



Investigation of Concrete Compressive Strength with Partial Cement Replacement Using Timber Ash

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Abstract

The increasing demand for sustainable construction materials has intensified research into biomass-derived supplementary cementitious materials (SCMs) capable of reducing ordinary Portland cement (OPC) consumption (Andrew, 2018; Scrivener et al., 2018). This study experimentally investigates the influence of timber ash incorporation on the compressive strength performance of concrete. Concrete cubes (150 mm × 150 mm × 150 mm) were produced using a nominal mix ratio of 1:2:4, with timber ash replacing cement at 0%, 10%, 20%, 30%, 35%, and 40% by weight. Specimens were cured for 28 days and subjected to compressive strength testing. The control concrete achieved the highest compressive strength of 23.96 MPa, while replacement levels of 10%, 20%, 30%, 35%, and 40% produced 13.09 MPa, 14.13 MPa, 9.02 MPa, approximately 8.45 MPa, and 8.59 MPa, respectively. The findings indicate that timber ash incorporation reduces compressive strength at the investigated replacement levels, although moderate replacement around 20% demonstrated better performance compared with higher substitution levels. The results suggest that timber ash has potential as a sustainable cement replacement material for applications where moderate strength requirements are acceptable, while further chemical activation, particle size optimisation, and durability studies are required before structural adoption.

Keywords: Timber ash; biomass ash; supplementary cementitious material; concrete; cement replacement; compressive strength; sustainable construction.

1 Introduction

Concrete remains the most extensively used construction material worldwide because of its versatility, availability, and mechanical performance (Mehta & Monteiro, 2014). However, the manufacture of ordinary Portland cement is associated with significant environmental impacts, particularly carbon dioxide emissions arising from limestone calcination and energy consumption (Andrew, 2018). The cement industry contributes substantially to global anthropogenic CO₂ emissions, creating a need for alternative binders and supplementary cementitious materials (Scrivener et al., 2018; Juenger et al., 2011).

The utilisation of agricultural and biomass ashes in cement-based materials has received considerable research attention because these materials contain reactive silica, alumina, and calcium compounds capable of participating in pozzolanic reactions (Siddique, 2014). Wood ash is generated from the combustion of wood and wood-derived materials, with approximately 6–10% ash by weight produced from wood combustion (Cheah & Ramli, 2011). Previous studies have demonstrated that ashes from rice husk, palm oil fuel, wood, and other biomass sources can improve sustainability and sometimes enhance concrete performance when appropriately processed (Juenger et al., 2011; Nascimento et al., 2023).

Timber ash is generated from combustion processes involving wood and timber products. Although traditionally treated as waste, its mineral composition may allow its reuse as a partial cement replacement material. Research indicates that wood ash is a promising and developable material, with optimal replacement levels typically ranging between 10% and 20% depending on chemical composition and processing conditions (Tekere Ercan et al., 2023). However, a major limitation associated with the use of wood ash is the variability of its properties. The suitability of wood ash as a partial replacement for ordinary Portland cement is strongly influenced by its physical and chemical characteristics, which are affected by factors such as tree species, geographical origin, combustion conditions, and ash collection methods (Nascimento et al., 2023; Martínez-García et al., 2022).

Recent advances in concrete mixture design have employed statistical optimisation techniques to enhance performance prediction and material efficiency (Agunwamba et al., 2024). The application of Scheffe's Simplex Lattice Model has demonstrated efficacy in improving performance indicators such as compressive strength and durability, offering a systematic approach that fosters a nuanced understanding of concrete components' relationships (Agunwamba et al., 2024). Furthermore, the Box–Behnken model has been successfully applied for prediction and optimisation of compressive strength in cement concrete, providing robust statistical frameworks for mixture design (Tiza et al., 2025). These statistical methods represent a paradigm shift from empirical methods, paving the way for tailored material properties and enhanced sustainability in construction (Agunwamba et al., 2024).

The incorporation of reclaimed materials in concrete has also been extensively reviewed, with studies demonstrating that reclaimed asphalt pavement can be utilised as coarse aggregates in cement concrete while maintaining mechanical properties comparable to traditional concrete (Tiza et al., 2024). These findings underscore the potential for waste-derived materials to contribute to sustainable construction practices when appropriately characterised and optimised.

This research evaluates the influence of timber ash replacement on the 28-day compressive strength of concrete. The objective is to determine the mechanical response of concrete containing different timber ash replacement percentages and identify feasible substitution levels for sustainable construction applications.

