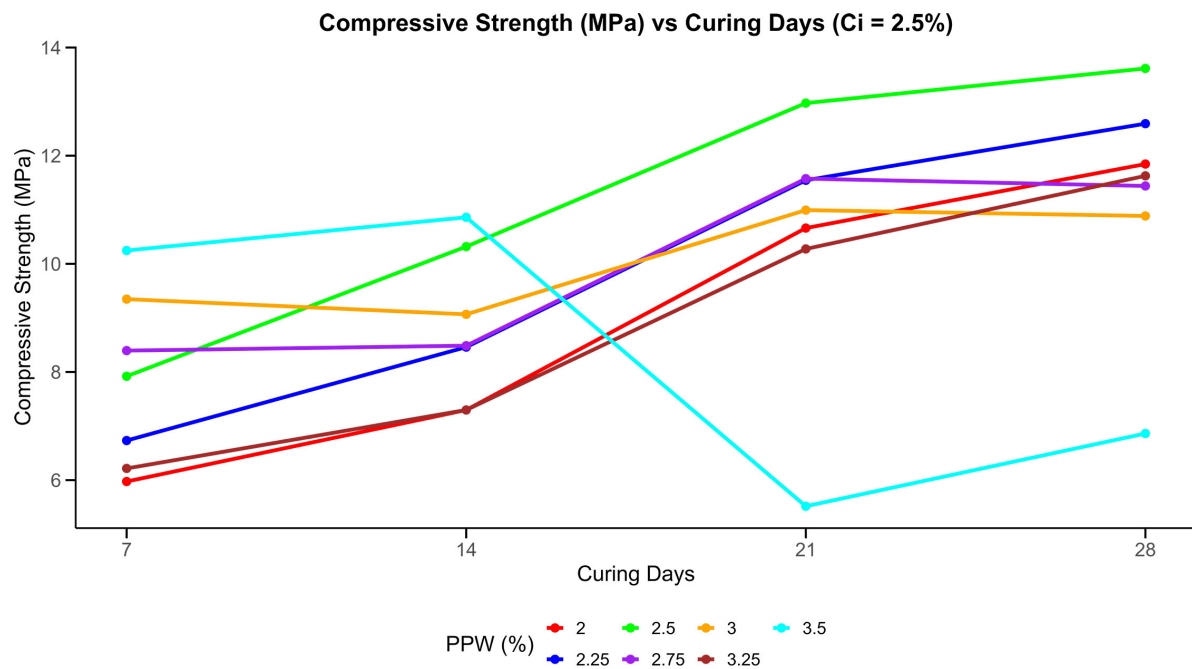
Figure 2. Slump test for preliminary test presented in **Table 4**.

Figure 2 illustrates the slump test results, highlighting the workability behavior of concrete mixes containing Cinchona Industrial Waste Ash (CIW) and Pulverized Plastic Waste (PPW). In line with BS EN 206, which defines acceptable slump values between 75 mm and 125 mm for normal workable concrete, most mixes, including P_1 (5% PPW), P_2 (10% PPW), P_4 (12.5% PPW), P_5 (7.5% PPW), P_6 (2.5% PPW), Ci_1 (5% CIW), and Ci_6 (2.5% CIW)—fell within or near this range, indicating good workability suitable for culvert construction. Conversely, mixes with higher CIW content, particularly Ci_2 (10% CIW) and Ci_3 (15% CIW), exhibited slump values exceeding 250 mm, suggesting excessive fluidity, poor cohesiveness, and risk of segregation. Ci_5 (7.5% CIW) showed a slightly reduced slump, indicating diminished workability. The findings confirm that CIW and PPW can be incorporated up to 12.5% without compromising workability, supporting the study's objective to develop optimal concrete mix designs using industrial and plastic waste.

4.2.3. Compressive Strength Test

The tests were done after curing in fresh water of about $23 \pm 2^\circ\text{C}$. The water was

assumed to be free of any impurities. All the test were replicated for $n = 3$, and the average was used to plot the results. The compressive strength test is a key measure of concrete's ability to resist load and maintain structural integrity, especially in applications such as culverts that endure substantial compressive forces from overburden and vehicular traffic. In this study, the test served as a primary benchmark to assess the mechanical performance of concrete mixes modified with CIW and PPW. The results, presented in **Figure 3** and **Figure 4**, facilitated direct comparison between modified and standard mixes, providing crucial insights into the suitability and reliability of the alternative materials for durable culvert construction.



