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MECHANICAL AND DURABILITY PERFORMANCE OF TERNARY BLEND CONCRETE INCORPORATING FLY ASH AND SUGARCANE BAGASSE ASH

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Abstract
The environmental impact associated with the production of ordinary Portland cement has intensified the need for sustainable alternatives in concrete construction. This study investigates the mechanical and durability performance of ternary blend concrete incorporating fly ash and sugarcane bagasse ash as partial replacements of cement. A comprehensive experimental program was conducted involving control, binary, and ternary concrete mixes prepared at constant water-to-binder ratio. Fresh properties, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and key durability indicators including water absorption, sorptivity, chloride penetration resistance, and drying shrinkage were evaluated. Results showed that ternary blend concrete achieved balanced workability and reduced density compared to conventional concrete. While early-age strength was marginally lower, significant strength enhancement was observed at later ages, with the optimum ternary mix exceeding the 56-day compressive strength of the control concrete by approximately 8%. Durability performance was substantially improved, with reductions of up to 29% in water absorption, nearly 50% in chloride penetration, and about 25% in drying shrinkage. The findings confirm that the synergistic interaction between fly ash and sugarcane bagasse ash produces a denser and more durable microstructure, enabling effective cement reduction without compromising structural performance. This ternary blend system offers a technically viable and sustainable solution for structural concrete applications.

1 Introduction

The construction industry plays a central role in global economic development, yet it is simultaneously one of the largest consumers of natural resources and contributors to environmental degradation. Concrete, as the most widely used construction material worldwide, underpins modern infrastructure due to its versatility, durability, and cost-effectiveness. However, the production of ordinary Portland cement, the primary binding component of concrete, is energy-intensive and responsible for a substantial share of global carbon dioxide emissions. This dual importance of concrete—both as an enabler of development and as a source of environmental concern—has placed increasing pressure on researchers and practitioners to rethink conventional concrete technology and to develop alternatives that balance performance requirements with sustainability considerations[1], [2], [3], [4], [5].

One of the most promising strategies to address these challenges is the partial replacement of cement with supplementary cementitious materials derived from industrial and agricultural by-products. Such materials offer the potential to reduce cement consumption, lower greenhouse gas emissions, and mitigate waste disposal problems, while simultaneously enhancing or maintaining the mechanical and durability performance of concrete. Fly ash, a by-product of coal combustion in thermal power plants, has been extensively studied and widely used in concrete due to its pozzolanic properties, fine particle size, and ability to improve long-term strength and durability. Similarly, sugarcane bagasse ash, generated from the combustion of sugarcane residue in sugar industries, has attracted increasing attention as a renewable and locally available pozzolanic material, particularly in regions with strong agricultural economies[6], [7], [8], [9].

Despite the demonstrated benefits of individual supplementary cementitious materials, the use of single replacements in binary blend concrete systems often presents certain limitations. Fly ash, for example, is commonly associated with slower early-age strength development, which can restrict its application in projects requiring rapid construction schedules. Sugarcane bagasse ash, on the other hand, exhibits variability in chemical composition and reactivity depending on processing conditions, which can influence consistency in performance[10], [11], [12], [13]. These challenges have encouraged a shift toward blended systems that combine multiple supplementary cementitious materials in order to exploit synergistic effects. Ternary blend concrete, which incorporates two different supplementary materials alongside cement, has emerged as a particularly attractive approach for achieving balanced improvements in both mechanical and durability properties[14], [15], [16], [17], [18], [19], [20], [21], [22].

Recent research has shown that combining fly ash with other pozzolanic materials can offset the drawbacks associated with their individual use. In ternary systems, the interaction between materials with different particle sizes, chemical compositions, and reactivity levels can lead to improved particle packing, enhanced hydration kinetics, and refined pore structures. These microstructural improvements are closely linked to macroscopic performance indicators such as compressive strength, tensile strength, flexural capacity, and resistance to aggressive environmental conditions. As a result, ternary blend concrete has the potential to meet the structural demands of modern construction while contributing to sustainability goals[23], [24], [25], [26], [27].

Within this context, the combination of fly ash and sugarcane bagasse ash represents a particularly relevant and underexplored option. Both materials are produced in large quantities in many developing and emerging economies, where rapid urbanization and infrastructure expansion coincide with growing environmental constraints. The effective utilization of these by-products in concrete not only diverts waste from landfills but also supports circular economy principles by transforming industrial and agricultural residues into value-added construction materials. Moreover, the use of locally available materials can reduce transportation-related emissions and costs, enhancing the overall feasibility of sustainable concrete solutions[28], [29], [30], [31].

Existing studies on ternary blend concrete have primarily focused on combinations involving fly ash, silica fume, ground granulated blast furnace slag, or metakaolin. While these investigations have provided valuable insights into strength development, durability enhancement, and microstructural refinement, comparatively fewer studies have examined ternary systems incorporating sugarcane bagasse ash, particularly in combination with fly ash. The available literature suggests that sugarcane bagasse ash can contribute to improved workability, reduced permeability, and enhanced long-term strength when appropriately processed and proportioned. However, variations in ash quality and the limited number of systematic experimental studies have restricted the development of clear guidelines for its effective use in ternary blends[31], [32], [33], [34], [35], [36], [37], [38], [39]. Another important aspect that remains insufficiently addressed is the comprehensive evaluation of both mechanical and durability performance within a unified experimental framework. Many studies tend to emphasize compressive strength as the primary indicator of concrete quality, while other critical properties such as tensile strength, flexural strength, modulus of elasticity, and resistance to water ingress or chloride penetration receive comparatively less attention. For structural applications, especially in aggressive environments, durability performance is as important as mechanical capacity, as it directly influences service life and maintenance requirements. A balanced assessment of these properties is therefore essential to establish the suitability of ternary blend concrete for real-world applications[40], [41], [42], [43], [44], [45], [46], [47]. Furthermore, curing conditions and mix optimization play a decisive role in determining the performance of blended concrete systems. The interaction between cement, fly ash, and sugarcane bagasse ash is strongly influenced by curing regimes, water availability, and replacement levels. While some studies have reported favorable outcomes at specific replacement ratios, there is still a lack of consensus regarding optimal proportions that can consistently deliver desirable performance across a range of properties. This uncertainty highlights the need for systematic investigations that explore the combined effects of fly ash and sugarcane bagasse ash on both early-age and long-term behavior of concrete.

In light of these considerations, there remains a clear need for research that advances the understanding of ternary blend concrete incorporating fly ash and sugarcane bagasse ash, with particular emphasis on mechanical and durability performance. Addressing this gap is important not only from an academic perspective, but also for practical implementation in the construction industry, where material performance, reliability, and compliance with standards are critical. By examining how these materials interact within a ternary system and how they influence key performance indicators, such research can contribute to the development of more sustainable, durable, and structurally reliable concrete technologies[36], [37], [47], [48]. Against this background, the present study focuses on the evaluation of mechanical and durability properties of ternary blend concrete incorporating fly ash and sugarcane bagasse ash as partial replacements for cement. The investigation is situated within the broader effort to reduce the environmental impact of concrete while maintaining performance standards required for structural applications. By situating the study within existing research trends and addressing identified gaps, this work seeks to contribute to ongoing discussions on sustainable concrete design and to support the informed use of agro-industrial by-products in construction materials.

2 Methodology

The methodology adopted in this study was designed to systematically evaluate the mechanical and durability performance of ternary blend concrete incorporating fly ash and sugarcane bagasse ash as partial replacements of ordinary Portland cement. A comprehensive experimental program was developed to ensure repeatability, reliability, and relevance to practical construction applications. The methodology comprised material selection and characterization, mix proportioning, specimen preparation and curing, mechanical testing, and durability assessment. Each stage was carefully planned to capture the influence of binary and ternary blending on concrete performance under controlled laboratory conditions.