2 Materials and Methods

2.1 Materials

Table 1 presents the physical properties of the fine and coarse aggregates used in this study. The fine aggregate was natural river sand classified as Zone II medium-grained sand, with a maximum particle size of 4.75 mm, specific gravity of 2.60–2.65, bulk density of 1600–1700 kg/m³, fineness modulus of 2.50–2.80, water absorption of 1.0–2.0%, and silt content below 5%, indicating suitability for concrete production (Neville, 2011; Mehta & Monteiro, 2014). The coarse aggregate was crushed granite with a nominal maximum size of 20 mm, specific gravity of 2.65–2.75, bulk density of 1450–1600 kg/m³, water absorption of 0.5–1.5%, and angular rough-textured particles classified as normal weight aggregate. These aggregate characteristics are consistent with those reported in previous studies on sustainable concrete production and are appropriate for the nominal 1:2:4 mix design adopted in this investigation (Tiza et al., 2024; Agunwamba et al., 2024).

Table 1. Physical properties of aggregates

Property	Fine Aggregate (Sand)	Coarse Aggregate (Granite)
Material Type	Natural River Sand	Crushed Granite
Maximum Size	4.75 mm	20 mm
Specific Gravity	2.60–2.65	2.65–2.75
Bulk Density	1600–1700 kg/m ³	1450–1600 kg/m ³
Fineness Modulus	2.50–2.80	—
Water Absorption	1.0–2.0%	0.5–1.5%

Property	Fine Aggregate (Sand)	Coarse Aggregate (Granite)
Silt Content	<5%	—
Particle Shape	Rounded/Sub-angular	Angular
Classification	Zone II Sand	Normal Weight Aggregate

2.2 Concrete Mix Design and Specimen Preparation

Table 2 summarises the experimental programme adopted in this study. Concrete was produced using a nominal mix ratio of 1:2:4 (cement:fine aggregate: coarse aggregate), with timber ash replacing cement at 0%, 10%, 20%, 30%, 35%, and 40% by weight. Concrete cubes measuring 150 mm × 150 mm × 150 mm were cast and cured for 28 days before compressive strength testing, with a loaded area of 22,500 mm² and strength expressed in MPa (N/mm²). This experimental design is consistent with established protocols for evaluating the mechanical performance of concrete containing supplementary cementitious materials and aligns with procedures reported in previous studies on sustainable concrete production (Tiza et al., 2024; Agunwamba et al., 2024; Tiza et al., 2025).

Table 2. Experimental programme

Parameter	Description
Replacement Material	Timber Ash
Replacement Levels	0%, 10%, 20%, 30%, 35%, 40%
Cement Type	Ordinary Portland Cement
Mix Ratio	1:2:4
Specimen Type	Concrete Cube
Dimension	150 mm × 150 mm × 150 mm
Loaded Area	22,500 mm ²
Curing Period	28 days
Test	Compressive Strength Test
Strength Unit	MPa (N/mm ²)

2.3 Compressive Strength Testing

The compressive strength was determined using an axial compression testing machine in accordance with standard procedures for concrete mechanical performance evaluation. Strength was calculated as the ratio of maximum crushing load to loaded area, expressed as Compressive Strength (MPa) = Maximum Crushing Load (N) / Loaded Area (mm²), with a loaded area of 22,500 mm² for the 150 mm cube specimens. This testing protocol aligns with established procedures for evaluating concrete mechanical performance in sustainable construction research and has been widely adopted in studies investigating waste-derived supplementary cementitious materials (Tiza et al., 2024; Agunwamba et al., 2024; Tiza et al., 2025).

3 Results and Discussion

3.1 Compressive Strength Performance

Figure 1 shows that increasing timber ash replacement generally reduced the 28-day compressive strength of concrete compared with the control mix. The control specimen recorded the highest strength of 23.96 MPa, while the 20% timber ash replacement (WA20) achieved the best performance among the ash-based mixes at 14.13 MPa. Further increases in timber ash content (30–40%) resulted in significant strength reduction due to reduced cement availability and lower formation of strength-enhancing hydration products, while **Figure 1** illustrates the strength development pattern across replacement levels.

