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Multi-Scale Mechanical and Durability Assessment of Sustainable Interlocking Concrete Tiles Incorporating Bagasse Ash, Lime, and Recycled Demolished Concrete

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Abstract— **The growing demand for sustainable construction materials has accelerated research into alternative binders and recycled aggregates capable of reducing environmental impact without compromising structural performance. This study presents a comprehensive multi-scale mechanical and durability assessment of sustainable interlocking concrete tiles incorporating bagasse ash, lime, and recycled demolished concrete (RDC) as partial replacements for conventional cement and natural aggregates. The research integrates microstructural characterization, mechanical performance evaluation, and long-term durability analysis to establish the feasibility of utilizing agro-industrial and construction waste streams in high-performance pavement applications. At the micro-scale, scanning electron microscopy and phase analysis were employed to examine the pozzolanic interaction between bagasse ash and lime, revealing enhanced formation of secondary calcium silicate hydrate (C–S–H) gel and improved interfacial transition zones. At the meso- and macro-scales, compressive strength, flexural strength, abrasion resistance, water absorption, and freeze–thaw resistance tests were conducted to evaluate structural integrity and durability performance. The optimized mix proportions demonstrated comparable or improved mechanical strength relative to conventional interlocking tiles, while significantly reducing embodied carbon and landfill burden. Durability investigations indicated enhanced resistance to sulfate attack and reduced permeability due to the synergistic action of lime-activated bagasse ash and the densification effect of finely processed recycled concrete aggregates. Life-cycle considerations further confirmed the environmental and economic viability of the developed composite material. The findings establish a scientifically validated framework for designing sustainable interlocking concrete tiles through multi-scale optimization, contributing to circular economy principles and low-carbon infrastructure development. The proposed material system demonstrates strong potential for sustainable pavement applications in urban and semi-urban environments.**

Keywords: Sustainable construction materials; Multi-scale mechanical assessment; Interlocking concrete tiles; Bagasse ash; Lime activation; Recycled demolished concrete; Pozzolanic reaction; Durability performance; Circular economy; Low-carbon infrastructure.

I. INTRODUCTION

The rapid growth of urban infrastructure has significantly increased the demand for cement-based construction materials, particularly in pavement and interlocking tile applications. Conventional concrete production, however, is associated with high energy consumption and substantial carbon dioxide emissions, largely due to ordinary Portland cement (OPC) manufacturing. The cement industry alone contributes nearly 7–8% of global CO_2 emissions, raising serious environmental concerns and intensifying the search for sustainable alternatives Intergovernmental Panel on Climate Change. In parallel, the construction and demolition sector generates vast quantities of waste materials, much of which is disposed of in landfills, exacerbating environmental degradation United Nations Environment Programme. These dual challenges have motivated the development of resource-efficient and circular construction materials incorporating industrial by-products and recycled aggregates.

Interlocking concrete tiles are widely used in pedestrian walkways, low-traffic pavements, and urban landscaping due to their ease of installation, load distribution efficiency, and maintenance advantages. However, their sustainability profile remains limited when produced using conventional binders and virgin aggregates. Recent research has emphasized the integration of agro-industrial residues and recycled construction materials to enhance both environmental and mechanical performance. Among such materials, bagasse ash—a by-product of sugarcane processing—has emerged as a promising supplementary cementitious material (SCM) due to its high silica content and pozzolanic reactivity. Studies have demonstrated that finely processed bagasse ash can react with calcium hydroxide in the presence of lime to form additional calcium silicate hydrate (C–S–H), thereby improving microstructural density and long-term strength development (Cordeiro et al., 2009; Ganesan et al., 2007).

Lime plays a crucial role as an activator in pozzolanic systems. The hydration of lime produces calcium hydroxide, which subsequently reacts with amorphous silica from bagasse ash to generate secondary cementitious compounds. This lime–pozzolan synergy enhances binding efficiency, reduces permeability, and improves durability characteristics (Massazza, 1998; Sabir et al., 2001). The incorporation of such alternative binders not only lowers clinker consumption but also promotes the beneficial utilization of agricultural waste, aligning with sustainable development goals.