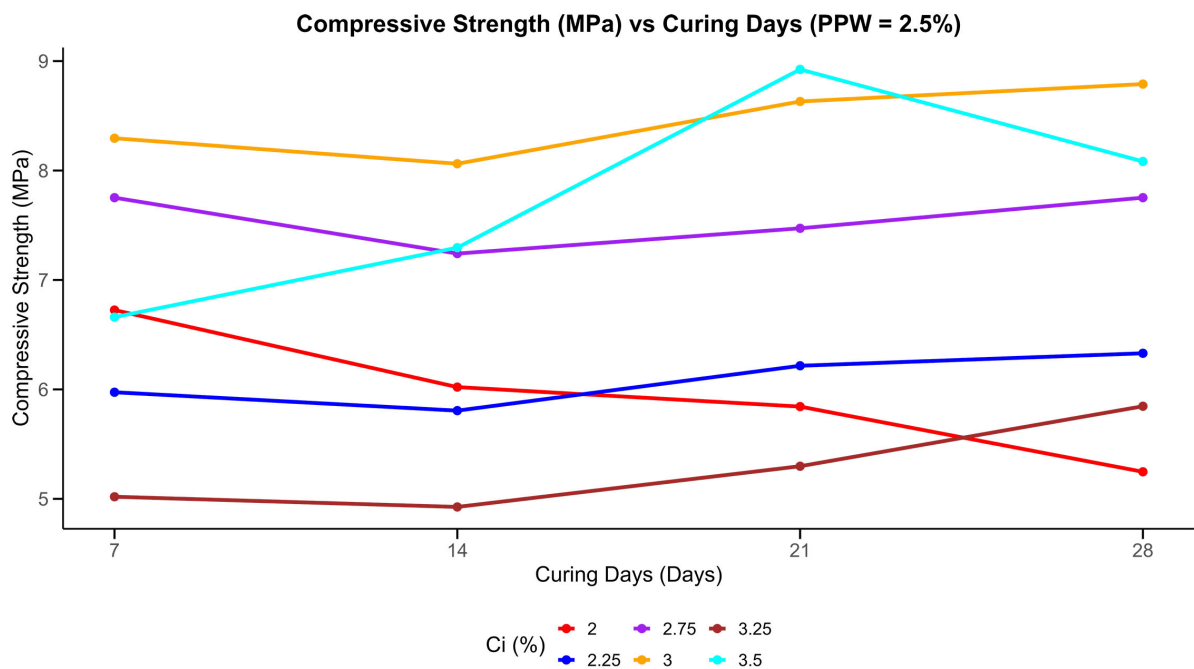
Source: (Researcher, 2025).

Figure 3. Summary of compressive strength test for preliminary batching for PPW.

Figure 3 illustrates the compressive strength development of concrete mixes with varying percentages of Pulverized Plastic Waste (PPW) over 7, 14, 21, and 28 days, supporting the study's goal of optimizing waste materials in culvert construction. The control mix (0% PPW) recorded the highest strength (24.22 MPa at 28 days), serving as the benchmark. Among modified mixes, P₆ (2.5% PPW) performed best, achieving 13.9 MPa, while P₁ (5% PPW) followed closely with 13.53 MPa, confirming that low PPW levels maintain strength. Mixes with higher replacements like P₂ (10%), P₄ (12.5%), and P₅ (7.5%) showed diminishing returns beyond the 10% - 12.5% threshold due to increased voids and weaker bonding. All mixes showed strength gain over time, confirming hydration activity. P₆ was identified as the optimal mix, balancing mechanical performance and sustainability. **Figure 4** proceeds to assess CIW-based mixes, discussed sep-

arately.

Figure 4 illustrates the compressive strength development of concrete mixes incorporating varying levels of Cinchona Industrial Waste Ash (CIW) as partial cement replacement. The control mix (0% CIW) exhibited the highest strength, reaching 24.22 MPa at 28 days. Among modified mixes, Ci_6 (2.5% CIW) achieved the best performance, peaking at 13.47 MPa, demonstrating CIW's pozzolanic benefit at low dosages. Higher replacements, such as Ci_3 (15%) and Ci_4 (12.5%), showed significantly reduced strengths, indicating poor hydration and bonding at elevated CIW levels. The results confirm that 2.5% CIW offers the best balance between sustainability and mechanical performance for culvert construction.



Source: (Researcher, 2025).

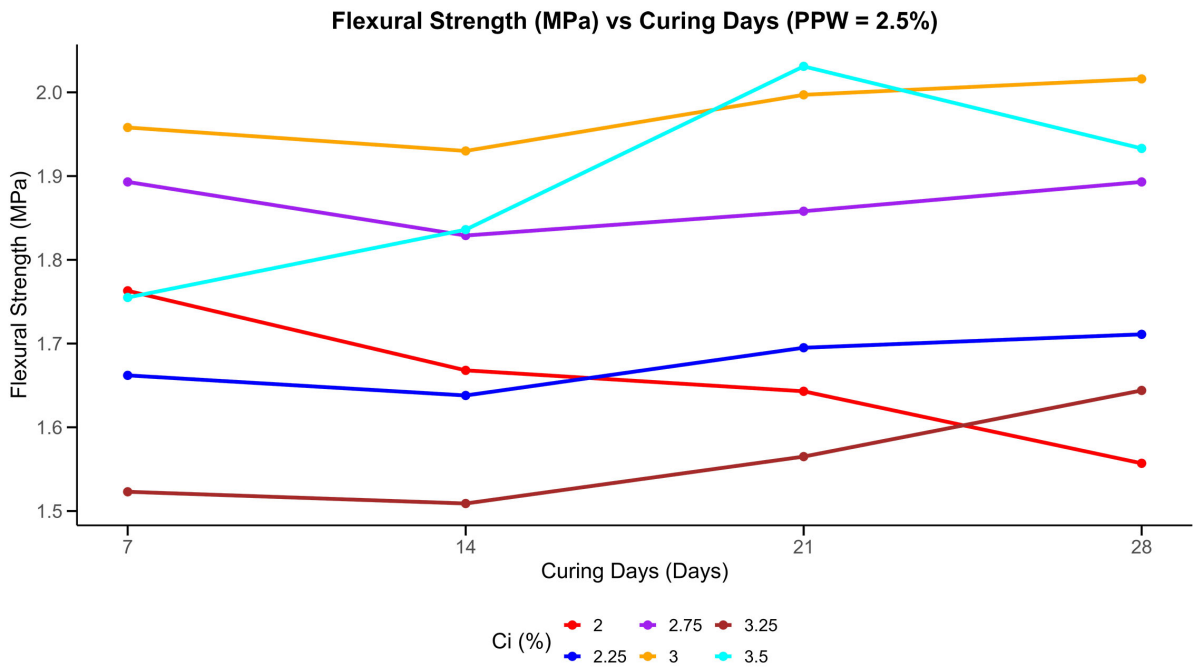
Figure 4. Summary of compressive strength test for preliminary batching for CIW.