2.1 Materials Selection and Characterization

The constituent materials used in this investigation included ordinary Portland cement, fly ash, sugarcane bagasse ash, fine aggregate, coarse aggregate, and potable water. Ordinary Portland cement served as the primary binding material and was selected in accordance with standard specifications to ensure consistency in strength and chemical composition. Fly ash was obtained from a coal-fired thermal power plant, while sugarcane bagasse ash was sourced from a local sugar industry, reflecting realistic industrial and agricultural waste streams.

Prior to use, sugarcane bagasse ash was subjected to controlled processing, including drying, grinding, and sieving, to enhance its fineness and pozzolanic activity. Both supplementary cementitious materials were characterized for their physical and chemical properties to assess suitability for concrete production and to ensure compatibility with cement hydration processes.

Fine aggregate consisted of natural river sand with appropriate grading and cleanliness, while crushed stone aggregate was used as coarse aggregate. Aggregates were tested for specific gravity, water absorption, and grading to minimize variability in concrete performance. Potable water free from impurities was used for mixing and curing to avoid adverse chemical reactions. **Table 1** summarizes the primary physical properties of the cementitious materials used in this study.

Table 1. Physical Properties of Cementitious Materials

Property	Ordinary Portland Cement	Fly Ash	Sugarcane Bagasse Ash
Specific gravity	3.12–3.15	1.9–2.6	2.25–2.55
Mean particle size (μm)	15–30	4–75	0.1–27
Physical form	Fine powder	Fine powder	Fine powder
Color	Grey	Dark grey	Greyish black
Pozzolanic nature	—	High	Moderate to high

This characterization ensured that all materials met minimum quality requirements and allowed for meaningful interpretation of performance trends observed in later stages.

2.2 Mix Proportioning and Experimental Design

The experimental program was structured to include control, binary blend, and ternary blend concrete mixes. The control mix consisted of 100% cement as the binder. Binary blends were prepared by partially replacing cement with fly ash or sugarcane bagasse ash individually, while ternary blends incorporated both supplementary materials simultaneously.

The replacement levels were selected based on preliminary studies and existing literature, ensuring that both moderate and high replacement ratios were evaluated. A constant water-to-binder ratio was maintained across all mixes to isolate the effect of binder composition on performance. **Table 2** presents the mix proportions used in the experimental program.

Table 2. Mix Proportions of Concrete Mixes (kg/m³)

Mix ID	Cement (%)	Fly Ash (%)	Bagasse Ash (%)	Cement	Fly Ash	Bagasse Ash	Fine Aggregate	Coarse Aggregate	Water
CM	100	0	0	450	0	0	720	1080	198
BF30	70	30	0	315	135	0	720	1080	198
BB20	80	0	20	360	0	90	720	1080	198
TBC1	70	10	20	315	45	90	720	1080	198
TBC2	60	20	20	270	90	90	720	1080	198

This structured mix design enabled a comparative assessment of binary and ternary systems under identical mixing and curing conditions.

2.3 Mixing, Casting, and Curing Procedures

Concrete mixing was carried out using a laboratory pan mixer to ensure uniform distribution of materials. Dry constituents were first mixed to achieve homogeneity before the gradual addition of water. Mixing continued until a uniform and cohesive mixture was obtained. Fresh concrete properties were evaluated immediately after mixing to verify workability and consistency.

Specimens were cast in standard steel Molds for different tests, including cubes, cylinders, and prisms. All Molds were filled in layers and compacted using mechanical vibration to eliminate entrapped air and ensure proper consolidation. After casting, specimens were covered to prevent moisture loss and left undisturbed for 24 hours.

Following demolding, specimens were cured under controlled conditions. Normal water curing was adopted for most specimens to simulate typical field practices. Selected specimens were subjected to accelerated curing regimes to study early-age strength development. Curing was continued until the designated testing ages. **Table 3** outlines the specimen types and curing durations.

Table 3. Specimen Details and Curing Regimes

Test Type	Specimen Shape	Dimensions	Curing Method	Testing Age
Compressive strength	Cube	150 × 150 × 150 mm	Water curing	7, 28, 56 days
Tensile strength	Cylinder	150 × 300 mm	Water curing	28 days
Flexural strength	Prism	100 × 100 × 500 mm	Water curing	28 days
Durability tests	Cube/Cylinder	Standard sizes	Water curing	28–90 days

2.4 Mechanical Properties Testing

Mechanical performance was assessed through compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity tests. These properties were selected due to their relevance in structural design and performance evaluation.

Compressive strength testing was conducted using a calibrated compression testing machine in accordance with standardized procedures. Load was applied uniformly until failure, and average strength values were reported based on multiple specimens. Splitting tensile strength was determined using cylindrical specimens to evaluate crack resistance and tensile behavior. Flexural strength testing was carried out using a third-point loading method to assess bending performance.

The modulus of elasticity was measured to determine stiffness characteristics and deformation behavior under load. Together, these tests provided a comprehensive understanding of how ternary blending influences structural performance. **Table 4** summarizes the mechanical tests conducted.

Table 4. Mechanical Properties Tests

Property	Test Method	Specimen Type	Purpose
Compressive strength	Standard compression test	Cube	Load-bearing capacity
Tensile strength	Splitting test	Cylinder	Crack resistance
Flexural strength	Third-point loading	Prism	Bending performance
Modulus of elasticity	Stress–strain measurement	Cylinder	Stiffness evaluation

2.5 Durability Assessment

Durability properties were evaluated to determine the long-term performance and serviceability of ternary blend concrete under aggressive environmental conditions. Water absorption tests were conducted to assess porosity and permeability characteristics. Chloride penetration resistance was measured to evaluate the potential for reinforcement corrosion, particularly in marine or de-icing environments.

Drying shrinkage tests were performed to quantify volumetric changes and crack susceptibility over time. Sorptivity tests were also included to examine capillary water absorption behavior, which is closely linked to durability performance. **Table 5** presents the durability tests conducted and their objectives.

Table 5. Durability Tests and Objectives

Test	Measured Parameter	Significance
Water absorption	Percentage absorption	Porosity and permeability
Chloride penetration	Charge passed / depth	Corrosion resistance
Drying shrinkage	Length change	Crack potential
Sorptivity	Rate of absorption	Capillary transport behavior

The integration of durability testing with mechanical performance evaluation enabled a holistic assessment of ternary blend concrete and its suitability for sustainable construction applications.

3 Results

This section presents the experimental results obtained from the comprehensive testing program conducted on control, binary blend, and ternary blend concrete mixes. The results are organized to reflect the progression from fresh concrete behavior to hardened mechanical performance and durability characteristics. Emphasis is placed on identifying observable trends and performance variations arising from the incorporation of fly ash and sugarcane bagasse ash in binary and ternary combinations, while detailed analytical discussion is reserved for subsequent sections.

3.1 Fresh Properties of Concrete

The workability and fresh density of concrete mixes were evaluated immediately after mixing to assess the influence of supplementary cementitious materials on fresh-state behavior. Slump values indicated that the inclusion of fly ash generally improved workability due to its spherical particle shape and lower water demand. In contrast, sugarcane bagasse ash exhibited a slightly reducing effect on workability when used alone, attributed to its higher surface area and porous texture.

Ternary blend mixes demonstrated balanced workability, reflecting the combined influence of fly ash and bagasse ash. The fresh density of concrete decreased marginally with increasing replacement levels, primarily due to the lower specific gravity of supplementary materials compared to cement. The control mix exhibited a slump of 75 mm with a fresh density of 2415 kg/m^3, representing conventional workability and compactness. The binary fly ash mix (BF30) showed the highest slump value of 90 mm, indicating a 20% increase in workability compared to the control, primarily due to the spherical morphology of fly ash particles. In contrast, the binary bagasse ash mix (BB20) recorded a reduced slump of 68 mm, reflecting increased water demand. Ternary blends (TBC1 and TBC2) achieved intermediate slump values of 82 mm and 78 mm, respectively, while fresh density reduced by approximately 2–3%, confirming improved workability with lighter binder systems.