Table 3. Compressive strength results at 28 days

Mix ID	Timber Ash (%)	Load (kN)	Strength (MPa)	Relative to Control (%)
Control	0	539	23.96	100.0
WA10	10	295	13.09	54.6
WA20	20	318	14.13	59.0
WA30	30	203	9.02	37.6
WA35	35	~190	~8.45	35.3
WA40	40	193	8.59	35.9

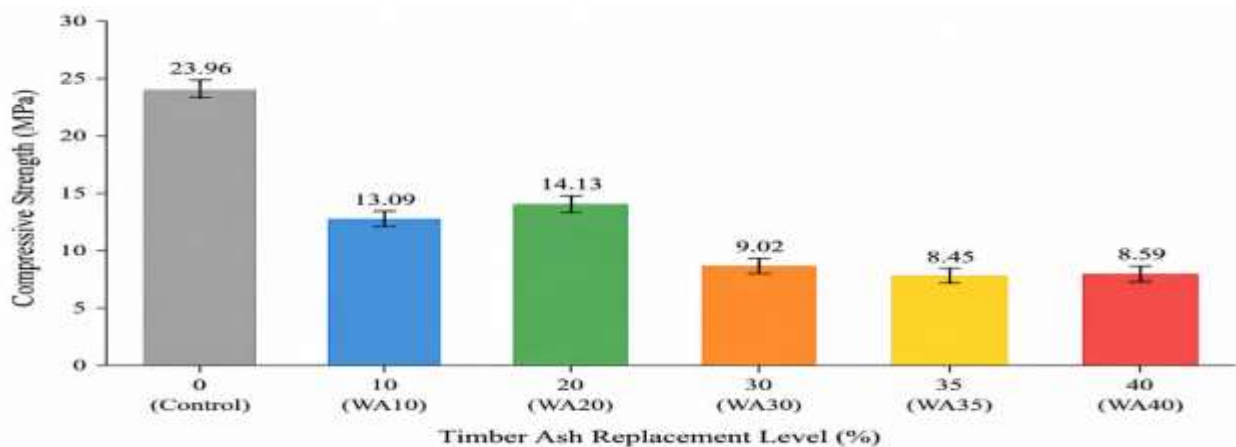


Figure 1. Compressive strength versus timber ash replacement level at 28 days.

The control concrete achieved 23.96 MPa at 28 days from a crushing load of 539 kN. Introducing timber ash reduced strength across all replacement levels. The 10% replacement mixture produced 13.09 MPa, representing a considerable reduction compared with the control. The 20% replacement level improved slightly to 14.13 MPa, suggesting that an optimum interaction between ash particles and cement hydration may exist at intermediate replacement levels. Higher replacement percentages resulted in further strength reductions. The 30%, 35%, and 40% mixes achieved 9.02 MPa, approximately 8.45 MPa, and 8.59 MPa, respectively. This behaviour may be attributed to dilution effects, reduced cement clinker availability, and insufficient reactive silica contribution from untreated timber ash (Cheah & Ramli, 2011; Teker Ercan et al., 2023).

3.2 Discussion of Strength Reduction Mechanisms

The observed strength reduction with increasing timber ash content is consistent with findings in the literature. Studies have shown that while increased wood ash content in concrete and mortars can have negative effects on strength and durability, it remains a promising and developable material, with an optimal replacement level of 10–20% depending on chemical composition (Tekere Ercan et al., 2023; Martínez-García et al., 2022). The reduction in compressive strength at higher replacement levels can be attributed to several interacting mechanisms. Wood ash typically contains high carbon content, which may lead to inconsistent mechanical and durability performance, limiting its application in concrete (Cheah & Ramli, 2011). The unburned carbon particles possess lower stiffness than cement particles and impair workability, resulting in a less dense microstructure. Furthermore, wood ash particles often exhibit internal pores and microcracks, which reduce particle density and strength. Inclusion of wood ash as partial replacement of cement adversely affects the slump of the concrete, with water absorption capacity increasing with higher wood ash content (Cheah & Ramli, 2011; Siddique, 2014).

A recent review of wood ash applications concluded that the majority of researchers suggest a 10% optimum substitution of wood ash in concrete (Martínez-García et al., 2022). The 20% replacement level identified in this study falls within the broader range reported in the literature. Some studies have found that 5% replacement yielded comparable performance to control mixtures, with 32.49 N/mm² versus 32.51 N/mm² (Oria-USifo, 2026). Research using a 1:1½:3 mix ratio found that compressive strength was maximum at 10% wood ash level (15.51 N/mm²) while control was 19.08 N/mm² at 28 days (Afolabi & Salako, 2025). These findings collectively indicate that optimal replacement levels are highly dependent on ash source, combustion conditions, and concrete mix design. Statistical optimisation approaches have been successfully applied to predict and enhance concrete compressive strength (Agunwamba et al., 2024; Tiza et al., 2025). The Scheffe's Simplex Lattice Model has demonstrated efficacy in optimising cement concrete mixtures, with comparative analyses showing distinct advantages over traditional optimisation techniques (Agunwamba et al., 2024). The Box–Behnken model has also been employed for prediction and optimisation of compressive strength, offering robust frameworks for mixture design in sustainable construction applications (Tiza et al., 2025). These methods provide valuable tools for future research aimed at optimising timber ash replacement levels.