4.2.4. Flexural Strength Test

The flexural strength test, conducted per BS EN 12390-5:2009 using prismatic specimens, evaluated the concrete's resistance to bending, crucial for culverts and slabs. **Figure 5** and **Figure 6** present results showing the structural integrity of mixes incorporating CIW and PPW.

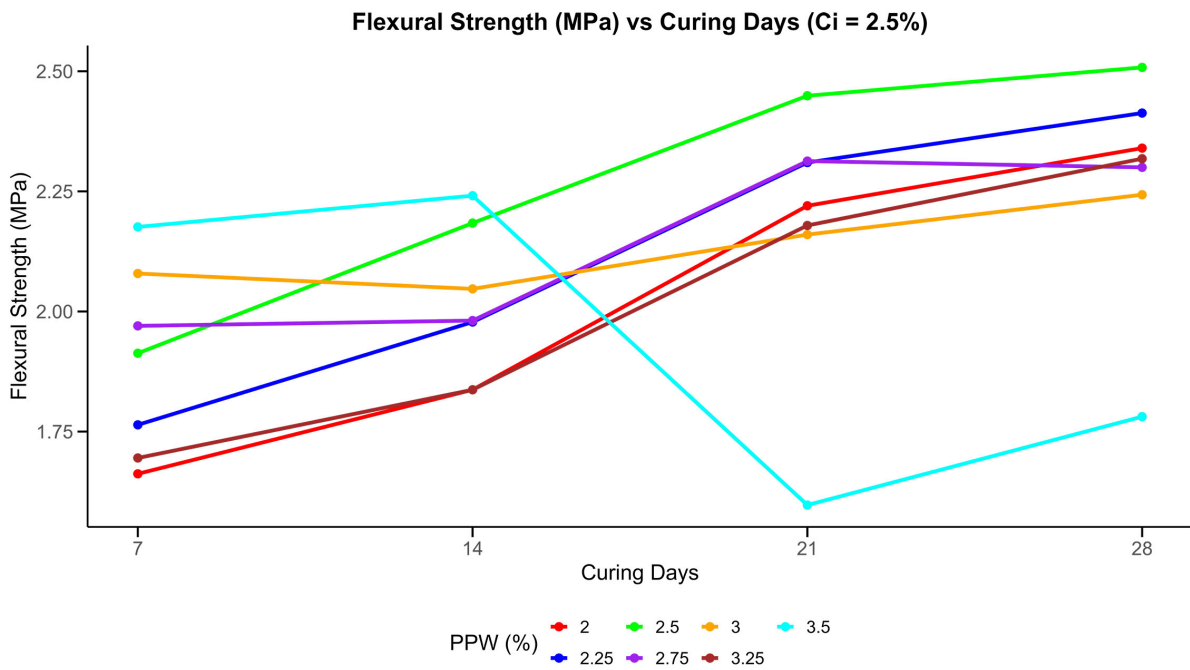
Figure 5 shows that P_6 (2.5% PPW) achieved the second-highest flexural strength after the control mix, reaching 2.67 MPa at 28 days. Pure PPW and P_5 followed closely at 2.53 MPa. Results highlight that low-level PPW enhances flexural performance, while higher content yields diminishing structural returns.

Figure 6 shows that the control mix had the highest split tensile strength (4.10 MPa at 28 days), followed by Ci_6 (2.5% CIW) and Ci_5 (7.5%). Higher CIW levels, particularly Ci_3 (15%), reduced tensile strength. Optimal performance was observed at low replacement levels, especially 2.5%.



Source: (Researcher, 2025).

Figure 5. Summary of flexural strength test for preliminary batching for PPW.