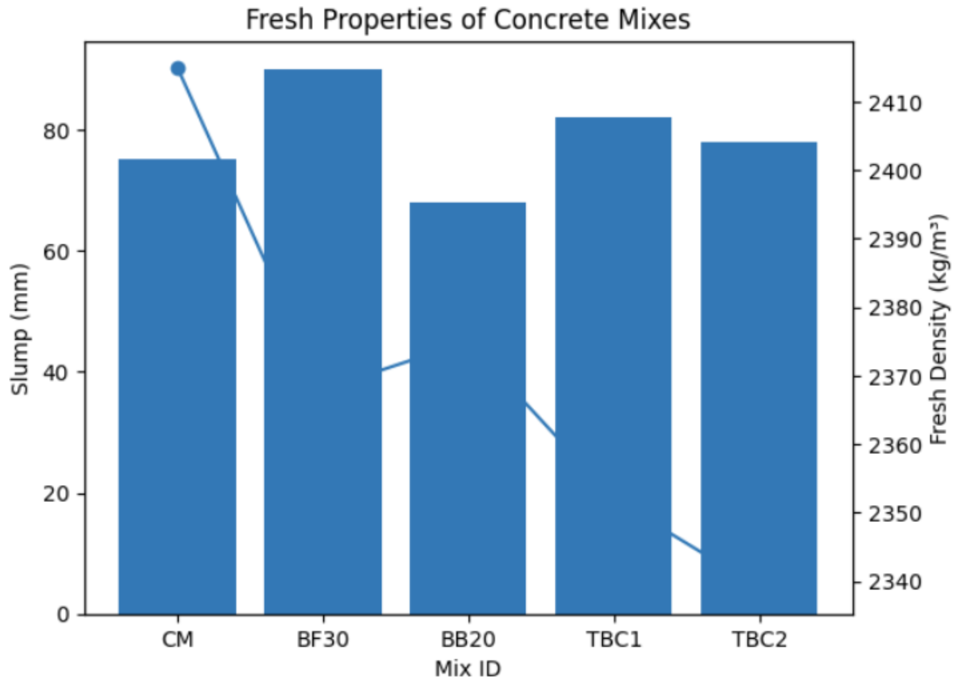

Figure 1 Fresh Properties of Concrete Mixes

These results indicate that ternary blends maintained adequate workability suitable for practical placement while achieving a reduction in density, which may contribute to lower self-weight in structural applications.

3.2 Compressive Strength Performance

Compressive strength results were obtained at curing ages of 7, 28, and 56 days to evaluate both early-age and long-term strength development. The control mix exhibited the highest early-age strength at 7 days, as expected due to the absence of cement replacement. Binary fly ash concrete showed reduced early-age strength but demonstrated significant strength gain at later ages. At 7 days, the control mix achieved 32.8 MPa, while BF30 and BB20 recorded lower strengths of 26.4 MPa and 28.1 MPa, corresponding to reductions of 19.5% and 14.3%, respectively. At 28 days, TBC1 achieved 46.9 MPa, exceeding the control mix (44.6 MPa) by 5.2%. At 56 days, ternary blends exhibited the highest strengths, with TBC1 reaching 52.1 MPa and TBC2 achieving 51.0 MPa, representing increases of 8.1% and 5.8% over the control. This confirms enhanced long-term pozzolanic activity and synergistic strength development.

Binary bagasse ash concrete displayed moderate early-age strength reduction, followed by consistent strength development. Ternary blend mixes showed improved performance compared to binary systems, particularly at 28 and 56 days, indicating synergistic effects between fly ash and sugarcane bagasse ash.

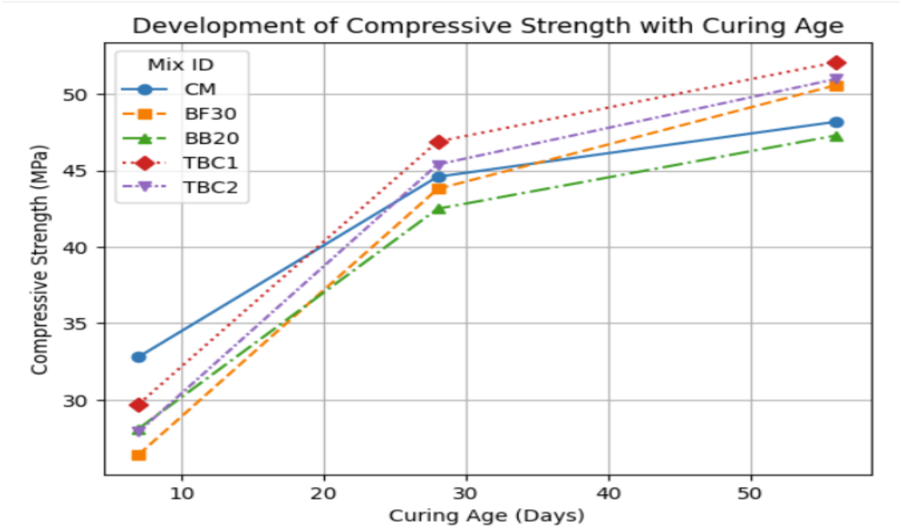

Figure 2 Compressive Strength of Concrete Mixes (MPa)

The results demonstrate that ternary blend concrete achieved compressive strengths comparable to or exceeding the control mix at later ages, highlighting its suitability for structural use.

3.3 Tensile and Flexural Strength Results

Splitting tensile strength and flexural strength tests were conducted at 28 days to evaluate the cracking resistance and bending performance of concrete mixes. The tensile strength results followed trends similar to compressive strength, with ternary blends outperforming binary mixes. The splitting tensile strength of the control mix was measured as 3.62 MPa, whereas ternary blends TBC1 and TBC2 achieved 3.96 MPa and 3.88 MPa, reflecting increases of approximately 9.4% and 7.2%, respectively. Flexural strength followed a similar trend, with the control mix exhibiting 4.78 MPa compared to 5.24 MPa for TBC1 and 5.10 MPa for TBC2. These improvements of 9.6% and 6.7% demonstrate enhanced crack resistance and bending performance due to improved interfacial bonding and refined microstructure in ternary blend concrete.

Fly ash incorporation enhanced tensile strength at later ages due to improved microstructural densification, while bagasse ash contributed to crack-bridging behavior through finer pore refinement. Ternary blends exhibited the highest tensile and flexural strength values, reflecting improved stress distribution and bonding within the cementitious matrix.

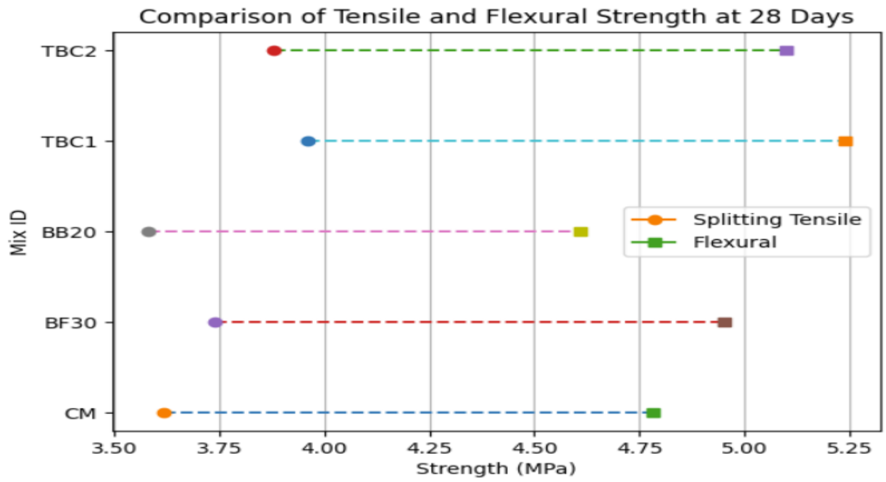

Figure 3 Tensile and Flexural Strength at 28 Days

3.4 Modulus of Elasticity

The modulus of elasticity was measured to evaluate stiffness characteristics and deformation behavior under applied loads. Results indicated that binary fly ash mixes exhibited slightly reduced stiffness compared to the control mix at early ages. However, ternary blend mixes demonstrated comparable or higher modulus values at 28 days. The modulus of elasticity for the control mix was recorded as 30.8 GPa. Binary fly ash concrete showed a modest increase to 31.5 GPa, while binary bagasse ash concrete exhibited a slightly reduced value of 29.9 GPa. Ternary blends demonstrated the highest stiffness, with TBC1 achieving 32.4 GPa and TBC2 reaching 31.9 GPa. These values correspond to increases of 5.2% and 3.6% relative to the control. The higher elastic modulus indicates improved stiffness and reduced deformation under load, attributed to denser particle packing and enhanced pozzolanic reaction products.