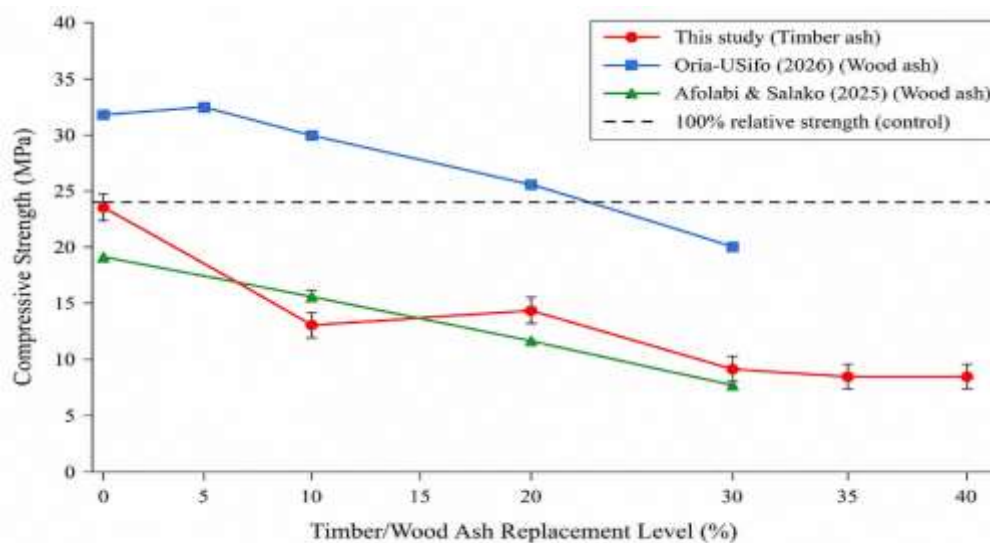


Figure 2. Suggested graphical comparison of compressive strength development across replacement levels.

The variability in reported optima reflects the diverse sources, combustion conditions, and processing methods of wood ash. The chemical composition of wood ash varies significantly depending on tree species, combustion temperature, and collection methods, with SiO₂ content ranging from approximately 8% to over 50% in reported literature (Nascimento et al., 2023). When the combined content of SiO₂, Al₂O₃, and Fe₂O₃ exceeds 70%, wood ash can satisfy the pozzolanic criteria of ASTM C618, though many wood ashes fall below this threshold (Tekere Ercan et al., 2023). The application of statistical modelling techniques for concrete mixture optimisation, such as those employed for reclaimed asphalt pavement concrete (Tiza et al., 2024), could provide valuable insights for optimising timber ash replacement levels in future studies.

3.3 Sustainability Considerations

Despite reduced mechanical performance, timber ash utilisation provides environmental benefits through waste valorisation and reduced dependency on Portland cement. The disposal of high volumes of organic waste is a global issue, and diverting wood ash from landfills contributes to circular economy practices (Martínez-García et al., 2022; Tiza et al., 2024).

Life cycle assessment studies have demonstrated that the use of wood ash in concrete to replace Portland cement shows the greatest potential environmental benefits among beneficial use options (da Costa et al., 2022). A screening-level LCA comparing management options concluded that all beneficial use options showed lower environmental indicator scores than those associated with landfilling, with the use of wood ash in concrete showing the most favourable outcomes (Tosti et al., 2020). For wood ash valorisation in construction materials, the environmental burdens are negligible compared to the effects avoided, with the substitution of conventional cement production being the primary hotspot for avoided impacts (da Costa et al., 2022). Figure 3 illustrates the valorisation pathway of timber ash, showing how timber waste can be transformed into a useful construction material. The process begins with timber waste generation, followed by combustion to produce ash, which can be processed through methods such as grinding, washing, or activation before being incorporated into concrete as a partial cement replacement. This approach promotes waste diversion from landfills, reduces cement consumption, and contributes to lower environmental impacts associated with cement production.

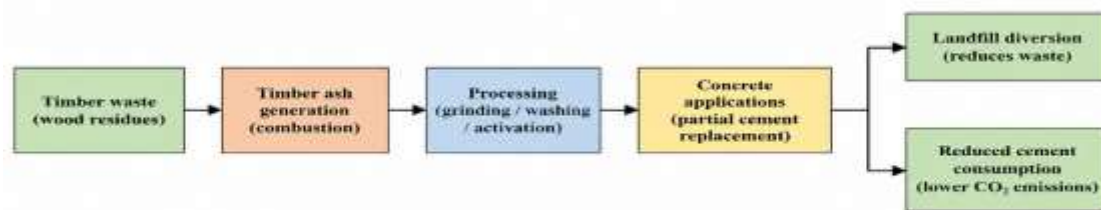


Figure 3. Suggested schematic of timber ash valorisation pathways.

