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Valorization Of Industrial Ash Waste As Eco-Friendly Binder For Pavement Applications: Experimental Study On Strength And Permeability Properties

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Abstract

As the construction industry faces increasing pressure to reduce its environmental footprint, the use of industrial byproducts as alternative construction materials presents a promising strategy for promoting sustainability. This study investigates the potential valorization of industrial ash waste, particularly fly ash and steel slag, as an eco-friendly binder in permeable pavement applications. The main objective is to engineer a sustainable binder mix that aligns with circular economy principles while maintaining structural and hydraulic performance, particularly in tropical climate conditions. A series of experimental tests was conducted on various ash-based binder formulations to evaluate compressive strength, permeability rate, and durability under simulated tropical environmental exposure. Complementary microstructural analyses using scanning electron microscopy (SEM) and X-ray diffraction (XRD) were also performed to explore the internal bonding characteristics and hydration behavior. The results revealed that specific combinations of fly ash and steel slag achieved compressive strength values comparable to conventional cement-based binders, while exhibiting significantly higher water permeability, an essential feature for stormwater management in urban areas. Moreover, the binder demonstrated good resistance to moisture-induced degradation. These findings suggest that industrial ash waste can be effectively transformed into high-performance, low-impact materials for green infrastructure. This research contributes to both material innovation and sustainable engineering practices, offering a viable solution for environmentally responsible pavement design in developing countries with tropical climates.

I. INTRODUCTION

The growing demand for sustainable infrastructure has prompted civil engineers and material scientists to seek innovative solutions that reduce environmental degradation while maintaining structural performance. One of the pressing environmental issues in the construction industry is the large-scale generation of industrial waste and its insufficient management, particularly in rapidly urbanizing regions. As governments and industries around the world promote circular economy principles, there is increasing interest in repurposing waste materials such as fly ash and steel slag as functional components in construction (Barreiro-Gen & Lozano, 2020; Corvellec et al., 2022; Mies & Gold, 2021). Circular economy strategies not only mitigate waste but also reduce the demand for virgin materials and lower carbon emissions in the built environment (Ekins et al., 2019; Webster, 2021).

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Industrial ash waste, especially fly ash from coal combustion and steel slag from metal production, is often discarded despite its latent pozzolanic properties and structural potential. Utilizing these by-products as alternative binders or aggregates in construction offers a promising path toward sustainable material innovation (Apithanyasai et al., 2020; Thuy Nguyen et al., 2024). Recent studies have shown the feasibility of incorporating ash waste in geopolymer concrete, bricks, and eco-binders, with varying degrees of success in terms of strength, durability, and environmental compatibility (Afrin et al., 2021; Huang et al., 2021; Moure Abelenda et al., 2021). However, while these innovations have advanced in some contexts, their use as functional binders in pavement engineering, particularly in permeable pavement systems, remains relatively limited compared to conventional concrete applications, especially in tropical climates.

Permeable pavements are increasingly recognized as effective solutions for urban stormwater management, mitigating surface runoff, reducing flooding risk, and enhancing groundwater recharge (Chen et al., 2021; Yu et al., 2021). In tropical regions, where heavy rainfall and urban heat exacerbate infrastructural stress, such systems are especially critical (Carruthers et al., 2024; Rahman et al., 2021). Conventional permeable pavement systems often rely on high-energy materials like Portland cement, which contradict the goals of ecological balance and low-impact design (Afrin et al., 2021). Consequently, the development of eco-friendly binders that can partially replace cement while maintaining an adequate balance between mechanical strength and hydraulic permeability is essential for sustainable pavement systems in tropical environments.

The integration of industrial ash waste into pavement design addresses two key challenges: environmental waste management and sustainable urban infrastructure. By valorizing these materials as part of functional engineering systems, the construction sector can significantly contribute to ecological resilience and circular economy implementation (Karstensen et al., 2019; Tambovceva et al., 2021). From a material efficiency perspective, substituting a portion of cement with industrial ash directly reduces cement consumption and associated CO_2 emissions, while simultaneously transforming waste streams into value-added construction resources. Such strategies support international sustainability agendas by promoting resource efficiency, lowering environmental footprints, and fostering innovation in material utilization (Grafström, 2020; Suchek et al., 2021).