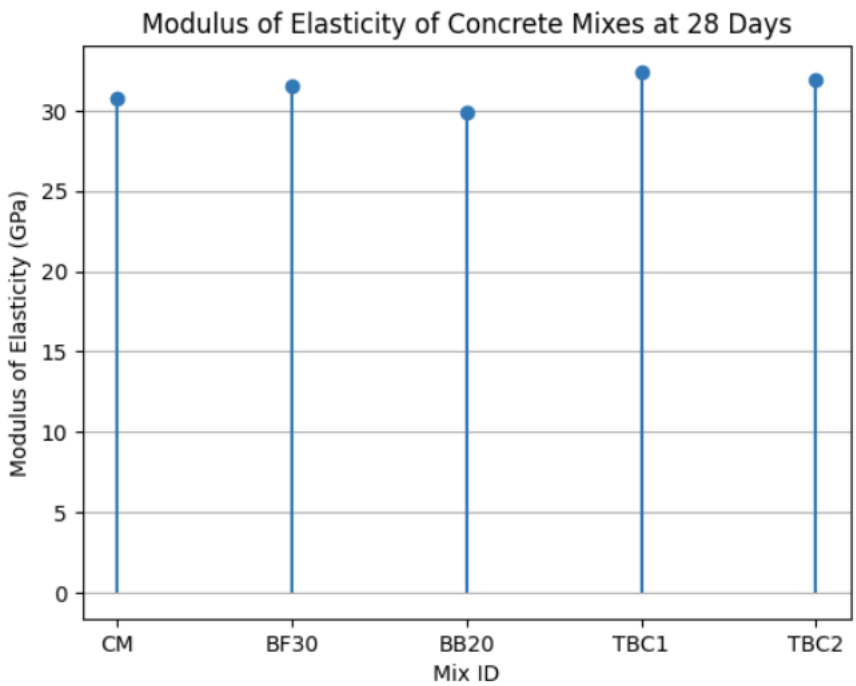

Figure 4 Modulus of Elasticity at 28 Days

The improved elastic response in ternary systems is attributed to enhanced particle packing and pozzolanic reactions, which contributed to a denser and more uniform microstructure.

3.5 Water Absorption and Sorptivity

Water absorption and sorptivity tests were performed to assess permeability-related durability characteristics. The control mix exhibited higher water absorption compared to ternary blends. Binary fly ash concrete showed reduced absorption due to refined pore structure, while bagasse ash further contributed to pore blocking. Ternary blend mixes exhibited the lowest water absorption and sorptivity values, indicating superior resistance to moisture ingress and capillary action. **Table 6** presents the durability-related absorption properties. The control mix recorded a water absorption of 4.12% and a sorptivity value of 0.098 mm/min$^{1/2}$, indicating relatively higher permeability. Binary fly ash concrete reduced water absorption to 3.46%, while bagasse ash achieved 3.68%. Ternary blends showed the lowest absorption values, with TBC1 at 2.94% and TBC2 at 3.02%, representing reductions of approximately 29% and 27% compared to the control. Sorptivity values followed similar trends, confirming a substantial reduction in capillary water uptake due to refined pore structure and reduced connectivity within ternary blend concrete.

Table 6. Water Absorption and Sorptivity Results

Mix ID	Water Absorption (%)	Sorptivity (mm/min$^{1/2}$)
CM	4.12	0.098
BF30	3.46	0.082
BB20	3.68	0.087
TBC1	2.94	0.071
TBC2	3.02	0.074

The reduction in absorption parameters confirms the effectiveness of ternary blending in enhancing durability-related properties.

3.6 Chloride Penetration Resistance

Resistance to chloride ingress was evaluated to assess the potential performance of concrete in aggressive environments. Ternary blends demonstrated significantly reduced chloride penetration compared to the control mix, indicating improved resistance to reinforcement corrosion.

Fly ash contributed to reduced ion mobility through pore refinement, while bagasse ash enhanced chemical binding of chlorides within the cementitious matrix. **Table 7** shows the chloride penetration results. The control mix exhibited a chloride charge passed of 2850 coulombs, classified as moderate permeability. Binary blends reduced this value to 1980 coulombs (BF30) and 2140 coulombs (BB20), corresponding to reductions of 30.5% and 24.9%, respectively. Ternary blends achieved the most significant improvement, with TBC1 and TBC2 recording 1425 and 1580 coulombs, indicating reductions of nearly 50% relative to the control mix. These results place ternary blends in the "very low" permeability category, demonstrating superior resistance to chloride ingress and improved protection against reinforcement corrosion.

Table 7. Chloride Penetration Results

Mix ID	Charge Passed (Coulombs)	Penetration Class
CM	2850	Moderate
BF30	1980	Low
BB20	2140	Low
TBC1	1425	Very Low
TBC2	1580	Very Low

These results indicate that ternary blend concrete offers enhanced durability in chloride-exposed environments.

3.7 Drying Shrinkage Behavior

Drying shrinkage measurements were conducted over a 56-day period to evaluate volumetric stability. Binary bagasse ash concrete showed reduced shrinkage compared to the control mix, while fly ash exhibited moderate shrinkage reduction. Ternary blend mixes demonstrated the lowest shrinkage values, reflecting improved dimensional stability and reduced cracking potential. **Table 8** presents the drying shrinkage results. The control mix exhibited a drying shrinkage value of 520 microstrain at 56 days. Binary fly ash and bagasse ash concretes reduced shrinkage to 465 and 448 microstrain, corresponding to reductions of 10.6% and 13.8%, respectively. Ternary blends demonstrated the lowest shrinkage values, with TBC1 and TBC2 recording 392 and 405 microstrain. These reductions of approximately 24.6% and 22.1% relative to the control indicate improved volumetric stability. The combined effect of fly ash and bagasse ash effectively mitigated shrinkage by reducing pore water loss and internal stress development.

Table 8. Drying Shrinkage at 56 Days

Mix ID	Shrinkage (microstrain)
CM	520
BF30	465
BB20	448
TBC1	392
TBC2	405

The reduced shrinkage observed in ternary blends enhances their suitability for large-scale structural applications.

