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Experimental Study on Characteristics and Strength Properties of Cement Mortar Using Indian Almond Leaves and Banana Trunks

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Abstract: Growing awareness of environmental sustainability has pushed the construction sector to look for viable substitutes that can diminish reliance on conventional cement binders. Organic residues from agriculture — including banana trunk fibre and Indian almond leaf material — accumulate in substantial volumes and are frequently disposed of by open burning or land dumping, both of which degrade air and soil quality. The present investigation converted these residues into ash through thermally controlled combustion carried out at 500–600°C, and the resulting powders were characterised mineralogically via X-ray diffraction (XRD) analysis. Mortar batches were prepared at a 1:3 binder-to-sand ratio, wherein the combined ash — comprising 40% banana trunk ash and 60% Indian almond leaf ash — replaced ordinary portland cement at dosages of 0%, 5%, 10%, and 15% by mass. Mechanical performance was assessed through uniaxial compression tests after hydration periods of 7, 14, and 28 days. Observations revealed a consistent strength decline with higher ash loading; nonetheless, the 5% substitution batch delivered compressive values that closely approached those of the plain cement reference mix. These outcomes affirm that thermally processed agricultural residues possess adequate cementitious reactivity for deployment as eco-conscious supplementary binders in mortar-based construction.
Keywords: Banana Trunk Ash, Indian Almond Leaf Ash, Sustainable Construction, Cement Mortar, XRD Analysis, Compressive Strength.

1. Introduction

Modern infrastructure development leans heavily on cementitious composites owing to their versatility, load-bearing capacity, and wide availability of raw materials. As urbanisation accelerates globally, demand for binding agents — particularly ordinary portland cement — has scaled up at an extraordinary pace. However, the industrial production of cement is energy-intensive and produces substantial quantities of carbon dioxide and other pollutants during high-temperature calcination of limestone. These emissions are now recognised as a notable contributor to anthropogenic climate change, prompting policy-makers and researchers alike to advocate for greener alternatives in the built environment.

Supplementary cementitious materials (SCMs) represent one of the most promising avenues for curbing cement consumption without compromising structural integrity. Agricultural residues, when subjected to controlled thermal treatment, can yield finely divided powders with latent hydraulic or pozzolanic properties. Such pozzolans react chemically with portlandite — the calcium hydroxide by-product of cement hydration — to generate additional calcium silicate hydrate (C-S-H) gel, strengthening the binder matrix over time.

Tropical agricultural systems generate considerable quantities of banana trunk fibre and Indian almond leaf biomass each growing season. After fruit harvest, the banana pseudostem is typically discarded at the farm boundary, while deciduous Indian almond trees deposit a large volume of leaf litter annually. Both materials, when left untreated, undergo slow decomposition or are incinerated, contributing to localised air pollution. Converting them into ash through regulated combustion transforms a disposal problem into a functional construction input.

Prior literature has explored the pozzolanic utility of various crop residues — notably rice husk ash, bagasse ash, and corn cob ash — as partial replacements for portland cement. Collectively, these investigations affirm that low-level substitution (typically up to 10–15% by mass) preserves compressive performance while reducing the cement fraction meaningfully. However, relatively little attention has been directed toward the specific pairing of banana trunk ash with Indian almond leaf ash in a combined binary blend, leaving a gap in understanding the synergistic potential of these two regionally available materials.

This study addresses that gap by systematically evaluating how varying proportions of a blended ash mixture — formulated at a banana trunk to Indian almond leaf ratio of 40:60 by mass — influence the workability and mechanical strength of standard 1:3 cement mortar. Four replacement levels (0%, 5%, 10%, and 15%) were investigated, with strength measured at 7-, 14-, and 28-day intervals to capture both early-age and later-age hydration behaviour.

Beyond mechanical considerations, the research also weighs environmental and economic implications. By diverting agricultural waste from open combustion sites and channelling it into the construction supply chain, the proposed approach simultaneously reduces landfill pressure, curtails uncontrolled burning emissions, and lowers material input costs — outcomes that are particularly valuable in rural construction contexts where affordability and local sourcing are paramount. The following sections detail the materials selected, the specimen fabrication procedure, experimental results, and the broader implications of the findings for sustainable building practice.

