

# *Multi-Scale Performance Assessment of Sustainable Interlocking Concrete Tiles: A Comprehensive Review of Bagasse Ash, Lime, and Recycled Demolished Concrete Integration*

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**Abstract**—The construction industry is undergoing a transformative shift toward sustainable material innovation, driven by the urgent need to reduce carbon emissions, conserve natural resources, and manage industrial and construction waste effectively. Interlocking concrete tiles (ICTs) have emerged as a promising alternative to conventional paving systems due to their structural efficiency, ease of installation, and reduced maintenance requirements. This comprehensive review critically examines the multi-scale performance of sustainable interlocking concrete tiles incorporating bagasse ash, lime, and recycled demolished concrete (RDC) as partial replacements for conventional constituents. At the micro-scale, the review synthesizes findings on pozzolanic reactivity, particle morphology, and interfacial transition zone (ITZ) refinement resulting from the synergistic interaction between bagasse ash and lime. The formation of secondary calcium silicate hydrates (C–S–H) and improved matrix densification are analyzed in relation to mechanical strength enhancement and durability performance. At the meso- and macro-scales, the study evaluates compressive strength, flexural resistance, abrasion behavior, water absorption, freeze–thaw resistance, and load transfer efficiency of interlocking systems containing recycled aggregates derived from demolished concrete. Particular attention is given to the influence of replacement ratios, curing regimes, and compaction techniques on structural reliability and long-term serviceability. Environmental performance indicators, including embodied energy reduction, waste valorization potential, and life-cycle assessment metrics, are comparatively assessed to establish sustainability benchmarks. The review further identifies existing research gaps in long-term durability modeling, field performance validation, and multi-objective optimization of mix design parameters. By integrating material science perspectives with structural and environmental performance evaluation, this study provides a holistic framework for advancing next-generation sustainable interlocking pavement systems.

**Keywords:** Sustainable interlocking concrete tiles; Bagasse ash; Lime stabilization; Recycled demolished concrete; Pozzolanic reactivity; Interfacial transition zone; Multi-scale performance assessment; Durability analysis; Waste valorization; Life-cycle assessment; Sustainable construction materials; Circular economy in infrastructure.

## I. INTRODUCTION

Rapid urbanization and infrastructure expansion have significantly increased the demand for concrete-based construction materials, leading to excessive consumption of natural resources and substantial environmental degradation. The cement and concrete industry alone contributes nearly 8% of global carbon dioxide emissions, primarily due to energy-intensive clinker production and extensive aggregate mining activities [1], [2]. In response, sustainable construction practices emphasizing waste utilization, resource efficiency, and reduced environmental impact have gained considerable attention in recent years.

Interlocking concrete tiles (ICTs) have emerged as an effective alternative to conventional rigid pavements owing to their modular design, ease of installation, superior load distribution, and simplified maintenance [3]. Their inherent flexibility allows for better stress accommodation under traffic loads and environmental variations, making them suitable for urban pavements, pedestrian walkways, and low-volume roads [4]. However, the sustainability of ICTs largely depends on the materials used in their production, particularly cement and natural aggregates, which remain environmentally burdensome. The incorporation of supplementary cementitious materials (SCMs) and recycled aggregates has been widely recognized as a viable strategy for enhancing the sustainability of concrete products. Among various agro-industrial by-products, bagasse ash—derived from sugarcane residue combustion—has demonstrated promising pozzolanic characteristics due to its high amorphous silica content [5]. When suitably processed, bagasse ash can partially replace cement, contributing to reduced carbon emissions while improving microstructural densification and long-term strength development [6]. The addition of lime further enhances the pozzolanic reactivity of bagasse ash by supplying free calcium hydroxide, facilitating the formation of secondary calcium silicate hydrate (C–S–H) phases [7].

Simultaneously, construction and demolition waste represents one of the largest waste streams globally, with recycled demolished concrete (RDC) offering substantial potential as a replacement for natural aggregates [8]. The utilization of RDC not only reduces landfill burden but also conserves virgin aggregate resources. Previous studies have reported that, with appropriate mix design and processing techniques, recycled aggregates can be effectively incorporated into concrete paving elements without compromising structural performance [9].

Nevertheless, challenges related to higher porosity, water absorption, and weaker interfacial transition zones necessitate careful evaluation, particularly for load-bearing interlocking systems [10].

A comprehensive understanding of ICT performance requires assessment across multiple length scales. At the micro-scale, material interactions, hydration products, and pore structure evolution govern strength and durability. At the meso-scale, aggregate distribution and interlocking geometry influence stress transfer and crack propagation. At the macro-scale, system-level performance, including load-bearing capacity, abrasion resistance, and long-term durability, determines field applicability [11]. Despite numerous experimental investigations, an integrated multi-scale performance assessment of ICTs incorporating bagasse ash, lime, and RDC remains limited in existing literature.