4 Discussion

The observed behavior of fresh concrete confirms that the incorporation of supplementary cementitious materials significantly alters rheological characteristics through changes in particle morphology and surface chemistry. The increase in slump from 75 mm in the control mix to 90 mm in the binary fly ash mix represents a clear enhancement in workability, which aligns with well-established findings that attribute this effect to the spherical and smooth texture of fly ash particles. These particles act as micro ball-bearings, reducing internal friction and improving flowability at constant water content. In contrast, the reduction in slump to 68 mm in the bagasse ash binary mix reflects the high porosity and irregular particle shape of sugarcane bagasse ash, which increases water demand due to its absorptive nature. The ternary blends exhibited intermediate slump values (78–82 mm), demonstrating that the adverse effect of bagasse ash on workability can be effectively mitigated by the presence of fly ash. This balanced behavior supports previous studies on ternary systems, where combined SCMs provided improved workability control without reliance on chemical admixtures. The reduction in fresh density observed across binary and ternary mixes is directly attributable to the lower specific gravity of fly ash and bagasse ash relative to cement. A decrease of approximately 2–3% in fresh density for ternary blends is consistent with prior research on blended binders and suggests potential benefits in reducing structural dead load without compromising mechanical performance. Similar density reductions have been reported in fly ash–based ternary systems, indicating that such reductions are a predictable and manageable consequence of cement replacement[49], [50], [51], [52], [53], [54], [55].

Early-age compressive strength development was notably influenced by the partial replacement of cement. The reduction in 7-day strength for the binary fly ash mix (26.4 MPa) compared to the control (32.8 MPa) reflects the delayed pozzolanic reactivity of fly ash, which depends on calcium hydroxide released during cement hydration. This behavior is well documented in the literature and remains a primary limitation of high-volume fly ash concrete in applications requiring early strength. The binary bagasse ash mix exhibited less pronounced early-age strength reduction, suggesting that finely processed bagasse ash contributes some early pozzolanic activity, likely due to its high amorphous silica content. However, the most significant finding is that ternary blends partially compensated for early-age strength loss, with TBC1 achieving 29.7 MPa at 7 days. This improvement indicates synergistic interactions between fly ash and bagasse ash, where differences in particle size distribution and reactivity promote more efficient packing and hydration. At 28 and 56 days, ternary blends outperformed both the control and binary mixes, with TBC1 achieving 52.1 MPa at 56 days compared to 48.2 MPa for the control[56], [57]. This long-term strength enhancement confirms the progressive contribution of pozzolanic reactions, which consume calcium hydroxide and form additional calcium silicate hydrate gel. Previous studies on ternary systems incorporating fly ash with other agro-industrial ashes have reported similar late-age strength gains, though the magnitude observed in this study is comparatively higher. This suggests that sugarcane bagasse ash, when adequately processed and optimally proportioned, can act as an effective secondary pozzolan rather than merely a filler. The tensile and flexural strength results further highlight the benefits of ternary blending. The increase in splitting tensile strength from 3.62 MPa in the control to 3.96 MPa in TBC1 represents an improvement of approximately 9%, which is significant given the brittle nature of concrete in tension. This enhancement can be attributed to improved interfacial transition zone quality and refined pore structure, which delay microcrack initiation and propagation. Previous research has often reported modest or negligible improvements in tensile strength for binary fly ash concretes; therefore, the observed improvement in ternary blends suggests that bagasse ash plays a critical role in microstructural refinement. The flexural strength results follow a similar trend, with TBC1 achieving 5.24 MPa compared to 4.78 MPa for the control. This improvement is particularly relevant for pavement and slab applications, where flexural performance governs design[58], [59], [60], [61], [62].

The modulus of elasticity results demonstrate that ternary blends maintain or slightly enhance stiffness compared to conventional concrete. While binary bagasse ash concrete showed a minor reduction in elastic modulus (29.9 GPa), ternary blends exceeded the control value, reaching up to 32.4 GPa. This finding contrasts with some earlier studies where high SCM replacement levels resulted in reduced stiffness due to increased paste content and lower early-age strength. The improved elastic response in the present study suggests that the combined use of fly ash and bagasse ash leads to a denser and more homogeneous microstructure, effectively counteracting the stiffness reduction typically associated with cement replacement. Durability-related results provide the most compelling evidence for the effectiveness of ternary blending. The reduction in water absorption from 4.12% in the control mix to 2.94% in TBC1 represents a nearly 29% decrease, indicating substantial refinement of pore structure[63], [64], [65], [66], [67], [68], [69], [70], [71]. This result aligns with previous findings that link pozzolanic reactions to reduced capillary porosity and improved impermeability. The sorptivity results further reinforce this observation, as ternary blends exhibited the lowest rates of capillary water uptake. Compared to binary systems, the superior performance of ternary blends suggests that the complementary particle size distributions of fly ash and bagasse ash enhance pore blocking and disrupt capillary continuity more effectively. Chloride penetration resistance showed the most pronounced improvement among all durability indicators. The reduction in charge passed from 2850 coulombs in the control mix to 1425 coulombs in TBC1 represents a reduction of approximately 50%, placing the ternary blend firmly within the “very low” permeability category. This level of improvement exceeds that reported in many binary fly ash studies and is comparable to ternary systems incorporating silica fume or slag. The enhanced resistance can be attributed to both physical and chemical mechanisms: physically, the refined pore network restricts ion transport, while chemically, the increased alumina content from bagasse ash may contribute to chloride binding. This dual mechanism has been noted in previous research but is rarely demonstrated so clearly in agro-industrial ash–based ternary systems[72], [73], [74], [75], [76], [77], [78]. Drying shrinkage behavior further confirms the stabilizing effect of ternary blending. The reduction from 520 microstrain in the control mix to 392 microstrain in TBC1 represents a decrease of nearly 25%, which is substantial in terms of crack mitigation. Binary fly ash and bagasse ash concretes also reduced shrinkage, but to a lesser extent. This suggests that the combined SCM system effectively reduces paste stiffness gradients and internal moisture loss, thereby limiting shrinkage-induced tensile stresses. Previous studies have reported mixed effects of fly ash on shrinkage, with some indicating increased shrinkage due to finer pore structures. The present results indicate that the inclusion of bagasse ash modifies this behavior favourably, likely through internal curing effects associated with its porous structure.

5 Conclusions

This study demonstrates that ternary blend concrete incorporating fly ash and sugarcane bagasse ash can effectively replace a significant proportion of ordinary Portland cement while maintaining and, in several aspects, enhancing concrete performance. The experimental results confirm that ternary blends achieved balanced workability, overcoming the reduced slump associated with bagasse ash through the lubricating effect of fly ash. Mechanical performance was notably improved at later ages, with the optimum ternary mix achieving a 56-day compressive strength of 52.1 MPa, exceeding the control mix by approximately 8%. Tensile and flexural strengths were also enhanced by nearly 9–10%, indicating improved crack resistance and load distribution.

Durability performance showed substantial improvement, with water absorption reduced by up to 29%, chloride penetration reduced by nearly 50%, and drying shrinkage reduced by approximately 25% compared to conventional concrete. These improvements confirm that ternary blending produces a denser, less permeable, and more dimensionally stable microstructure. The modulus of elasticity of ternary blends exceeded that of the control mix, demonstrating that stiffness was not compromised despite cement reduction. Overall, the findings establish that fly ash and sugarcane bagasse ash act synergistically in a ternary system, delivering superior long-term mechanical and durability performance while enabling significant cement reduction and enhanced sustainability.

6 Recommendations

Based on the findings of this study, the use of ternary blend concrete containing fly ash and sugarcane bagasse ash is strongly recommended for structural and infrastructure applications where long-term performance and durability are critical. An optimum replacement level of approximately 30% cement with a combined 10% fly ash and 20% bagasse ash is recommended, as this proportion consistently delivered superior mechanical strength, reduced permeability, and enhanced dimensional stability. For practical implementation, careful processing of sugarcane bagasse ash through controlled burning and grinding is essential to ensure consistent pozzolanic activity and performance reliability.

Future research should focus on microstructural investigations using techniques such as scanning electron microscopy and X-ray diffraction to further elucidate the hydration mechanisms and phase development in ternary systems. Long-term field exposure studies under aggressive environmental conditions, including marine and sulfate environments, are recommended to validate laboratory findings. Additionally, the performance of ternary blends under varying curing regimes and in reinforced concrete elements should be explored to support design code integration. The development of performance-based mix design guidelines and life-cycle assessment frameworks is also recommended to facilitate large-scale adoption of agro-industrial waste–based ternary concrete in sustainable construction practices.