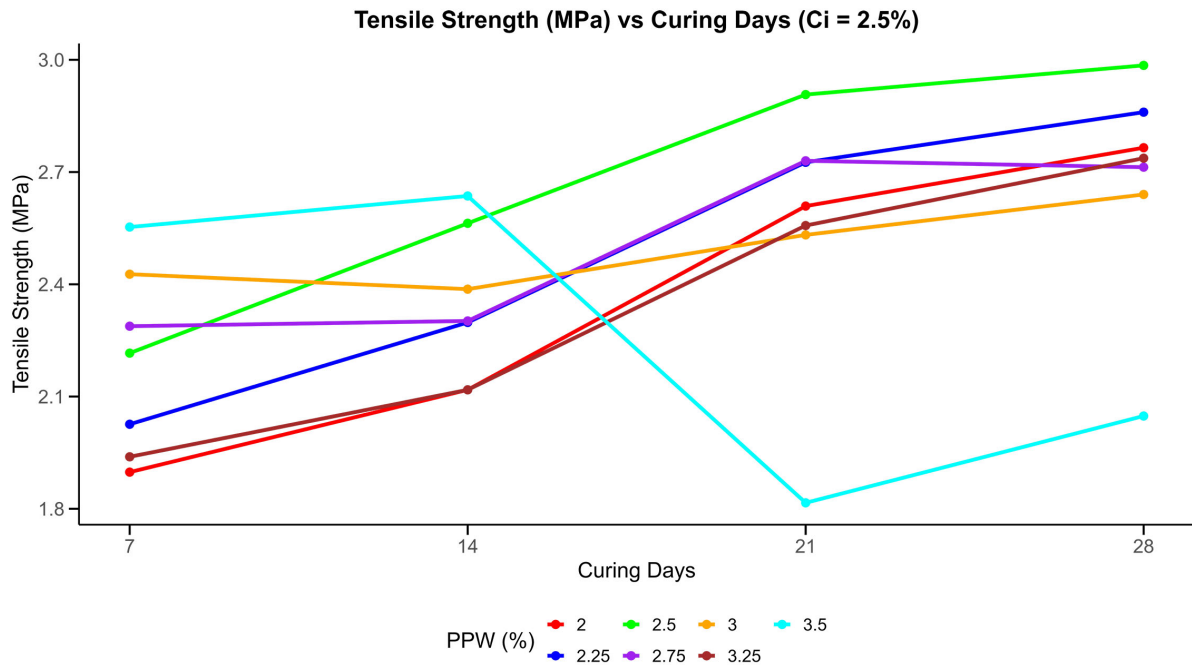
Source: (Researcher, 2025).

Figure 6. Summary of flexural strength test for preliminary batching for CIW.

4.2.5. Tensile Strength

The split tensile strength test, conducted per BS EN 12390-6:2009 using cylindrical specimens, assessed concrete’s resistance to cracking and bending, key for pavements and culverts. Unlike compressive strength, this test evaluates tensile behav-

ior under diametral loading. Results from **Figure 7** and **Figure 8** reveal the impact of PPW and CIW on the tensile performance of modified concrete, offering critical insights into their structural viability and effectiveness as partial replacements for sand and cement, respectively.



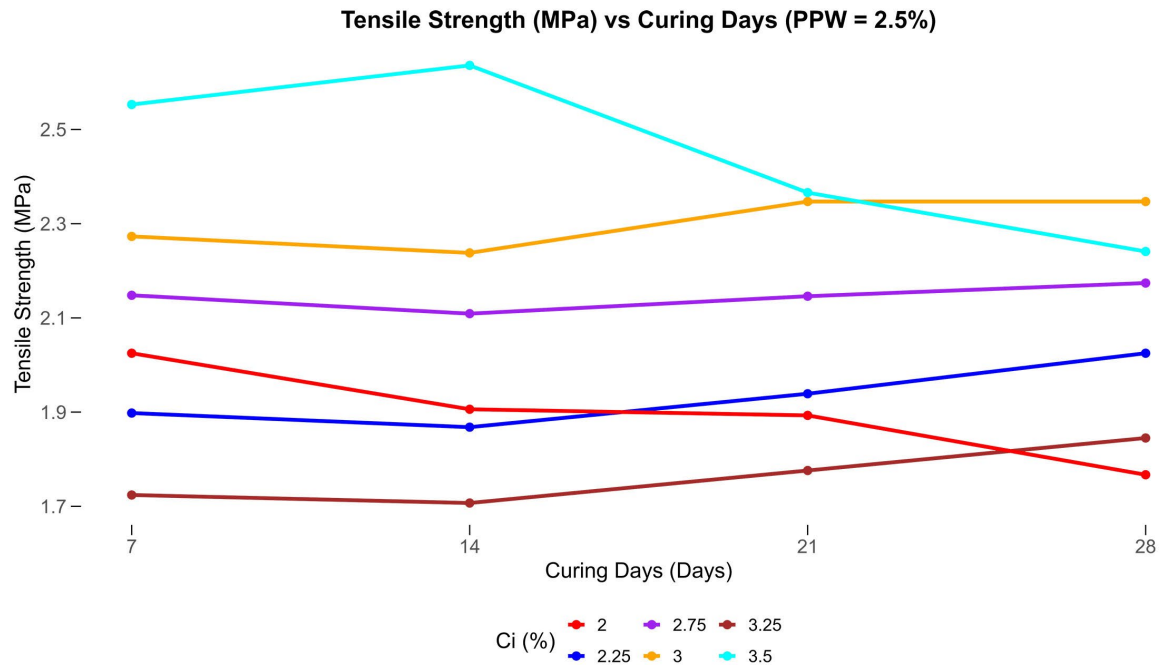
Source: (Researcher, 2025).

Figure 7. Summary of tensile strength test for preliminary batching for PPW.