However, a consequential life cycle assessment approach is necessary to evaluate the broader environmental implications, as it expands the system boundaries to include market changes induced by the modification in the product system (da Costa et al., 2022). The modelling approach can affect the selection of the best alternative, as demonstrated in comparative LCA studies where consequential and attributional approaches yielded contrasting conclusions regarding substitution benefits. Sustainable construction requires balancing environmental advantages with engineering performance (Tiza, 2022; Tiza, 2023). Future improvement strategies may include ash grinding, chemical activation, controlled combustion, and combination with other supplementary cementitious materials (Tekir Ercan et al., 2023; Agunwamba et al., 2024).

3.4 Practical Implications

The results indicate that untreated timber ash has limited suitability as a direct high-volume cement replacement material for structural concrete. However, its application in low-strength concrete, non-load-bearing components, and environmentally oriented construction products may be possible. Previous studies have demonstrated that wood ash can effectively replace up to 5% of cement in structural concrete applications without significant compromise in strength or durability (Oria-USifo, 2026). Beyond this level, the decrease in strength suggests that higher replacements are more suitable for non-structural uses, such as blocks or pavements, where lower strength

requirements apply (Oria-USifo, 2026). Other research concluded that the optimum replacement level is 15% for applications such as ramps, floor slabs, and other structural works of low compressive strength requirement (Shehu, 2025). The use of statistical optimisation models, such as Scheffe's Simplex Lattice Model and Box–Behnken design, offers promising avenues for enhancing the performance of timber ash concrete through systematic mixture design and optimisation (Agunwamba et al., 2024; Tiza et al., 2025). These approaches have been successfully applied to other sustainable concrete materials, including reclaimed asphalt pavement concrete (Tiza et al., 2024), demonstrating their versatility and effectiveness in advancing sustainable construction practices.

4 Conclusion

This study investigated the influence of timber ash replacement on the 28-day compressive strength of concrete. The following conclusions are drawn:

1. The control mixture recorded the highest strength of 23.96 MPa, while all timber ash mixtures showed reduced strength. Among the replacement levels studied, 20% timber ash replacement provided the highest strength among ash-containing mixes at 14.13 MPa.
2. Increasing replacement beyond 20% significantly reduced strength, with 30%, 35%, and 40% replacements achieving 9.02 MPa, 8.45 MPa, and 8.59 MPa, respectively.
3. The strength reduction is attributed to cement dilution, reduced clinker availability, high unburned carbon content, and insufficient pozzolanic contribution from untreated timber ash (Cheah & Ramli, 2011; Teker Ercan et al., 2023).
4. Untreated timber ash has limited suitability as a direct high-volume cement replacement material for structural concrete. However, its application in low-strength concrete, non-load-bearing components, and environmentally oriented construction products may be possible (Oria-USifo, 2026; Martínez-García et al., 2022).
5. Additional investigations involving chemical composition analysis, durability testing, and optimisation techniques—including statistical modelling approaches such as Scheffe's Simplex Lattice Model and Box–Behnken design—are recommended before structural adoption (Teker Ercan et al., 2023; Agunwamba et al., 2024; Tiza et al., 2025).

5 Recommendations for Future Research

Future studies should investigate:

1. **Chemical composition and pozzolanic activity** of timber ash, including XRF and XRD analysis to determine reactive silica, alumina, and calcium content (Teker Ercan et al., 2023).
2. **Influence of ash fineness and grinding duration** on reactivity and strength development, as mechanical activation may enhance pozzolanic performance (Martínez-García et al., 2022).
3. **Durability properties** including water absorption, permeability, and resistance to chemical attack, which are critical for service-life prediction (Tiza et al., 2024).
4. **Statistical optimisation** using Scheffe's Simplex Lattice Model and Box–Behnken design to predict and optimise compressive strength of timber ash concrete (Agunwamba et al., 2024; Tiza et al., 2025).
5. **Life-cycle assessment** comparing timber ash concrete with conventional concrete using consequential LCA approaches to evaluate net environmental benefits (da Costa et al., 2022; Tosti et al., 2020).
6. **Ternary blend development** combining timber ash with more reactive SCMs such as metakaolin or silica fume to enhance overall performance (Nascimento et al., 2023).
7. **Long-term performance studies** to evaluate the durability and mechanical properties of timber ash concrete under various environmental exposure conditions (Tiza et al., 2024).

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