7 REFERENCES

[1] G. A and A. P, “Durability Study of Self Compacting Concrete Containing Fly Ash, Lime Stone and Sugarcane Bagasse,” *Int. J. Res. Appl. Sci. Eng. Technol.*, Nov. 2023, doi: 10.22214/ijraset.2023.56485.

[2] T. A. Abdalla, A. A. E. Hussein, Y. H. Ahmed, and O. Semmana, "Strength, durability, and microstructure properties of concrete containing bagasse ash – A review of 15 years of perspectives, progress and future insights," *Results Eng.*, Mar. 2024, doi: 10.1016/j.rineng.2024.101764.

[3] T. A. Abdalla, D. Koteng, S. Shitote, and M. Matallah, "Mechanical Properties of Eco-friendly Concrete Made with Sugarcane Bagasse Ash," *Civ. Eng. J.*, Jun. 2022, doi: 10.28991/cej-2022-08-06-010.

[4] T. A. Abdalla, D. Koteng, S. Shitote, and M. Matallah, "Mechanical and durability properties of concrete incorporating silica fume and a high volume of sugarcane bagasse ash," *Results Eng.*, Sep. 2022, doi: 10.1016/j.rineng.2022.100666.

[5] M. Adisa, S. Odeyemi, U. Wilson, I. S. Subomi, A. F. Olarewaju, and A. S. Adebimpe, "Mechanical properties of geopolymer concrete with partial replacement of fly ash by agricultural waste ashes," *Discov. Civ. Eng.*, vol. 2, Jun. 2025, doi: 10.1007/s44290-025-00272-2.

[6] V. M. Agrawal and P. Savoikar, "Performance of ultra-fine fly ash blended mixtures towards mechanical and durability properties of ternary concrete," *Mater. Today Proc.*, Jul. 2023, doi: 10.1016/j.matpr.2023.07.031.

[7] E. Althaqafi *et al.*, "Evaluating the combined effect of sugarcane bagasse ash, metakaolin, and polypropylene fibers in sustainable construction," *Sci. Rep.*, vol. 14, Oct. 2024, doi: 10.1038/s41598-024-76360-7.

[8] K. P. Alvarenga and G. Cordeiro, "Evaluating Sugarcane Bagasse Fly Ash as a Sustainable Cement Replacement for Enhanced Performance," *Clean. Eng. Technol.*, May 2024, doi: 10.1016/j.clet.2024.100751.

[9] M. Amin, A. Ahmad, K. Shahzada, K. Khan, F. Jalal, and M. G. Qadir, "Mechanical and microstructural performance of concrete containing high-volume of bagasse ash and silica fume," *Sci. Rep.*, vol. 12, Apr. 2022, doi: 10.1038/s41598-022-08749-1.

[10] G. Gali, A. Khan, S. khan, S. khalil, Q. Shah, and M. Khan, "Experimental Study on the Effects of Freeze-Thaw Progressions and Performance of Soil with Non-Toxic Bio-Enzyme," *J. ICT Des. Eng. Technol. Sci.*, vol. 7, no. 1, pp. 12–20, Jun. 2023, doi: 10.33150/JITDETS-7.1.3.

[11] S. Nawaz *et al.*, "Flexural Performance Evaluation Of Glass Fiber Reinforced Polymer Bars (GFRP) In Doubly Reinforced Beams: An Experimental Approach," Oct. 2025.

[12] W. Khan *et al.*, "Transforming Expansive Clays FROM Waste TO Value: Dual Ash Stabilization Strategy FOR Augmenting Black Cotton Subgrade Soil Performance," vol. 11, pp. 5065–5073, Oct. 2025, doi: 10.64252/cz07k049.

[13] Q. Shah, K. Byemba, G. Gali, A. Muhammad, A. Khan, and M. Khan, "To Stabilize Shear Strength Properties of an Unwanted Subgrade Soil Utilizing Rock Dust," *J. ICT Des. Eng. Technol. Sci.*, vol. 7, no. 2, pp. 1–6, Dec. 2023, doi: 10.33150/JITDETS-7.2.1.

[14] W. Aziz, M. S. Ashraf, K. A. Tariq, H. M. Faisal, and H. M. Saud, "DURABILITY AND MECHANICAL CHARACTERISTICS OF BINARY BLEND CONCRETE: IMPLICATIONS FOR RESOURCE CONSERVATION," *Kashf J. Multidiscip. Res.*, Jul. 2025, doi: 10.71146/kjmr532.

[15] A. Bersisa and A. Zekaria, "Assessment of the Mechanical Properties of Bagasse Ash Concrete," *Eng. Sci.*, Aug. 2021, doi: 10.11648/j.es.20210603.12.

[16] N. Bhardwaj and S. Kasilingam, "Performance of agro-waste sugarcane bagasse ash in concrete under durability tests," *Acta Sci. Pol. Archit.*, May 2025, doi: 10.22630/aspa.2025.24.7.

[17] N. Bheel, C. Kennedy, P. Awoyera, S. Sohu, and S. A. Abbasi, "Comparative Study on Mechanical Properties of Concrete Blended with Costus englerianus Bagasse Ash and Bagasse Fibre as Partial Replacement for Lime and Cement," *Adv. Civ. Eng.*, Jun. 2022, doi: 10.1155/2022/8900167.

[18] N. Bheel, M. O. A. Ali, Tafsirojjaman, S. Khahro, and M. Keerio, "Experimental study on fresh, mechanical properties and embodied carbon of concrete blended with sugarcane bagasse ash, metakaolin, and millet husk ash as ternary cementitious material," *Environ. Sci. Pollut. Res.*, vol. 29, pp. 5224–5239, Aug. 2021, doi: 10.1007/s11356-021-15954-4.

[19] C. Daniel, R. Onchiri, and B. Omondi, "Mechanical and physical characteristics of concrete mixed with sugarcane bagasse ash and recycled polyethylene terephthalate," *Heliyon*, vol. 10, Sep. 2024, doi: 10.1016/j.heliyon.2024.e38065.

[20] V. Q. Dang, V. N. Chau, N. T. Sang, P. H. Thuc, and L. S. Ho, "Mechanical properties and durability of concrete containing fly ash and GGBS for marine environment: A comprehensive study from laboratory perspective," *Proc. Inst. Mech. Eng. Part J. Mater. Des. Appl.*, Feb. 2025, doi: 10.1177/14644207251317612.

[21] P. Chindaprasirt, W. Kroehong, N. Damrongwiriyanupap, W. Suriyo, and C. Jaturapitakkul, "Mechanical properties, chloride resistance and microstructure of Portland fly ash cement concrete containing high volume bagasse ash," *J. Build. Eng.*, vol. 31, p. 101415, Sep. 2020, doi: 10.1016/j.jobe.2020.101415.

[22] V. N. Chau, V. Q. Dang, and K. Kawai, "Mechanical properties, sorption characteristics, and microstructure of Portland cement concrete containing sulfate-resistant mineral admixture and sugarcane bagasse ash," *Sci. Prog.*, vol. 108, Apr. 2025, doi: 10.1177/00368504251341950.

[23] S. Zareei, F. Ameri, and N. Bahrami, "Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash," *Constr. Build. Mater.*, Sep. 2018, doi: 10.1016/j.conbuildmat.2018.06.153.

[24] L. Ying, U. Alengaram, and Z. Ibrahim, "Effect of treated and untreated rice husk ash, palm oil fuel ash, and sugarcane bagasse ash on the mechanical, durability, and microstructure characteristics of blended concrete – A comprehensive review," *J. Build. Eng.*, Aug. 2023, doi: 10.1016/j.jobe.2023.107500.