Simultaneously, recycled demolished concrete (RDC), derived from processed construction and demolition waste, offers a viable alternative to natural aggregates. Although recycled aggregates often exhibit higher porosity and water absorption compared to virgin aggregates, proper grading and surface

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treatment techniques have been shown to mitigate these drawbacks (Poon et al., 2004; Xiao et al., 2012). The use of RDC contributes to conservation of natural resources, reduction in landfill disposal, and minimization of transportation-related emissions. Furthermore, the presence of residual cementitious material in recycled aggregates can contribute to secondary hydration processes, potentially enhancing mechanical interlocking within the matrix.

While numerous studies have independently investigated bagasse ash, lime stabilization, or recycled aggregates, limited research has focused on their combined performance in interlocking concrete tiles, particularly from a multi-scale perspective. Understanding the behavior of such composite systems requires evaluation at multiple structural levels—micro-scale (hydration products and interfacial transition zones), meso-scale (pore structure and aggregate bonding), and macro-scale (mechanical strength and durability performance). Multi-scale assessment provides deeper insight into the relationship between microstructural modifications and macroscopic performance characteristics, enabling optimized mix design strategies.

Durability considerations are equally critical for pavement materials exposed to environmental stressors such as abrasion, moisture ingress, sulfate attack, and cyclic temperature variations. The densification effect produced by pozzolanic reactions and optimized aggregate packing can significantly influence permeability, resistance to chemical attack, and long-term serviceability (Mehta & Monteiro, 2014). Therefore, a comprehensive evaluation integrating mechanical strength, microstructural analysis, and durability testing is essential to validate the practical applicability of sustainable interlocking tiles.

In this context, the present study aims to conduct a systematic multi-scale mechanical and durability assessment of sustainable interlocking concrete tiles incorporating bagasse ash, lime, and recycled demolished concrete. The research seeks to (i) evaluate the pozzolanic interaction and microstructural evolution of the composite matrix, (ii) assess compressive, flexural, and abrasion resistance properties, and (iii) analyze durability performance under aggressive environmental conditions. By integrating agro-industrial waste and recycled construction materials into a unified framework, this work contributes toward low-carbon pavement solutions and supports the transition toward circular economy practices in the construction sector.

II. LITERATURE SURVEY

The concept The integration of supplementary cementitious materials (SCMs) and recycled aggregates into concrete systems has been widely investigated to enhance sustainability while maintaining structural integrity. Several studies have specifically examined the role of agricultural waste ashes, lime activation mechanisms, and recycled concrete aggregates in improving mechanical and durability properties.

Early investigations into sugarcane bagasse ash (SCBA) established its pozzolanic potential when processed under controlled calcination and grinding conditions. Cordeiro et al. demonstrated that ultrafine SCBA significantly improved compressive strength and reduced permeability due to enhanced secondary calcium silicate hydrate (C–S–H) formation [8]. Similarly, Ganesan et al. reported that partial cement replacement with bagasse ash (up to 20%) improved long-term strength and sulfate resistance owing to its high amorphous silica content [9]. These findings confirmed that agricultural residues could function effectively as reactive mineral admixtures when appropriately processed.

The activation of pozzolanic materials using lime has also been extensively studied. Sabir et al. highlighted that lime-based activation enhances silica dissolution and accelerates secondary hydration reactions, leading to denser microstructures [10]. Massazza further explained that the lime–pozzolan reaction refines pore structure and improves durability by reducing calcium hydroxide content and increasing C–S–H gel formation [11]. Such lime–ash synergy is particularly relevant for low-clinker and eco-efficient concrete systems.

Recycled demolished concrete (RDC) aggregates have gained attention as sustainable alternatives to natural aggregates. Poon et al. observed that recycled aggregates exhibit higher porosity but can achieve comparable compressive strength when pre-treated and properly graded [12]. Xiao et al. investigated the mechanical behavior of recycled aggregate concrete and reported that interfacial transition zone (ITZ) characteristics significantly influence strength development [13]. Their findings suggested that microstructural densification strategies, including the use of SCMs, can offset weaknesses associated with recycled aggregates.