Therefore, this review aims to critically analyze the combined influence of bagasse ash, lime, and recycled demolished concrete on the mechanical, durability, and environmental performance of sustainable interlocking concrete tiles. By synthesizing findings from microstructural studies, mechanical testing, durability evaluation, and life-cycle assessments, this work seeks to establish a holistic framework for designing next-generation eco-efficient interlocking pavement systems aligned with circular economy principles.

## II. LITERATURE SURVEY

The integration of supplementary cementitious materials and recycled aggregates into concrete products has been widely investigated to enhance sustainability while maintaining structural performance. In the context of interlocking concrete tiles (ICTs), multi-scale material interactions play a decisive role in determining mechanical strength, durability, and long-term serviceability.

### A. Micro-Scale Behavior of Bagasse Ash and Lime-Modified Systems

Pozzolanic materials such as bagasse ash (BA) have been extensively studied for their high amorphous silica content and potential to form secondary hydration products. Cordeiro et al. [11] demonstrated that finely ground sugarcane bagasse ash significantly improves compressive strength due to enhanced pozzolanic activity and pore refinement. The formation of additional calcium silicate hydrate (C-S-H) phases contributes to microstructural densification, thereby reducing permeability and enhancing durability.

Further investigations by Ganesan et al. [12] reported that controlled burning and grinding processes are critical in optimizing the reactivity of bagasse ash. Their study revealed that appropriate fineness improves particle packing and reduces capillary porosity. Similarly, Bahurudeen and Santhanam [13] emphasized the influence of calcination temperature on silica crystallinity, showing that amorphous silica-rich ash exhibits superior pozzolanic performance compared to crystalline forms.

The synergistic effect of lime in activating pozzolanic reactions has also been documented. Chindaprasirt et al. [14] observed that lime supplementation enhances the reaction kinetics between silica-rich ashes and calcium hydroxide, leading to improved early-age strength. The lime-activated systems exhibited reduced microcracking and a denser interfacial

transition zone (ITZ). This microstructural refinement is particularly important for interlocking tiles, where load transfer efficiency depends on matrix integrity.

Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses conducted by Singh et al. [15] confirmed the progressive formation of C-S-H gel and reduced portlandite content in bagasse ash-lime blended systems. These micro-scale transformations directly influence macro-scale performance indicators such as compressive and flexural strength.

### B. Performance of Recycled Demolished Concrete Aggregates

The use of recycled demolished concrete (RDC) as a replacement for natural aggregates has gained global attention due to environmental and economic considerations. Silva et al. [16] provided a comprehensive evaluation of recycled aggregate properties, highlighting higher water absorption and porosity compared to natural aggregates. These characteristics may adversely affect workability and strength unless properly addressed through mix design modifications.

Xiao et al. [17] demonstrated that recycled aggregate concrete (RAC) can achieve satisfactory mechanical properties when replacement levels are optimized and pre-treatment techniques are employed. Their experimental findings indicated that compressive strength reductions are manageable at moderate replacement ratios (below 30–40%).

Kou and Poon [18] examined the durability performance of RAC and reported that while water absorption and chloride penetration may increase, the incorporation of supplementary cementitious materials mitigates these drawbacks by refining pore structure. This finding is particularly relevant for ICT applications exposed to cyclic loading and environmental variations.

In addition, Limbachiya et al. [19] investigated the performance of paving blocks produced using recycled aggregates and observed that proper compaction and curing significantly enhance abrasion resistance and load-bearing capacity. Their results suggest that RDC-based interlocking tiles can meet standard requirements for pedestrian and light-traffic pavements.

### C. Mechanical and Durability Performance of Interlocking Concrete Tiles

Interlocking concrete pavements have been studied extensively for their structural behavior under static and dynamic loads. Shackel [20] highlighted that the load distribution mechanism in interlocking systems depends not only on tile strength but also on joint sand behavior and block geometry. The interlock effect improves stress transfer and reduces localized cracking.

Knapton [21] demonstrated that compressive strength and abrasion resistance are key performance indicators for paving blocks subjected to vehicular loading. Studies incorporating waste-derived materials into paving blocks have shown promising results when mix proportions are carefully optimized.

Recent research by Kurda et al. [22] emphasized the importance of durability evaluation, including freeze-thaw resistance and sulfate attack performance, especially for recycled aggregate-based concrete products. Their findings indicated that microstructural densification through SCM

incorporation compensates for the inherent weaknesses of recycled aggregates.

Moreover, life-cycle assessment (LCA) studies conducted by Gursel et al. [23] confirmed that partial replacement of cement and natural aggregates significantly reduces embodied carbon and energy consumption. The environmental benefits become more pronounced when agro-industrial and construction waste streams are valorized simultaneously.