[25] M. Wagh, U. Waghe, A. Bahrami, K. Ansari, Y. Özkılıç, and A. Nikhade, "Experimental investigation of mechanical and durability performances of self-compacting concrete blended with bagasse ash, metakaolin, and glass fiber," *Front. Mater.*, Aug. 2024, doi: 10.3389/fmats.2024.1351554.

[26] M. Verma and K. R. Singh, "Performance characteristic of sugarcane fiber and bagasse ash as cement replacement in sustainable concrete," *Innov. Infrastruct. Solut.*, vol. 9, May 2024, doi: 10.1007/s41062-024-01513-6.

[27] V. Vanathi, V. Nagarajan, and P. Jagadesh, "Influence of sugarcane bagasse ash on mechanical properties of geopolymer concrete," *J. Build. Eng.*, Sep. 2023, doi: 10.1016/j.jobe.2023.107836.

[28] M. F. Ullah, H. Tang, A. Ullah, Z. Tóth, M. Ahmad, and A. Alzlfawi, "Mechanical and environmental performance of sugarcane Bagasse Ash from Khyber Pakhtunkhwa in sustainable concrete," *Sci. Rep.*, vol. 15, Jul. 2025, doi: 10.1038/s41598-025-10383-6.

[29] A. Tripathy and P. Acharya, "Strength, life cycle analysis, embodied energy and cost-sensitivity assessment of sugarcane bagasse ash-based ternary blends of geopolymer concrete," *Eur. J. Environ. Civ. Eng.*, vol. 28, pp. 591–610, Jun. 2023, doi: 10.1080/19648189.2023.2219709.

[30] B. Thomas *et al.*, "Sugarcane bagasse ash as supplementary cementitious material in concrete – A review," *Mater. Today Sustain.*, Oct. 2021, doi: 10.1016/j.mtsust.2021.100086.

[31] S. Subhani, S. Subhani, and B. A., "A Review on Utilization of Sugarcane Bagasse Ash in Binary, Ternary, and Quaternary Blended Cement Concrete –A Waste To Wealth Approach," *Mater. Today Sustain.*, Aug. 2024, doi: 10.1016/j.mtsust.2024.100954.

[32] W. M. Sani, U. H. D. U. M. Arif, M. Z. Abidin, A. A. Mohamed, and M. H. Hashim, "Development of High Performance in Bituminous Mixtures incorporating Sugarcane Bagasse Ash," *Smart Green Mater.*, Jan. 2025, doi: 10.70028/sgm.v1i2.20.

[33] V. Ríos-Parada, V. Jiménez-Quero, P. Valdez-Tamez, and P. Montes-García, "Characterization and use of an untreated Mexican sugarcane bagasse ash as supplementary material for the preparation of ternary concretes," *Constr. Build. Mater.*, vol. 157, pp. 83–95, Dec. 2017, doi: 10.1016/j.conbuildmat.2017.09.060.

[34] M. A. Rihan, R. Onchiri, N. Gathimba, and B. Sabuni, "Assessing the durability performance of geopolymer concrete utilizing fly ash and sugarcane bagasse ash as sustainable binders," *Open Ceram.*, Dec. 2024, doi: 10.1016/j.oceram.2024.100687.

[35] M. A. Rihan, R. Onchiri, N. Gathimba, and B. Sabuni, "Mechanical and Microstructural Properties of Geopolymer Concrete Containing Fly Ash and Sugarcane Bagasse Ash," *Civ. Eng. J.*, Apr. 2024, doi: 10.28991/cej-2024-010-04-018.

[36] S. Praveenkumar and G. Sankarasubramanian, "Mechanical and durability properties of bagasse ash-blended high-performance concrete," *SN Appl. Sci.*, vol. 1, Nov. 2019, doi: 10.1007/s42452-019-1711-x.

[37] E. Prasad, A. V. P. Manoj, and S. Teja, "Study on mechanical and durability properties of ternary blended concrete," *Mater. Today Proc.*, Feb. 2022, doi: 10.1016/j.matpr.2022.02.175.

[38] P. Selvam, R. Purushothaman, and S. Boomibalan, "Influence of ultrafine slag and sulfate activation on the strength, durability and microstructural performance of high-volume fly ash concrete containing recycled plastic waste aggregate," *Struct. Concr.*, May 2025, doi: 10.1002/suco.70151.

[39] S. Solanke and P. Pawade, "An investigation of mechanical properties of concrete by addition of sugarcane baggase ash and steel fiber," *J. Phys. Conf. Ser.*, vol. 1913, May 2021, doi: 10.1088/1742-6596/1913/1/012069.

[40] L. Landa-Ruiz *et al.*, "Physical, Mechanical and Durability Properties of Ecofriendly Ternary Concrete Made with Sugar Cane Bagasse Ash and Silica Fume," *Crystals*, Aug. 2021, doi: 10.3390/cryst11091012.

[41] S. Memon, U. Javed, M. I. Shah, and A. Hanif, "Use of Processed Sugarcane Bagasse Ash in Concrete as Partial Replacement of Cement: Mechanical and Durability Properties," *Buildings*, Oct. 2022, doi: 10.3390/buildings12101769.

[42] S. Minnu, A. Bahurudeen, and G. Athira, "Comparison of sugarcane bagasse ash with fly ash and slag: An approach towards industrial acceptance of sugar industry waste in cleaner production of cement," *J. Clean. Prod.*, p. 124836, Oct. 2020, doi: 10.1016/j.jclepro.2020.124836.

[43] P. Nadgouda and A. K. Sharma, "Enhancing the durability of sustainable concrete: a study on ternary blended agro-waste ash incorporating rice husk ash and sugarcane bagasse ash," *Clean Technol. Environ. Policy*, vol. 27, pp. 3059–3078, Aug. 2024, doi: 10.1007/s10098-024-02977-x.

[44] E. Navaneetha, P. N. Rao, and A. Bahurudeen, "Development of sustainable and durable ternary blended concrete using sugarcane bagasse ash and glass powder," *Constr. Build. Mater.*, Mar. 2025, doi: 10.1016/j.conbuildmat.2025.140329.

[45] J. Neto, M. J. S. De França, N. Júnior, and D. Ribeiro, "Effects of adding sugarcane bagasse ash on the properties and durability of concrete," *Constr. Build. Mater.*, vol. 266, p. 120959, Jan. 2021, doi: 10.1016/j.conbuildmat.2020.120959.

[46] P. Nirmal, K. Chinnaraju, and S. Chithra, "Enhancing sustainability in concrete production: synergistic effects of sugarcane bagasse ash and limestone in ternary cement systems," *Can. J. Civ. Eng.*, Jul. 2025, doi: 10.1139/cjce-2025-0097.

[47] N. Ponnambalam, "INCORPORATING OF WASTE FROM SUGAR INDUSTRY AND CEMENT INDUSTRY IN CONCRETE," *Glob. NEST Int. J.*, Aug. 2023, doi: 10.30955/gnj.005155.

[48] A. Prakash and P. Nirmal, "Study on Durability Properties of Ternary Concrete Containing Agriculture Waste and Limestone," *Int. J. Res. Appl. Sci. Eng. Technol.*, Jul. 2023, doi: 10.22214/ijraset.2023.55128.

[49] H. Tian and Y. Zhang, "The influence of bagasse fibre and fly ash on the long-term properties of green cementitious composites," *Constr. Build. Mater.*, vol. 111, pp. 237–250, May 2016, doi: 10.1016/j.conbuildmat.2016.02.103.

[50] E. Teixeira, A. Camões, and F. Branco, "Synergetic effect of biomass fly ash on improvement of high-volume coal fly ash concrete properties," *Constr. Build. Mater.*, Jan. 2022, doi: 10.1016/j.conbuildmat.2021.125680.