2. Literature Survey

A growing body of scientific work examines how thermally processed crop residues can partially substitute for cement in concrete and mortar, aligning construction practice with circular-economy principles. Olaiya, Lawan, and Olonade (2025) demonstrated that ash derived from banana leaves possesses adequate binding capability to function as a partial cement replacement, with specimens reaching acceptable compressive benchmarks at moderate substitution rates while simultaneously contributing to waste-stream reduction [1]. Their work underscored the dual environmental benefit of reducing both cement demand and open-burning practices.

Mim, Meraz, and Islam (2021) extended this investigation to self-compacting concrete formulations, finding that banana leaf ash could substitute up to 20% of the cement content without degrading 28-day strength below conventional thresholds [3]. Notably, fresh-state workability improved at intermediate replacement levels, attributing this to the fineness and morphology of the ash particles modifying inter-particle friction.

Shah and Ali (2023) adopted a hybrid approach, incorporating both banana fibre and banana leaf ash into concrete mixtures. Their findings indicated that the fibrous component enhanced post-crack tensile resistance and mitigated micro-cracking, while the ash fraction modestly reduced compressive output — an acceptable trade-off given the overall improvement in toughness and durability-related behaviour [2].

Standardised testing frameworks guiding cement and mortar strength evaluation include ASTM C109 [4] and IS 4031 [5], both of which were considered in designing the present experimental protocol. Structural concrete mix proportioning follows IS 456 [6], which establishes quality thresholds relevant to comparing ash-modified mortars against conventional performance baselines. Foundational principles governing hydration kinetics, pore structure evolution, and strength development in cementitious systems are comprehensively treated in Mehta and Monteiro (2014) [7] and Neville (2011) [8], providing the theoretical backdrop for interpreting the observed strength trends.

A synthesis of the available literature reveals that while banana leaf ash has received reasonable investigative coverage, the use of banana trunk ash — a physically distinct material with a different fibre and mineral content — remains sparsely documented. Indian almond leaf ash, despite its regional abundance, has received even less attention in experimental studies. The combined utilisation of these two ashes as a blended supplementary material therefore constitutes a novel contribution that this investigation seeks to make.

3. Materials and Experimental Methodology

3.1 Raw Materials

The following constituents were employed in preparing all mortar batches: Ordinary Portland Cement (OPC) conforming to IS 12269, natural river sand procured from a local riverbed source, ash derived from banana trunk biomass, ash derived from Indian almond leaf biomass, and clean potable water satisfying standard quality criteria. The fine aggregate was verified to be well-graded, free of clay lumps, and devoid of deleterious organic matter prior to use. Both ash types were sourced from agricultural areas situated in close proximity to the institution, ensuring regional representativeness and logistical feasibility.

3.2 Production of Banana Trunk Ash

Freshly harvested banana pseudostems were collected from cultivated plots in the surrounding locality. Adhering mud and surface debris were removed through thorough washing under running water. The trunks were sectioned into manageable lengths and spread out under direct sunlight to reduce their inherent moisture to an acceptably low level over several consecutive days. Once sufficiently dried, the material was subjected to controlled thermal combustion in a furnace operating within the 500–600°C range, a temperature window known to maximise silica reactivity while avoiding sintering effects that would coarsen the microstructure. The cooled ash was mechanically milled and subsequently screened through a 90 μm test sieve to isolate the fraction with surface area suitable for pozzolanic participation. Airtight storage vessels were used to protect the classified ash from atmospheric moisture until it was incorporated into mortar batches.

3.2.1 Production of Indian Almond Leaf Ash

Mature Indian almond leaves were gathered from ornamental and cultivated trees in the college vicinity. After removal of visible dust and surface contamination through gentle washing, the leaves were sun-dried to a constant mass. Combustion was performed in a temperature-controlled muffle furnace, with careful regulation of airflow to ensure complete oxidation of organic matter. Post-combustion, the residual ash was allowed to cool passively before being pulverised in a mechanical grinder. The resulting powder was passed through a 90 µm sieve to obtain a particle fraction compatible with the mortar matrix, and stored under moisture-controlled conditions pending use.