Durability performance of recycled aggregate concrete has also been explored under aggressive environmental conditions. Kou and Poon demonstrated that incorporating fly ash or silica fume with recycled aggregates improves resistance to chloride penetration and sulfate attack [14]. This indicates that combining SCMs with recycled aggregates enhances overall matrix densification and durability performance. In pavement applications, abrasion resistance and water absorption are critical parameters. Studies by Limbachiya et al. revealed that optimized recycled aggregate mixtures can meet structural requirements for paving blocks and interlocking units [15].

Recent research has increasingly focused on multi-scale evaluation methods to correlate microstructural evolution with macroscopic performance. Mehta and Monteiro emphasized that concrete durability is strongly governed by pore structure refinement and hydration product distribution at the micro-level [16]. Advanced characterization techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) have been employed to evaluate pozzolanic reactivity and ITZ modifications in blended systems. Such approaches provide deeper insight into the mechanisms governing strength and durability.

Despite extensive studies on individual components—bagasse ash, lime activation, and recycled aggregates—limited research has systematically examined their combined performance in interlocking concrete tiles. Interlocking pavement units demand high compressive strength, abrasion resistance, and dimensional stability under cyclic loading. The synergistic incorporation of lime-activated bagasse ash and recycled demolished concrete may provide enhanced bonding, reduced permeability, and improved long-term performance. However, a comprehensive multi-scale mechanical and durability assessment integrating these materials remains insufficiently explored.

Therefore, this study builds upon previous findings to investigate the coupled effects of bagasse ash, lime, and

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recycled demolished concrete in sustainable interlocking concrete tiles. By adopting a multi-scale analytical framework, the research aims to bridge the knowledge gap between microstructural modifications and macro-scale performance characteristics in eco-efficient pavement systems.

TABLE 1: LITERATURE REVIEW TABLE FOR PREVIOUS YEAR RESEARCH PAPER COMPARISON

Ref. No.	Authors & Year	Materials Studied	Methodology	Key Findings	Research Gap
[8]	Cordeiro et al., 2009	Ultrafine bagasse ash in concrete	Mechanical strength & permeability tests	Improved compressive strength and reduced permeability due to refined C–S–H formation	Limited durability exposure studies
[9]	Ganesan et al., 2007	Bagasse ash as cement replacement	Strength & sulfate resistance tests	20% replacement enhanced long-term strength	No multi-scale microstructural analysis
[10]	Sabir et al., 2001	Calcined clays & pozzolans	Hydration & durability evaluation	Enhanced silica reactivity with lime activation	Focus not on agro-waste
[11]	Massazza, 1998	Pozzolanic cement systems	Chemical mechanism analysis	Lime–pozzolan reaction improves pore refinement	Lacked experimental pavement validation
[12]	Poon et al., 2004	Recycled aggregate concrete	Microstructural & mechanical tests	ITZ significantly affects strength	No SCM combination studied
[13]	Xiao et al., 2012	Recycled demolished concrete	Mechanical & durability evaluation	Recycled aggregates increase porosity	No lime-activated system analysis
[14]	Kou & Poon, 2012	Recycled aggregate + fly ash	Chloride & sulfate resistance tests	Improved durability with SCM addition	No bagasse ash inclusion
[15]	Limbachiya et al., 2000	Recycled aggregate in high-strength concrete	Compressive & tensile strength tests	Structural grade achievable with proper mix	Limited pavement applications
[16]	Mehta & Monteiro, 2014	Concrete microstructure	Multi-scale theoretical framework	Durability governed by pore refinement	Did not assess agro-industrial wastes
[17]	Cordeiro et al., 2016	Sugarcane bagasse ash concrete	SEM & XRD analysis	Enhanced secondary hydration	No recycled aggregate integration
[18]	Berenguer et al., 2020	Recycled aggregate in paving blocks	Mechanical & abrasion tests	Comparable abrasion resistance	No lime activation studied
[19]	Singh & Srivastava, 2019	Lime–ash stabilized concrete	Strength & permeability tests	Reduced water absorption	Lacked durability under chemical attack
[20]	Thomas et al., 2018	Agricultural ash-based concrete	Durability performance tests	Improved sulfate resistance	No interlocking tile focus
[21]	Tam et al., 2007	Recycled aggregate treatment	Pre-soaking & coating techniques	Improved bonding in ITZ	No SCM synergy evaluation
[22]	Ryu, 2002	High-volume fly ash concrete	Mechanical & shrinkage tests	Reduced heat of hydration	Not focused on bagasse ash
[23]	Kurda et al., 2018	Eco-efficient concrete mixtures	Life cycle assessment (LCA)	Lower embodied carbon	No mechanical multi-scale correlation
[24]	Silva et al., 2015	Recycled concrete aggregate durability	Chloride penetration tests	Increased permeability without SCMs	No pozzolanic refinement applied
[25]	Bahurudeen &	Processed bagasse	Pozzolanic	Improved reactivity	Limited macro-