**D. Multi-Scale Assessment and Research Gaps**

Although numerous studies have independently examined bagasse ash, lime activation, and recycled aggregates, integrated investigations focusing on ICT systems remain limited. Most research addresses either microstructural characteristics or macro-level mechanical properties, with

insufficient linkage between scales. The interaction between pozzolanic matrix refinement and recycled aggregate-induced porosity requires deeper exploration, particularly concerning long-term durability and field performance.

Furthermore, the optimization of replacement ratios balancing strength, durability, and environmental impact has not been comprehensively addressed using multi-objective frameworks. Long-term performance modeling, creep behavior under repeated loading, and real-world validation studies are still underrepresented in existing literature.

Therefore, a holistic multi-scale performance assessment that integrates microstructural analysis, mechanical evaluation, durability testing, and sustainability metrics is essential for advancing the application of bagasse ash–lime–RDC-based interlocking concrete tiles.

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

Ref.	Authors & Year	Material Focus	Scale of Study	Key Findings	Identified Gap
[11]	Cordeiro et al., 2009	Ultrafine Bagasse Ash	Micro	Improved C–S–H formation and strength gain	Limited durability analysis
[12]	Ganesan et al., 2007	Bagasse Ash in Concrete	Micro–Macro	Enhanced compressive strength at 10–20% replacement	No interlocking tile application
[13]	Bahurudeen & Santhanam, 2015	Processed Bagasse Ash	Micro	Calcination temperature controls reactivity	Field performance not evaluated
[14]	Chindaprasirt et al., 2007	Lime-Activated Systems	Micro	Improved pozzolanic kinetics	No recycled aggregate integration
[15]	Singh et al., 2011	Bagasse Ash Concrete	Micro	Reduced portlandite; denser matrix	Long-term durability missing
[16]	Silva et al., 2014	Recycled Aggregates	Micro–Meso	High porosity and absorption	No SCM synergy studied
[17]	Xiao et al., 2005	Recycled Aggregate Concrete	Macro	Acceptable strength at moderate replacement	Interlocking behavior not studied
[18]	Kou & Poon, 2009	Recycled Aggregates + SCM	Micro–Macro	Improved durability via pore refinement	No paving block focus
[19]	Limbachiya et al., 2000	Recycled Aggregate Concrete	Macro	Structural feasibility confirmed	Multi-scale assessment absent
[20]	Shackel, 1990	Interlocking Pavements	System	Effective load distribution mechanism	Sustainable materials not considered
[21]	Knapton, 1980	Concrete Block Paving	System	Structural design methodology proposed	Environmental analysis missing
[22]	Kurda et al., 2014	RAC + LCA	Macro–Environmental	Reduced embodied carbon	No agro-waste integration
[23]	Gursel et al., 2016	Concrete LCA	Environmental	Cement dominates carbon footprint	No interlocking tile focus
[24]	Siddique, 2008	Industrial Waste in Concrete	Macro	SCM improves durability	Bagasse ash not emphasized

[25]	Thomas et al., 2018	Agricultural Ashes	Micro–Macro	Improved resistance to chloride ingress	No RDC combination studied
[26]	Tam et al., 2007	Recycled Aggregate Processing	Meso	Treatment improves aggregate quality	SCM interaction unaddressed
[27]	Evangelista & de Brito, 2010	RAC Durability	Macro	Acceptable mechanical behavior	Multi-objective optimization missing
[28]	Rashwan et al., 2016	Bagasse Ash Mortar	Micro	Increased later-age strength	No paving tile testing
[29]	Medina et al., 2014	Recycled Concrete Blocks	Macro	Viable for non-structural units	Abrasion resistance not studied
[30]	Poon et al., 2004	High Volume Recycled Aggregate	Macro	Reduced strength at high replacement	Microstructure linkage absent
[31]	Mehta & Monteiro, 2014	Sustainable Concrete Theory	Multi-scale	Microstructure governs durability	No empirical ICT focus
[32]	de Brito & Saikia, 2013	RAC Review	Macro	Replacement <30% feasible	No lime-ash synergy discussion
[33]	Berndt, 2009	Fly Ash & Durability	Micro–Macro	SCM reduces permeability	Agro-waste comparison limited
[34]	Gholampour et al., 2017	Recycled Aggregate Concrete	Macro	Strength slightly reduced but acceptable	Interlocking geometry impact missing
[35]	Kurad et al., 2019	Multi-scale Concrete Modeling	Multi-scale	Integrated micro–macro relationship	Not applied to ICT systems

### III. SUSTAINABLE INTERLOCKING CONCRETE TILES

Sustainable interlocking concrete tiles (SICTs) represent an advanced evolution of conventional concrete block pavements, integrating environmental responsibility with structural efficiency. Unlike monolithic rigid pavements, interlocking systems consist of modular precast concrete units arranged in specific geometric patterns that enable mechanical interlock and effective load transfer. When designed with sustainable materials such as agricultural ashes, industrial by-products, and recycled aggregates, these systems significantly reduce embodied carbon, natural resource depletion, and construction waste generation.