The split tensile strength plot reveals clear trends for concrete mixes with varying levels of PPW as partial sand replacements. The control mix, with no PPW, showed the highest strength across all curing periods, reaching 4.10 MPa at 28 days due to uninterrupted matrix integrity. P₆ (2.5% PPW) followed as the second-best performer, suggesting that low-level PPW enhances crack resistance through better stress distribution. P₁ (5%) ranked third, maintaining consistent strength gain. However, mixes with higher PPW content (P₂ to P₄) showed diminishing tensile strength, while P₅ (7.5%) and Pure PPW performed the weakest, likely due to poor bonding and internal discontinuities. Split tensile strength test for cinchona as partial replacement of sand is presented in **Figure 8**.

Figure 8 shows the split tensile strength performance of concrete with CIW as partial cement replacement was assessed across 7 - 28 days. The control mix exhibited the highest strength (4.10 MPa at 28 days) due to uninterrupted cement hydration. Ci₆ (2.5% CIW) ranked second, showing strong performance attributed to enhanced matrix densification. Ci₅ (7.5%) followed with steady strength gain, indicating a favorable balance of pozzolanic reactivity and cohesion. Ci₄ (12.5%) also performed well, though with tapering gains. Surprisingly, the Pure CIW mix (100% replacement) outperformed some partial mixes, likely due to delayed pozzolanic activity. Ci₂ (10%) and Ci₃ (15%) showed

declining effectiveness, while Ci_1 (5%) performed the weakest, possibly due to poor reactivity at that dosage. These results highlight that CIW, at low dosages (2.5% - 7.5%), can enhance tensile strength, but excessive replacement undermines performance.



Source: (Researcher, 2025).

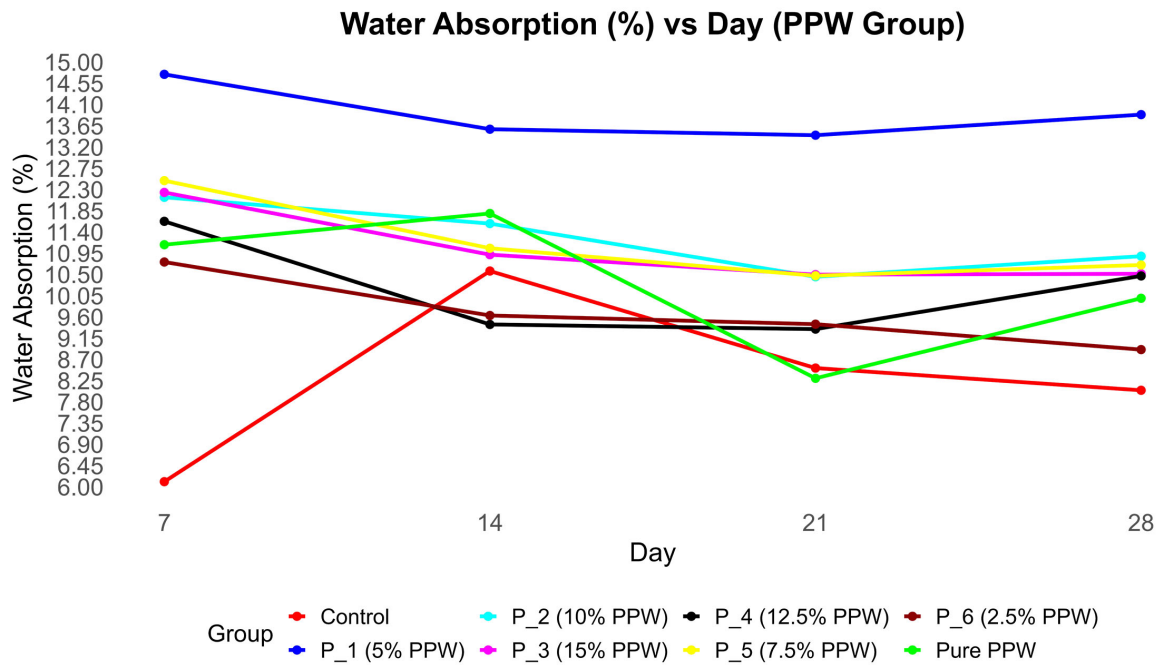
Figure 8. Summary of tensile strength test for preliminary batching for CIW.

4.2.6. Water Absorption

The study evaluated concrete durability using the water absorption test, selected for its efficiency and reliability in assessing moisture ingress. As porosity and permeability directly affect durability, this method offered immediate insight into the concrete's resistance to environmental exposure. Acid resistance testing, requiring longer observation, was deferred. **Figure 9** and **Figure 10** illustrate the water absorption performance of concrete mixes with PPW and CIW as partial replacements for sand and cement, respectively, highlighting their impact on concrete's preliminary durability characteristics.