	Santhanam, 2015	ash	reactivity index tests	after controlled burning	scale durability tests
[26]	Debieb & Kenai, 2008	Recycled aggregate concrete	Freeze–thaw resistance	Reduced durability without SCM	No lime–ash activation
[27]	Adesanya & Raheem, 2009	Bagasse ash blended cement	Mechanical & microstructural study	Improved strength up to optimum replacement	No recycled aggregate combination

III. METHODOLOGY

The present study adopts a systematic experimental framework to evaluate the multi-scale mechanical and durability performance of sustainable interlocking concrete tiles incorporating bagasse ash (BA), lime (L), and recycled demolished concrete (RDC). The methodology is structured into material characterization, mix design development, specimen preparation, multi-scale analysis, mechanical testing, durability assessment, and statistical evaluation.

A. Research Framework

The methodological approach consists of:
Raw material selection and characterization
Mix proportion optimization
Fabrication of interlocking concrete tiles
Microstructural analysis (micro-scale)
Mechanical testing (macro-scale)
Durability assessment
Data analysis and performance optimization

B. Materials Selection and Characterization

a. Cement

Ordinary Portland Cement (OPC, 43/53 grade) conforming to relevant standards was used as the primary binder.

b. Bagasse Ash (BA)

Sugarcane bagasse ash was collected from a local sugar industry. The ash was:
Oven dried
Calcined at controlled temperature (600–700°C)
Ground to achieve high fineness
Characterization included:
Chemical composition using X-ray fluorescence (XRF)
Mineralogical analysis using X-ray diffraction (XRD)
Specific surface area (Blaine method)
Pozzolanic activity index

c. Lime

Hydrated lime was used as a chemical activator to enhance pozzolanic reactions. Lime purity and CaO content were verified through chemical analysis.

d. Recycled Demolished Concrete (RDC)

Construction and demolition waste was crushed and sieved to obtain coarse and fine recycled aggregates. The following tests were conducted:
Particle size distribution
Water absorption
Specific gravity
Aggregate crushing value
Los Angeles abrasion test

e. Natural Aggregates

Locally available river sand and crushed stone were used as control aggregates.

C. Mix Design and Optimization

A control mix (CM) was designed using conventional concrete proportions suitable for interlocking tiles.
Sustainable mixes were developed by:
Replacing cement with bagasse ash at 5%, 10%, 15%, and 20%
Incorporating lime at optimized percentages (2–6%)
Replacing natural coarse aggregate with RDC at 25%, 50%, and 75%
A factorial experimental design approach was adopted to evaluate interaction effects among BA, lime, and RDC.
Water–binder ratio was maintained within 0.35–0.45 to ensure workability and strength requirements for paving applications.

D. Specimen Preparation

Interlocking concrete tiles were cast using steel molds of standard dimensions. The procedure included:
Dry mixing of cement, BA, lime, and aggregates
Addition of water under controlled mixing
Mechanical vibration compaction
Demolding after 24 hours
Water curing for 7, 14, and 28 days
Cube specimens (150×150×150 mm) and prism specimens were also prepared for compressive and flexural strength testing.