The increasing emphasis on circular economy principles in construction has accelerated the development of eco-efficient paving technologies. Sustainable interlocking tiles aim to combine durability, mechanical reliability, and environmental performance while maintaining cost-effectiveness and ease of installation.

#### A. Structural Concept and Load Transfer Mechanism

Interlocking concrete tiles function through:

**Horizontal interlock** – Achieved via joint sand and friction between adjacent units.

**Vertical interlock** – Ensured through shear transfer and confinement.

**Rotational interlock** – Provided by geometric shape and edge restraint.

This multi-directional load distribution mechanism allows interlocking systems to perform effectively under traffic loads, thermal variations, and minor subgrade movements. Unlike rigid slabs, localized damage can be repaired without complete pavement replacement, enhancing lifecycle sustainability.

#### B. Sustainable Material Integration

Sustainability in interlocking tiles is primarily achieved through strategic material substitutions:

##### Supplementary Cementitious Materials (SCMs)

###### Bagasse ash

Fly ash

Rice husk ash

Ground granulated blast furnace slag (GGBS)

These materials partially replace cement, reducing CO<sub>2</sub> emissions and improving microstructural densification via pozzolanic reactions.

###### Lime Activation

Lime enhances pozzolanic reactivity of silica-rich agrowastes by accelerating calcium silicate hydrate (C–S–H) formation, improving early-age strength and matrix stability.

##### Recycled Demolished Concrete (RDC)

Recycled aggregates derived from construction and demolition waste:

Reduce landfill burden

Conserve natural aggregates

Lower embodied energy

Although recycled aggregates exhibit higher porosity, optimized mix design and SCM incorporation mitigate performance concerns.

### C. Multi-Scale Performance Characteristics

Sustainable interlocking tiles must be evaluated across multiple scales:

#### Micro-Scale

Pozzolanic reaction kinetics

Interfacial transition zone (ITZ) refinement

Pore structure reduction

Secondary C–S–H formation

#### Meso-Scale

Aggregate distribution

Interlocking geometry

Crack propagation behavior

#### Macro-Scale

Compressive strength

Flexural strength

Abrasion resistance

Water absorption

Freeze–thaw durability

Load-bearing capacity

Multi-scale analysis ensures structural integrity while maximizing sustainability benefits.

## IV. CONCLUSION

Sustainable interlocking concrete tiles (SICTs) represent a technically viable and environmentally responsible alternative to conventional pavement systems, particularly in the context of increasing resource scarcity and carbon emission concerns. The integration of bagasse ash, lime, and recycled demolished concrete demonstrates strong potential to transform interlocking pavements into circular, low-carbon infrastructure solutions without compromising structural performance.

From a microstructural perspective, the incorporation of finely processed bagasse ash, especially when activated with lime, enhances pozzolanic reactivity and promotes the formation of secondary calcium silicate hydrate (C–S–H) gel. This results in pore refinement, densification of the cementitious matrix, and improvement in interfacial transition zone (ITZ) characteristics. Such micro-scale improvements translate into measurable macro-scale performance gains, including increased compressive strength, improved abrasion resistance, and enhanced durability against moisture ingress and environmental exposure.

At the aggregate level, recycled demolished concrete contributes significantly to sustainability by reducing reliance on virgin aggregates and diverting construction waste from landfills. Although recycled aggregates inherently exhibit higher porosity and water absorption, optimized mix proportioning, adequate curing regimes, and the synergistic use of supplementary cementitious materials effectively mitigate associated performance limitations. The structural interlock mechanism of modular tiles further enhances load transfer efficiency, making these systems suitable for pedestrian zones, parking areas, and low- to medium-traffic pavements.

Environmentally, the simultaneous utilization of agro-industrial waste and construction demolition waste supports circular economy objectives, reduces embodied carbon, and improves overall life-cycle performance. Sustainable interlocking

systems also offer advantages such as ease of maintenance, reusability, and adaptability, which extend service life and lower long-term environmental impact.

Despite these advancements, several research gaps remain. Long-term field performance validation, durability modeling under cyclic loading, freeze–thaw exposure, and multi-objective optimization of replacement ratios require deeper investigation. Additionally, standardization of design guidelines for sustainable interlocking tile production is necessary to facilitate broader industrial adoption.

In summary, the multi-scale performance assessment confirms that sustainable interlocking concrete tiles integrating bagasse ash, lime, and recycled demolished concrete can achieve a balanced combination of structural reliability, durability, and environmental efficiency. With continued research and optimization, such systems hold strong potential to contribute significantly to resilient, low-carbon urban infrastructure development.

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