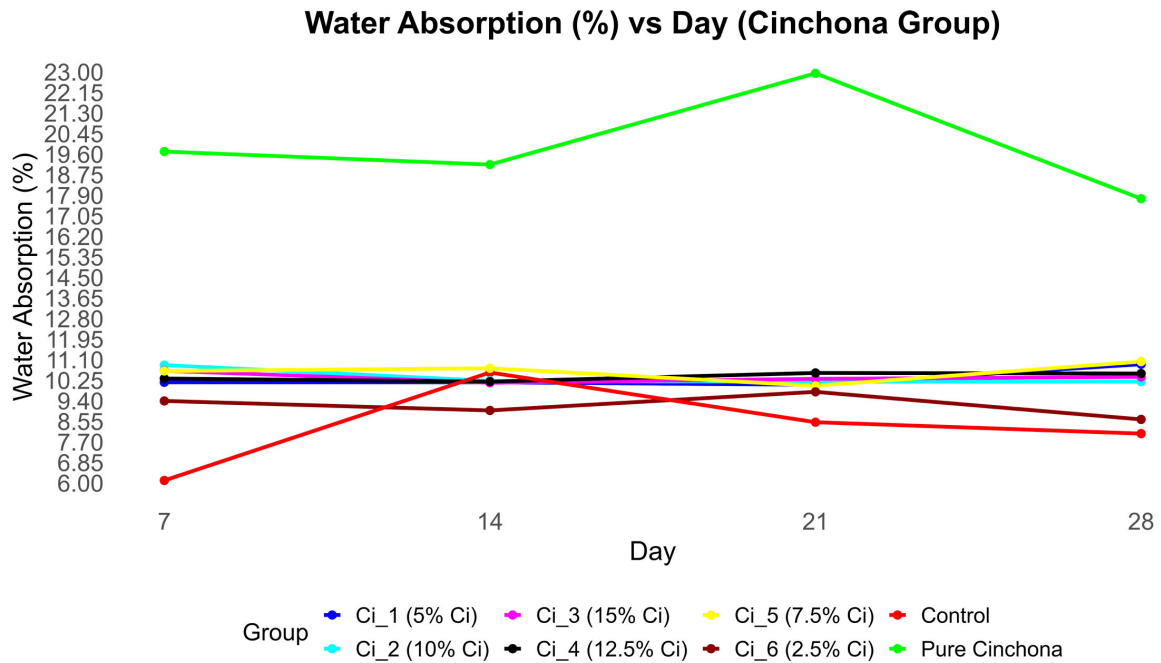
Figure 9 indicates that water absorption tests where the control mix had the lowest moisture uptake, followed closely by P₆ (2.5% PPW), indicating superior durability. Pure PPW also performed well due to its impermeability. Higher PPW contents increased porosity, with P₁ (5%) showing the highest absorption, suggesting reduced resistance to moisture ingress.

Figure 10 showed the control mix had the lowest permeability, indicating highest durability. Ci₆ (2.5% CIW) followed closely, proving effective at refining pores. Moderate CIW levels (5% - 15%) maintained acceptable absorption, while Pure Cinchona (100% CIW) recorded the highest, confirming compromised durability at excessive replacement levels.



Source: (Researcher, 2025).

Figure 9. Summary of water absorption test for preliminary batching for PPW.



Source: (Researcher, 2025).

Figure 10. Summary of water absorption test for preliminary batching for CIW.

4.2.7. Comparison of Preliminary Test

Table 10 indicates that P₆ (2.5% PPW) was the most suitable sand replacement, meeting 3 out of 4 performance criteria with minimal deviation from the control. Ci₆ (2.5% CIW) emerged as the best cement substitute, passing 2 out of 4 tests.

Despite slight deviations in compressive strength and water absorption, Ci₆ remains the most promising for further development.

Table 10. Comparison of performance of preliminary batches.

Metric	Control	Pure		2.5%		5%		7.5%		10%		12.5%		15%	
		PPW	CIW	PPW	CIW	PPW	CIW	PPW	CIW	PPW	CIW	PPW	CIW	PPW	CIW
Slump	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✗	✗
Compressive	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Flexural	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗
Tensile	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Water absorption	✓	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗

Source: (Researcher, 2025).

4.3. Estimation of Optimal Design Mix

This section focused on identifying the optimal concrete design mix using PPW as sand replacement and CIW as cement replacement. Evaluation was based on compressive, flexural, and tensile strength, plus water absorption. P₆ (2.5% PPW), labeled L₁, emerged as the most suitable PPW mix, passing 3 out of 4 performance tests. Similarly, Ci₆ (2.5% CIW) showed the most promising performance among CIW mixes. To refine these findings, 13 combinations presented in **Table 11** (L₁ - L₁₃) were developed—L₁ - L₇ varied PPW with constant CIW (2.5%), and L₈ - L₁₃ varied CIW with constant PPW (2.5%). This two-phase approach enabled a systematic evaluation of individual and combined replacement effects on strength and durability performance.

Table 11. Mix design r = tested.

Sample	PPW	Ci
L_1	2.5	2.5
L_2	2.25	2.5
L_3	2	2.5
L_4	2.75	2.5
L_5	3	2.5
L_6	3.25	2.5
L_7	3.5	2.5
L_8	2.5	2.25
L_9	2.5	2
L_10	2.5	2.75
L_11	2.5	3
L_12	2.5	3.25
L_13	2.5	3.5

Source: (Researcher, 2025).

The thirteen mix designs, labeled L_1 through L_{13} , were evaluated. When the compressive strength of concrete is known, its tensile and flexural strengths can be estimated using standard empirical relationships from established codes such as ACI 318, Eurocode 2, and IS 456:2000. The tensile strength of concrete is typically about 8% - 12% of its compressive strength and can be estimated as follows:

$$\text{Eurocode 2 (EN 1992-1-1): } f_{ctm} = 0.30 \times f_{ck}^{\frac{2}{3}}$$

$$\text{For } f_{ck} = 25 \text{ MPa: } f_{ctm} = 0.30 \times 25^{\frac{2}{3}} \approx 2.6 \text{ MPa}$$

$$\text{ACI 318 Approximation: } f_{ct} = 0.56 \times \sqrt{f'_c} \text{ (in MPa)} \Rightarrow \\ f_{ct} = 0.56 \times \sqrt{25} \approx 2.8 \text{ MPa} .$$

Estimated Range of Tensile Strength: 2.6 MPa to 2.8 MPa, but 2.8 was used.