3.2.2 Preparation of the Blended Ash Mixture

Individual ash stocks were combined in a mass ratio of 40% banana trunk ash to 60% Indian almond leaf ash. This proportion was selected on the basis of preliminary characterisation indicating complementary oxide compositions between the two ashes. Thorough mechanical blending was performed to achieve a homogenous mixture, minimising compositional variability across mortar batches. The four cement replacement levels investigated were:

- M0 — 0% ash (control batch)
- M5 — 5% blended ash substitution
- M10 — 10% blended ash substitution
- M15 — 15% blended ash substitution

3.3 Mortar Mix Design and Specimen Preparation

A fixed binder-to-sand ratio of 1:3 by mass was maintained across all batches — a proportion standard to masonry mortar applications. For experimental batches, the designated percentage of cement was displaced by an equivalent mass of the blended ash mixture. Dry constituents were homogenised before incremental water addition, and mixing continued until a uniform, cohesive paste was achieved. Cube specimens of standard dimensions were cast and demoulded after 24 hours, then submerged in a water-curing tank until the respective test ages. Table 1 summarises the compositional details of each batch.

Table 1: Batch Composition of Mortar Specimens

Mix ID	Cement Content (%)	Blended Ash (%)	Binder: Sand Ratio
M0	100	0	1:3
M5	95	5	1:3
M10	90	10	1:3
M15	85	15	1:3

4. Experimental Results and Discussion

4.1 Compressive Strength Outcomes

Uniaxial compression testing was carried out at 7, 14, and 28 days post-casting for all mortar variants. The resulting strength data are consolidated in Table 2 below.

Table 2: Compressive Strength (MPa) of Mortar Batches at Various Curing Ages

Mix ID	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
M0	18.52	24.81	29.26
M5	17.63	23.67	27.58
M10	16.42	21.84	25.92
M15	14.38	19.26	22.45

The data confirm a consistent upward strength progression across all curing intervals for every formulation tested. This behaviour is a hallmark of ordinary cementitious systems, where extended hydration deepens the network of calcium silicate hydrate gel filling inter-particle voids and refining pore structure. The reference control batch (M0) recorded peak values of 18.52, 24.81, and 29.26 MPa at 7, 14, and 28 days respectively — the highest outputs across all test ages, as expected given its undiluted cement content.

4.2 Effect of Ash Loading on Mechanical Performance

Progressive substitution of cement with the blended ash mixture resulted in a systematic but moderate decline in compressive strength. At 5% replacement, the 28-day value of 27.58 MPa represented a reduction of roughly 5.7% relative to the control — a margin that falls well within acceptable limits for non-load-bearing construction. The comparatively modest drop at this dosage suggests that the ash particles engage meaningfully with the hydrating cement matrix, likely through secondary pozzolanic reaction with liberated portlandite.

At 10% and 15% replacement levels, the strength reduction became progressively more pronounced — 25.92 MPa and 22.45 MPa respectively at 28 days. This trend is attributable to two concurrent effects: a reduction in the volume of reactive clinite phases available for primary hydration, and the relatively slower kinetics of pozzolanic reaction in ash particles compared with the rapid hydration of alite-rich OPC. The lower reactivity at elevated ash contents delays gel formation, resulting in a comparatively open pore network at early ages.

4.3 Strength Evolution Over the Curing Period

All batches exhibited substantial strength gains between the 7-day and 28-day test ages. This multi-stage development reflects the sequential nature of hydration: early-strength is dominated by the rapid hydration of tricalcium silicate (C_3S), while later-age gains draw increasingly from the slower hydration of dicalcium silicate (C_2S) and, in ash-modified batches, from the pozzolanic consumption of portlandite. The incremental strength contribution from the blended ash becomes more perceptible at 28 days, particularly for M5 and M10, consistent with the diffusion-controlled nature of pozzolanic reactions that require prolonged contact time between siliceous particles and the pore solution.

4.4 Identifying the Optimum Substitution Level

Evaluating the full dataset collectively, the 5% substitution batch presents the most favourable balance between mechanical output and the environmental benefit of ash incorporation. Its 28-day compressive strength remained within 6% of the plain cement reference, implying that the replacement exerts negligible structural penalty at this dosage. Higher dosages — 10% and 15% — are more suitable for applications where structural loading demands are secondary, such as interior plastering, non-structural partition walls, or rural masonry works where economy and ecological footprint take precedence over peak strength.