While prior studies have explored the environmental benefits of using recycled or industrial by-products, experimental validation of ash-based binders that simultaneously address strength and permeability requirements for permeable pavement applications remains scarce, particularly under tropical climate conditions. Most existing research emphasizes either mechanical performance or environmental benefits in isolation, with limited integration of performance indicators relevant to permeable pavements, such as interconnected pore structure, moisture resistance, and hydraulic efficiency (Liu et al., 2020; Seifeddine et al., 2022). This lack of holistic experimental assessment represents a critical research gap.

In addition to technical evaluation, this study considers the broader systemic impact of adopting ash-based binders in urban settings. Embedding waste valorization into mainstream engineering practice requires not only material feasibility but also shifts in regulatory standards, supply chains, and professional culture (Corvellec et al., 2022; Jaeger-Erben et al., 2021). This research contributes to such a transition by providing empirically grounded experimental evidence on the performance of ash-based eco-binders, specifically tailored for permeable pavement systems in tropical climates. Ultimately, this study seeks to advance sustainable construction by bridging environmental necessity and engineering innovation. By experimentally demonstrating that an optimized ash-based binder mixture can reduce cement usage while maintaining functional pavement performance, the findings reinforce the practical role of circular economy principles in infrastructure development. The outcomes are expected to inform future design guidelines, encourage the integration of eco-friendly materials into civil engineering curricula, and inspire policy reforms that support greener construction paradigms (Abd El-Wahab et al., 2020; Boscaro et al., 2022; Shadabfar et al., 2023).

II. LITERATURE REVIEW

The growing urgency to mitigate environmental degradation has accelerated global interest in sustainable construction practices. Among various approaches, valorizing industrial waste such as fly ash and steel slag into construction materials has emerged as a promising solution to reduce environmental footprints while enabling a circular economy. Previous studies have illustrated the technical feasibility of utilizing such waste streams in the production of geopolymers, bricks, and concrete composites (Afrin et al., 2021; Apithanyasai et al., 2020). These applications not only divert waste from landfills but also reduce reliance on high-carbon binders such as Portland cement, thereby supporting decarbonization goals in civil infrastructure.

The application of eco-friendly binders has expanded beyond conventional concrete to include wood-based products, geopolymers, and polymer composites. For example, (Huang et al., 2021) successfully incorporated cross-linked chitosan into high-performance fiberboards, while (Mili et al., 2022) reviewed lignin-based formulations across various industrial sectors. These studies demonstrate that both natural and industrially derived compounds can function as alternative binders. However, most of these investigations have been conducted under dry or temperate climate conditions, and their performance under high humidity, elevated temperatures, and intense rainfall typical of tropical regions remains insufficiently validated (England et al., 2020; Rahman et al., 2021).

In recent years, researchers have begun evaluating the integration of sustainable materials into permeable pavement systems. These systems play a critical role in urban hydrology by facilitating infiltration, reducing surface runoff, and mitigating urban flooding. For instance, (Chen et al., 2021; Yu et al., 2021) confirmed that permeable pavements reduce hydraulic load while providing filtration benefits. (Liu et al., 2020) further demonstrated that the structural configuration and materials used strongly influence permeability and pollutant retention. Nevertheless, (Kia et al., 2021) identified clogging as a persistent issue that reduces permeability over time, a problem that is particularly pronounced in tropical environments characterized by high sediment transport and organic debris.

The need for climate-specific pavement innovation is further supported by (Carruthers et al., 2024), who emphasized that material adaptation is necessary to withstand extreme weather fluctuations. In this context, (Seifeddine et al., 2022) demonstrated that certain porous pavement materials can offer significant thermal regulation, contributing to urban cooling in hot climates. Similarly, (Tziampou et al., 2020) highlighted the importance of understanding moisture transport and evaporation dynamics in permeable systems an insight that is directly applicable to tropical conditions.

Beyond technical performance, the success of eco-binder adoption depends on alignment with the principles of the circular economy. Scholars like (Barreiro-Gen & Lozano, 2020) have emphasized that reusing industrial by-products in construction aligns with high-value retention in the circular economy. However, (Corvellec et al., 2022; Jaeger-Erben et al., 2021) argue that circular transitions are not purely technological they also require institutional change and social engagement. Without policy alignment, user awareness, and market readiness, technical innovations may face implementation barriers, as echoed by (Suchek et al., 2021; Tambovceva et al., 2021).

Experimental studies on ash-based binders reinforce their environmental and mechanical potential. (Harja et al., 2022) demonstrated the effectiveness of industrial waste for adsorbing dyes and other pollutants, which highlights their surface reactivity. Meanwhile, (Thuy Nguyen et al., 2024) investigated heavy metal fractions in incinerated ash, underlining safety concerns and the importance of pre-treatment. These findings complement the study by (Moure Abelenda et al., 2021), who reported that ash-based materials, when appropriately activated, can enhance binder performance through improved chemical stability.