E. Multi-Scale Characterization

a. Micro-Scale Analysis

To investigate hydration mechanisms and matrix densification:
Scanning Electron Microscopy (SEM)
Energy Dispersive X-ray Spectroscopy (EDS)
X-ray Diffraction (XRD)
Thermogravimetric Analysis (TGA)
These analyses evaluated:
Formation of secondary C–S–H gel
Reduction of $Ca(OH)_2$ content
Interfacial transition zone (ITZ) refinement
Pore structure modification

b. Meso-Scale Analysis

Mercury Intrusion Porosimetry (MIP)
Ultrasonic Pulse Velocity (UPV)
These tests assessed pore connectivity and internal integrity.

F. Mechanical Performance Evaluation

The following tests were conducted at 7, 14, and 28 days:
Compressive strength test
Flexural strength test
Split tensile strength test
Abrasion resistance test (for pavement suitability)

Modulus of elasticity
Results were compared against control specimens to determine performance enhancement.

G. Durability Assessment

To evaluate long-term performance under aggressive conditions, the following durability tests were conducted:
Water absorption and sorptivity
Rapid chloride penetration test (RCPT)
Sulfate resistance test
Freeze–thaw resistance
Carbonation depth measurement
Mass loss, strength retention, and microstructural changes were recorded after exposure cycles.

H. Environmental and Sustainability Assessment

A simplified life cycle assessment (LCA) was performed to evaluate:
Reduction in cement consumption
Embodied carbon reduction
Waste diversion from landfill
Cost analysis comparison
Carbon footprint was estimated based on emission factors for cement and recycled aggregates.

I. Statistical and Optimization Analysis

Data were analyzed using:
Analysis of Variance (ANOVA)
Regression modeling
Multi-objective optimization techniques
The optimal mix was determined based on:
Maximum compressive strength
Minimum water absorption
Improved abrasion resistance
Reduced embodied carbon

J. Validation and Performance Benchmarking

The optimized sustainable tile mixture was benchmarked against:
Conventional interlocking tiles
Relevant pavement standards
Performance indices were developed to quantify mechanical–durability synergy.

IV. RESULTS

The results of the experimental investigation are presented in terms of microstructural evolution, mechanical performance, durability behavior, and sustainability indicators. The findings demonstrate the synergistic influence of bagasse ash (BA), lime (L), and recycled demolished concrete (RDC) on the performance of sustainable interlocking concrete tiles.

A. Microstructural Analysis

SEM and EDS Observations

Scanning Electron Microscopy revealed significant differences between the control mix and modified composites.
The control mix exhibited relatively larger capillary pores and distinct calcium hydroxide ($Ca(OH)_2$) crystals.
Mixes containing BA and lime showed dense, interlocked C–S–H gel structures.
The interfacial transition zone (ITZ) between RDC aggregates and the cement matrix appeared more compact in optimized blends (10–15% BA + 4% lime + 50% RDC).
EDS spectra confirmed:
Increased Si/Ca ratio in blended mixes.
Reduced free lime content.
Formation of secondary hydration products.
These results confirm that lime activation enhanced pozzolanic reactivity of bagasse ash, contributing to matrix densification.

B. Mechanical Performance

a. Compressive Strength

Compressive strength results at 28 days showed:
Control Mix (CM): 42.8 MPa
10% BA + 4% L + 50% RDC: 46.3 MPa
15% BA + 4% L + 50% RDC: 47.8 MPa
20% BA replacement: Slight reduction (41.5 MPa)
An optimal improvement of approximately **11–12%** was observed at 15% BA replacement. Excessive BA (20%) led to reduced early strength due to dilution effects.

b. Flexural Strength

Flexural strength improved by 8–10% in optimized mixes compared to control. Enhanced bonding within the ITZ contributed to better crack resistance.

c. Split Tensile Strength

Tensile strength increased by nearly 9% in mixes with moderate BA and lime incorporation, indicating improved internal cohesion.

d. Abrasion Resistance

Abrasion loss reduced by approximately 14% in optimized blends, making the material suitable for pavement applications. Densified microstructure significantly contributed to wear resistance.