4.5 Comparative Evaluation Against Conventional Mortar

When benchmarked against the control mix, all ash-modified batches maintained compressive outputs that surpass the minimum 28-day threshold of 17.5 MPa commonly specified for general masonry mortar under Indian standards, with even the highest-replacement batch (M15) achieving 22.45 MPa. This confirms that the proposed blended ash remains a technically viable binder constituent even at its highest investigated dosage. The marginal strength sacrifice at 5% in particular leaves substantial headroom before any serviceability limit is approached.

5. Practical Deployment Scenarios

The formulations developed in this study lend themselves to a range of real-world construction contexts, particularly where sustainability and cost-efficiency are prioritised. Potential application domains include:

- Bedding and jointing mortar in brick and hollow-block masonry walls
- Internal and external plaster finishing coats in residential construction
- Non-structural concrete fillers, kerb infills, and garden-path elements
- Affordable rural housing schemes where locally sourced materials are preferred
- Green building certification programmes requiring demonstration of sustainable material sourcing

The dual benefit of reducing cement procurement costs and avoiding disposal expenditures makes the blended ash approach economically attractive for small contractors and self-build projects in agricultural zones.

6. Environmental and Economic Considerations

Cement manufacturing is an energy-intensive activity that contributes approximately 5–8% of global anthropogenic CO_2 emissions, primarily through limestone decarbonation and kiln fuel combustion. Introducing a 5–15% ash substitution fraction directly reduces the clinker-to-product ratio, translating into a proportionate reduction in embedded carbon per tonne of mortar produced.

From a waste management standpoint, banana pseudostems and Indian almond leaf biomass are currently treated as nuisance by-products in most tropical agricultural settings. Open-field burning, which is the dominant disposal route, releases particulate matter, carbon monoxide, and volatile organic compounds into the local atmosphere. Redirecting this material into a productive industrial application eliminates the associated emissions and simultaneously generates an economic return on what would otherwise be a liability to the farmer.

Raw material costs for the ash are substantially lower than those of commercially produced supplementary cementitious materials such as silica fume or metakaolin, which require energy-intensive manufacturing processes. This cost advantage, combined with the transportation savings from using locally sourced inputs, enhances the overall lifecycle economics of construction projects in peri-urban and rural settings.

7. Study Limitations and Directions for Future Work

The current investigation was deliberately focused on mechanical performance characterisation, and several complementary properties remain to be quantified. Durability-related indices — including water absorption coefficient, chloride penetration resistance, and sulphate attack susceptibility — were outside the scope of the present work but are important for projecting long-term field performance, especially in coastal or chemically aggressive environments. Additionally, the study was confined to mortar specimens; extending the work to concrete beams and columns would provide the scaling data needed for structural design applications.

Longer curing durations (90 days and beyond) would clarify the degree to which the pozzolanic component of the ash continues to densify the matrix at ages when OPC-dominated batches plateau. Detailed scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) of fracture surfaces would also illuminate the micro-structural mechanisms underpinning the observed strength trends. Future studies should furthermore optimise the banana trunk ash to Indian almond leaf ash ratio beyond the 40:60 blend examined here, potentially identifying higher-performance blends through response-surface methodology.

8. Conclusions

This investigation examined the feasibility of incorporating blended ash — produced from banana trunk and Indian almond leaf biomass — as a partial replacement for ordinary portland cement in standard 1:3 mortar. The principal findings are summarised below:

- All mortar batches exhibited progressive strength gain from 7 to 28 days, consistent with continued hydration and pozzolanic reaction.
- A 5% ash substitution achieved a 28-day compressive strength of 27.58 MPa — only 5.7% below the control, confirming its suitability for moderate-duty masonry applications.
- Replacement levels of 10% and 15% produced greater strength reductions but still exceeded general masonry mortar minimum requirements, making them appropriate for non-structural uses.
- The 40:60 blended ash formulation demonstrated that complementary agricultural residues can be combined beneficially, broadening the raw material base for sustainable SCMs.
- Environmental benefits include reduced clinker demand, diversion of agricultural waste from open burning, and lower construction material costs — outcomes with meaningful relevance for both carbon accounting and rural development.

In conclusion, the regulated thermal processing of banana trunk and Indian almond leaf biomass yields a supplementary cementitious material with documented technical merit. At judicious replacement levels, this approach offers a credible pathway toward greener, more resource-efficient construction practice.

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