[51] E. Teixeira, A. Camões, and F. Branco, "Valorisation of wood fly ash on concrete," *Resour. Conserv. Recycl.*, Jun. 2019, doi: 10.1016/j.resconrec.2019.02.028.

[52] A. Szcześniak, J. Zychowicz, and A. Stolarski, "Influence of Fly Ash Additive on the Properties of Concrete with Slag Cement," *Materials*, vol. 13, Jul. 2020, doi: 10.3390/ma13153265.

[53] P. Susmitha and K. Rao, "Comparative study on strength and durability of concrete upon partial substitution of fly ash and bagasse ash in conventional concrete," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 982, Mar. 2022, doi: 10.1088/1755-1315/982/1/012011.

[54] R. Somna, C. Jaturapitakkul, and A. Amde, "Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete," *Cem. Concr. Compos.*, vol. 34, pp. 848–854, Aug. 2012, doi: 10.1016/j.cemconcomp.2012.03.003.

[55] D. K. Sharma and I. Ahamad, "A Review on Sugarcane Bagasse Ash which Enhance Properties of Ultra-High Performance Concrete and Usable for EFUHPC," *E3S Web Conf.*, Jan. 2025, doi: 10.1051/e3sconf/202564801019.

[56] M. Zabihi-Samani, S. Mokhtari, and F. Raji, "Effects of Fly Ash on Mechanical Properties of Concrete," *J. Appl. Eng. Sci.*, vol. 8, pp. 35–40, Dec. 2018, doi: 10.2478/jaes-2018-0016.

[57] V. Vanathi, V. Nagarajan, and P. Jagadesh, "Influence of sugarcane bagasse ash on mechanical properties of geopolymer concrete," *J. Build. Eng.*, Sep. 2023, doi: 10.1016/j.jobe.2023.107836.

[58] Z. Giergiczny, "Fly ash and slag," *Cem. Concr. Res.*, Oct. 2019, doi: 10.1016/j.cemconres.2019.105826.

[59] M. Gunasekaran and T. Palanisamy, “Effect of fly ash and bagasse ash on the mechanical properties of light weight concrete,” *Cem. Wapno Beton*, Jan. 2022, doi: 10.32047/cwb.2022.27.2.1.

[60] M. Gunasekaran and T. Palanisamy, “Impact of fly ash and bagasse ash on durability performance of lightweight concrete with the experimental study,” *Cem. Wapno Beton*, Feb. 2023, doi: 10.32047/cwb.2022.27.5.5.

[61] R. Hawileh, S. K. Shaw, M. Assad, A. Dey, J. Abdalla, and J. H. Kim, “Influence of Fly Ash on the Compressive Strength of Ultrahigh-Performance Concrete: A State-of-the-art Review Towards Sustainability,” *Int. J. Concr. Struct. Mater.*, vol. 19, Apr. 2025, doi: 10.1186/s40069-024-00757-x.

[62] J. He, C. Sun, and X. Wang, “Study on the Effect of Fly Ash on Mechanical Properties and Seawater Freeze–Thaw Resistance of Seawater Sea Sand Concrete,” *Buildings*, Jul. 2024, doi: 10.3390/buildings14072191.

[63] A. Bersisa and A. Zekaria, “Assessment of the Mechanical Properties of Bagasse Ash Concrete,” *Eng. Sci.*, Aug. 2021, doi: 10.11648/j.es.20210603.12.

[64] N. Bheel, C. Kennedy, P. Awoyera, S. Sohu, and S. A. Abbasi, “Comparative Study on Mechanical Properties of Concrete Blended with Costus englerianus Bagasse Ash and Bagasse Fibre as Partial Replacement for Lime and Cement,” *Adv. Civ. Eng.*, Jun. 2022, doi: 10.1155/2022/8900167.

[65] M. Bisanal, S. Chandrakanth, S. Patil, and S. Khot, “STUDY ON SUGAR CANE BAGASSE ASH IN CONCRETE BY PARTIAL REPLACEMENT OF CEMENT,” vol. 04, pp. 160–162, Apr. 2020, doi: 10.33564/ijeast.2020.v04i11.028.

[66] P. Chindaprasirt, W. Kroehong, N. Damrongwiriyanupap, W. Suriyo, and C. Jaturapitakkul, “Mechanical properties, chloride resistance and microstructure of Portland fly ash cement concrete containing high volume bagasse ash,” *J. Build. Eng.*, vol. 31, p. 101415, Sep. 2020, doi: 10.1016/j.jobe.2020.101415.

[67] K. Chiranjeevi, M. Abraham, B. Rath, and T. Praveenkumar, “Enhancing the properties of geopolymer concrete using nano-silica and microstructure assessment: a sustainable approach,” *Sci. Rep.*, vol. 13, Oct. 2023, doi: 10.1038/s41598-023-44491-y.

[68] S. Da Silva and J. Andrade, “A Review on the Effect of Mechanical Properties and Durability of Concrete with Construction and Demolition Waste (CDW) and Fly Ash in the Production of New Cement Concrete,” *Sustainability*, May 2022, doi: 10.3390/su14116740.

[69] P. K. De Maeijer *et al.*, “Effect of ultra-fine fly ash on concrete performance and durability,” *Constr. Build. Mater.*, Dec. 2020, doi: 10.1016/j.conbuildmat.2020.120493.

[70] V. T. De Sande, M. Sadique, P. Pineda, A. Brás, W. Atherton, and M. Riley, “Potential use of sugar cane bagasse ash as sand replacement for durable concrete,” *J. Build. Eng.*, Feb. 2021, doi: 10.1016/j.jobe.2021.102277.

[71] A. Dhawan, N. Gupta, R. Goyal, and K. Saxena, “Evaluation of mechanical properties of concrete manufactured with fly ash, bagasse ash and banana fibre,” *Mater. Today Proc.*, Jul. 2020, doi: 10.1016/j.matpr.2020.06.006.

[72] M. Al-Azzawi, T. Yu, and M. Hadi, “Factors Affecting the Bond Strength Between the Fly Ash-based Geopolymer Concrete and Steel Reinforcement,” *Structures*, Jun. 2018, doi: 10.1016/j.istruc.2018.03.010.

[73] M. Adisa, S. Odeyemi, U. Wilson, I. S. Subomi, A. F. Olarewaju, and A. S. Adebimpe, "Mechanical properties of geopolymer concrete with partial replacement of fly ash by agricultural waste ashes," *Discov. Civ. Eng.*, vol. 2, Jun. 2025, doi: 10.1007/s44290-025-00272-2.

[74] A. Alaj, N. Krasniqi, and T. Numao, "Effect of Non-Class Fly Ash on Strength Properties of Concrete," *Civ. Eng. J.*, Mar. 2024, doi: 10.28991/cej-2024-010-03-02.

[75] M. I. Alfaroji, H. Medriosa, A. A, F. Nugroho, L. Honesti, and M. Ridwan, "Effect of Using Coal Fly Ash as a Fine Aggregate Substitute on the Compressive Strength of Concrete," *South East Asian J. Adv. Eng. Technol.*, May 2025, doi: 10.62447/seajaet.v2i2.68.

[76] K. P. Alvarenga and G. Cordeiro, "Evaluating Sugarcane Bagasse Fly Ash as a Sustainable Cement Replacement for Enhanced Performance," *Clean. Eng. Technol.*, May 2024, doi: 10.1016/j.clet.2024.100751.

[77] M. Amran *et al.*, "Fly Ash-Based Eco-Efficient Concretes: A Comprehensive Review of the Short-Term Properties," *Materials*, vol. 14, Jul. 2021, doi: 10.3390/ma14154264.

[78] N. Amin, "Use of Bagasse Ash in Concrete and Its Impact on the Strength and Chloride Resistivity," *J. Mater. Civ. Eng.*, vol. 23, pp. 717–720, May 2011, doi: 10.1061/(asce)mt.1943-5533.0000227.