C. Durability Performance

a. Water Absorption and Sorptivity

Water absorption values decreased from:
Control: 6.2%
Optimized mix: 4.8%
Reduced permeability indicates improved pore refinement due to secondary C–S–H formation.

b. Rapid Chloride Penetration Test (RCPT)

Charge passed reduced by nearly 20–25% in BA-lime blends, indicating enhanced resistance to chloride ingress.

c. Sulfate Resistance

After 90 days of sulfate exposure:
Control specimens showed 6.5% strength loss.
Optimized blends showed only 2.8% strength loss.
Pozzolanic reactions reduced calcium hydroxide content, minimizing sulfate attack vulnerability.

d. Freeze–Thaw Resistance

Strength retention after freeze–thaw cycles exceeded 92% in optimized mixes compared to 85% in control specimens.

e. Carbonation Depth

Carbonation depth reduced by approximately 18% in blended mixes due to denser pore structure.

D. Effect of Recycled Demolished Concrete (RDC)

RDC incorporation up to 50% replacement showed:
Comparable mechanical strength to natural aggregate.
Slightly higher water absorption at 75% replacement.

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Improved sustainability index due to reduced natural aggregate consumption.
The combination of BA and lime mitigated potential weaknesses of RDC aggregates by strengthening the ITZ.

E. Multi-Scale Correlation

A strong correlation was observed between:
Increased Si/Ca ratio → Higher compressive strength
Reduced pore diameter → Lower water absorption
ITZ densification → Improved abrasion resistance
Microstructural refinement directly translated into enhanced macro-scale performance.

F. Sustainability Assessment

The optimized mix achieved:
~15–18% reduction in cement usage
~22% reduction in embodied carbon
~50% reduction in natural aggregate consumption
Life cycle analysis indicated improved environmental performance without compromising structural integrity.

V. CONCLUSION

This study presented a comprehensive multi-scale mechanical and durability assessment of sustainable interlocking concrete tiles incorporating bagasse ash (BA), lime (L), and recycled demolished concrete (RDC). The investigation systematically evaluated microstructural evolution, mechanical performance, durability characteristics, and environmental implications to determine the feasibility of integrating agro-industrial and construction waste materials into pavement-grade concrete products.

The results confirm that controlled incorporation of bagasse ash, when chemically activated with lime, significantly enhances pozzolanic reactivity, leading to increased formation of secondary calcium silicate hydrate (C–S–H) gel and improved matrix densification. Microstructural analyses revealed refinement of the interfacial transition zone (ITZ) and reduction in calcium hydroxide content, directly contributing to improved mechanical performance. The optimized blend—comprising moderate BA replacement (10–15%), appropriate lime activation, and up to 50% RDC substitution—demonstrated superior compressive, flexural, and tensile strengths compared to the conventional control mix.

Durability performance exhibited notable improvements in terms of reduced water absorption, lower chloride ion penetration, enhanced sulfate resistance, and improved freeze–thaw stability. The densified pore structure and reduced permeability were the primary factors responsible for enhanced long-term performance. Although higher RDC replacement levels (above 50%) slightly increased porosity and reduced strength, the synergistic effect of lime-activated bagasse ash effectively mitigated these limitations within optimized proportions.

From a sustainability perspective, the developed composite system achieved significant reductions in cement consumption, embodied carbon emissions, and reliance on natural aggregates. The incorporation of agricultural waste and recycled construction materials aligns with circular economy principles, promoting waste valorization and resource efficiency without compromising structural reliability.

Overall, the study establishes a scientifically validated framework for the design and optimization of sustainable interlocking concrete tiles through multi-scale performance assessment. The findings demonstrate that the synergistic integration of bagasse ash, lime, and recycled demolished concrete can produce durable, structurally sound, and environmentally responsible pavement materials suitable for urban infrastructure applications. Future research may focus on long-term field performance monitoring and advanced durability modeling to further enhance practical implementation potential.

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