The flexural strength, also known as modulus of rupture, is generally higher than the direct tensile strength and is calculated using:

$$\text{ACI 318 Formula: } f_r = 0.62 \times \sqrt{f'_c} : f_r = 0.62 \times \sqrt{25} \approx 3.1 \text{ MPa}$$

$$\text{IS 456:2000: } f_{cr} = 0.7 \times \sqrt{f_{ck}} = 0.7 \times \sqrt{25} = 3.5 \text{ MPa}$$

Estimated Range of Flexural Strength: 3.1 MPa to 3.5 MPa. Suitable water absorption is 8% while slump is 125 mm. These are used to assign different weights to emphasize structural strength: Compressive Strength: 30%, Flexural Strength: 20%, Tensile Strength: 20%, Water Absorption: 15%, Slump: 15%. Each metric was normalized as in Equation (1) to Equation (4):

$$S = \min \left(1.0, \frac{\text{Value}}{\text{Target}} \right) \quad (1)$$

For water absorption:

$$S = \min \left(1.0, \frac{\text{target}}{\text{Value}} \right) \quad (2)$$

For slump

$$S = \max \left(0, 1 - \frac{\text{abs}(\text{value}-\text{target})}{\text{target}} \right) \quad (3)$$

Then the Performance Index (PI) was computed as:

$$PI = 0.30S_c + 0.20S_f + 0.20S_t + 0.15S_w + 0.15S_s \quad (4)$$

Equation (4) is used to compute the results presented in **Table 11**.

Table 12 presents the results of the performance index (PI) analysis and corresponding mix designs using varying PPW and CIW contents. L_2 (2.25% PPW, 2.5% CIW) achieved the highest PI, demonstrating a strong balance in compressive, flexural, and tensile strength, low water absorption, and ideal slump. This optimal mix meets structural and durability requirements for culvert construction while promoting sustainability. The synergy between PPW and CIW enhances microstructure and strength. In contrast, higher replacement levels (such as, L_{13})

reduced performance. Thus, moderate substitution rates, as seen in L₂, offer the best technical and environmental outcomes for culvert applications.

Table 12. Performance Index for the mix design in **Table 11**.

Mix	Compressive (MPa)	Flexural (MPa)	Tensile (MPa)	Water Absorption (%)	Slump (mm)	PI
L_2	12.592	2.413	2.86	8.504	127.67	0.777
L_1	13.613	2.508	2.986	8.634	142.58	0.775
L_3	11.841	2.34	2.765	7.998	123.88	0.772
L_8	11.545	2.31	2.726	8.308	124.78	0.759
L_4	11.575	2.313	2.73	6.721	111.25	0.750
L_10	10.885	2.243	2.64	6.321	122.35	0.744
L_6	11.627	2.318	2.737	5.014	103.42	0.742
L_12	11.545	2.31	2.726	8.308	108.28	0.740
L_11	11.44	2.3	2.713	6.721	99.77	0.732
L_9	10.275	2.179	2.557	4.969	131.27	0.723
L_5	10.885	2.243	2.64	6.321	95.81	0.712
L_13	10.093	2.16	2.532	5.835	112.54	0.710
L_7	8.083	1.933	2.241	10.868	119.03	0.621

Source: (Researcher, 2025).

4.4. Determination of Optimal Design Mix

The determination of optimal design mix is based on L₂, which had a combination of 2.25% replacement of PPW with sand and 2.5% replacement of CIW with cement. The following batches in **Table 13** based on L₂ were tested.

Table 13. Percentages of sample whose batches were tested for optimal design mix.

Batch	PPW %	Ci
OP_0 (initial)	2.25	2.5
OP_1	2.25	2.45
OP_2	2.25	2.4
OP_3	2.25	2.35
OP_4	2.25	2.3
OP_5	2.25	2.25
OP_6	2.2	2.5
OP_7	2.15	2.5
OP_8	2.3	2.5
OP_9	2.35	2.5
OP_10	2.4	2.5
OP_11	2.2	2.45

Continued

OP_12	2.15	2.4
OP_13	2.1	2.35
OP_14	2.3	2.55
OP_15	2.35	2.6
OP_16	2.4	2.65
OP_17	2.45	2.7

Source: (Researcher, 2025).

The PI was computed for each batch (OP_1 to OP_17) was computed each parameter weight based on its relevance to concrete performance as presented in **Table 14**.

Table 14. Parameter weights for computation of performance indices.

Parameter	Ideal Target	Weight
Compressive Strength	25 MPa	25%
Flexural Strength	3.5 MPa	20%
Tensile Strength	2.8 MPa	20%
Water Absorption	8%	15%
Slump	125 mm	10%
Initial Setting Time	300 minutes	5%
Final Setting Time	600 minutes	5%

Table 15 was computed as follows.

$$\begin{aligned}
 PI_{OP_i} &= 0.25 \left(1 - \frac{25 - 16.078}{25} \right) + 0.2 \left(1 - \frac{3.5 - 2.726}{3.5} \right) + 0.2 \left(1 - \frac{2.8 - 2.478}{2.8} \right) \\
 &+ 0.15 \left(1 - \frac{8 - 6.169}{8} \right) + 0.1 \left(1 - \frac{125 - 117.2443}{125} \right) + 0.05 \left(1 - \frac{300 - 289.653}{300} \right) \quad (5) \\
 &+ 0.05 \left(1 - \frac{600 - 482.756}{600} \right) \\
 &= 0.6770
 \end{aligned}$$

Table 15 indicates that the optimal design mix is OP_7, which has PPW of 2.15% and CIW of 2.5%.

Table 15. Performance index for the batches used for determination of optimal design mix.

Slump	Batch	Days	Compressive	Flexural	Tensile	Water Absorption	Initial Setting	Final Setting	PI	Rank
117.2443	OP_1	28	16.078	2.726	2.478	6.169%	289.653	482.756	0.6770	6
109.9166	OP_2	28	15.073	2.640	2.407	11.739%	294.050	490.083	0.6535	7
105.2393	OP_3	28	14.432	2.583	2.360	9.939%	296.856	494.761	0.6373	9
102.9515	OP_4	28	14.118	2.555	2.337	10.895%	298.229	497.049	0.6296	10

Continued

96.517	OP_5	28	13.236	2.473	2.270	8.068%	302.090	503.483	0.6069	12
83.00462	OP_6	28	11.383	2.294	2.121	8.235%	310.197	516.995	0.5591	15
97.179	OP_7	28	21.554	3.156	2.827	11.634%	301.693	502.821	0.7700	1
88.744	OP_8	28	19.624	3.012	2.710	11.523%	306.754	511.256	0.7288	4
100.335	OP_9	28	21.199	3.130	2.806	11.361%	299.799	499.665	0.7653	2
92.3082	OP_10	28	19.503	3.002	2.703	12.815%	304.615	507.692	0.7290	3
83.76114	OP_11	28	17.697	2.860	2.587	12.964%	309.743	516.239	0.6893	5
75.54927	OP_12	28	15.962	2.716	2.470	9.695%	314.670	524.451	0.6497	8
86.486	OP_13	28	14.047	2.548	2.332	9.744%	308.108	513.514	0.6178	11
81.29684	OP_14	28	13.204	2.470	2.268	9.572%	311.222	518.703	0.5971	13
93.629	OP_15	28	11.958	2.351	2.169	8.874%	303.823	506.371	0.5782	14
85.98582	OP_16	28	10.982	2.253	2.087	11.161%	308.409	514.014	0.5528	16
80.6117	OP_17	28	10.296	2.182	2.027	10.945%	311.633	519.388	0.5342	17

4.5. Discussion

The performance of concrete modified with CIW and PPW is theoretically supported by the principles of pozzolanic activity and microstructural densification. CIW, rich in reactive silica and lime, engages in secondary hydration reactions, forming additional calcium silicate hydrate (C-S-H) gel that enhances strength and reduces porosity. This aligns with the observed improvement in compressive, tensile, and flexural strength at lower CIW replacement levels (2.5% - 2.75%), particularly in mix L₂. Empirical studies on industrial waste utilization confirm that pozzolanic ashes contribute to strength development [6], especially at early and mid-term curing stages, consistent with the 28-day results recorded here.

PPW functioned primarily as a micro-filler and void reducer, supporting theories in sustainable concrete design [16]. In this study, mixes with 2.25% - 2.5% PPW (e.g., L₂ and L₁) demonstrated superior workability and mechanical performance, confirming these findings. However, higher replacement levels (e.g., 3.25% - 3.5%) led to matrix discontinuities, reinforcing findings by [11] [15] [16] that excessive plastic reduces cohesion and compressive strength.

From a sustainability perspective, these results align with the principles of industrial ecology and circular economy. The reuse of CIW and PPW not only reduces dependency on virgin materials but also addresses waste management challenges in Kenya. Compared to traditional concrete, the selected mix (L₂) achieved a 44% reduction in cement and sand use without compromising critical performance indicators, a compelling case for eco-efficient infrastructure.

5. Conclusion and Recommendations

5.1. Conclusion

This study demonstrates that partial substitution of cement with CIW and sand

with PPW offers a viable pathway toward sustainable concrete mix designs, particularly for culvert construction. Among the thirteen tested mixes, L₂ (2.5% PPW and 2.25% CIW) achieved the best overall performance in compressive strength, flexural and tensile capacity, water absorption, and slump. These results are theoretically supported by the pozzolanic reactivity of CIW and the particle packing enhancement provided by PPW. While CIW contributed significantly to strength at low dosages, PPW improved workability and water resistance, reinforcing the benefits of combined use. However, the study was limited to laboratory-scale tests, with durability aspects such as chloride ingress, sulphate attack, freeze-thaw resistance, and long-term field performance not evaluated. In addition, the target values and weight factors used in the performance index were assigned based on engineering judgment and relevant design guidelines rather than empirical derivation or formal validation.

5.2. Recommendations

The L₂ combination should be adopted in pilot-scale culvert construction to validate field performance under dynamic and environmental loads. Future studies should assess chloride penetration, sulphate attack, and freeze-thaw resistance to complement water absorption data. Further research should assess applicability in other elements such as pavements, low-load-bearing walls, and precast blocks.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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