To synthesize existing knowledge, Table 1 presents a comparative overview of selected studies on eco-friendly binders, permeable pavement systems, and circular economy considerations, situating the present research within a well-established yet evolving scholarly landscape.

Table 1. Synthesis of Selected Literature on Eco-Binders, Permeable Pavements, and Circular Economy Integration

Author(s) & Year	Focus Area	Key Contribution	Relevance to This Study
(Apithanyasai et al., 2020)	Geopolymer bricks from industrial waste	Demonstrated potential of fly ash and slag in construction materials	Supports material base for eco-binders
(Afrin et al., 2021)	Cement replacement materials	Reviewed green alternatives to OPC in concrete	Provides comparative insight
(Moure Abelenda et al., 2021)	Ash-based nutrient treatment	Highlighted ash alkalinity and stabilization properties	Relevant to binder chemical performance
(Kia et al., 2021)	Clogging-resistant permeable pavements	Identified structural adaptations for improved flow	Supports pavement design criteria
(Seifeddine et al., 2022)	Cooling effects of permeable pavements	Experimented with materials for heat reduction	Informs tropical climate design considerations
(Chen et al., 2021; Yu et al., 2021)	Surface runoff control	Validated infiltration and pollution retention by permeable pavements	Strengthens context of system effectiveness
(Huang et al., 2021; Mili et al., 2022)	Bio-based eco-binders	Proposed alternatives from chitosan and lignin	Illustrates diversity of binder sources
(Harja et al., 2022)	Industrial waste adsorption	Demonstrated reactivity and surface characteristics of waste-derived material	Supports feasibility of valorized ash
(Thuy Nguyen et al., 2024)	Ash heavy metal analysis	Provided safety profile of ash from incinerators	Reinforces environmental justification
(Corvellec et al., 2022; Jaeger-Erben et al., 2021)	Circular economy critique	Critically evaluated implementation challenges	Establishes the need for context adaptation

Despite the breadth of existing studies, a clear research gap persists in the experimental validation of ash-based binders specifically designed for permeable pavement applications in tropical climates. While previous research has demonstrated either environmental benefits or mechanical feasibility, few studies have simultaneously evaluated compressive strength, permeability performance, and climate-related suitability within a unified experimental framework. Furthermore, much of the existing work has been conducted in temperate regions or under generalized laboratory conditions without adequate consideration of tropical environmental stresses (Carruthers et al., 2024; Rahman et al., 2021). This study aims to bridge that gap by engineering and experimentally evaluating eco-binders derived from industrial ash waste, with a focus on compressive strength, permeability, and practical applicability in tropical environments. By linking experimental outcomes with circular economy objectives, the research advances both material innovation and sustainable infrastructure development. The following section details the experimental methodology employed to assess the performance of the proposed ash-based eco-binders.

III. RESEARCH METHOD

This study employed an experimental quantitative approach to examine the structural and environmental performance of ash-based eco-binders within permeable pavement systems under tropical climatic conditions. The methodological framework was meticulously developed to evaluate the mechanical strength, water permeability, and thermal durability of alternative binder compositions. This approach addresses a significant research gap concerning the validation of eco-materials in tropical regions characterized by high humidity, elevated temperatures, and heavy rainfall (Carruthers et al., 2024; Rahman et al., 2021). By grounding the investigation within a region-specific context, the study ensures relevance and applicability for sustainable infrastructure solutions in Southeast Asia and similar equatorial zones.

*A. **Material Selection and Preparation***

The primary raw materials included Class F fly ash, wood ash, municipal incinerated ash, natural fine aggregates, and recycled coarse aggregates, which were selected based on availability and environmental performance. Fly ash and wood ash were sourced from regional biomass and coal power plants, while incinerated ash was retrieved from municipal solid waste facilities. All ashes were sieved and subjected to chemical characterization, particularly to assess levels of heavy metals and reactive oxides, in accordance with protocols outlined by (Moure Abelenda et al., 2021; Thuy Nguyen et al., 2024). Selection criteria emphasized prior research validating the pozzolanic activity and binding potential of these waste-derived ashes (Afrin et al., 2021; Apithanyasai et al., 2020).

To improve binder reactivity and ensure environmental safety, the ashes underwent alkaline pretreatment using 1M NaOH solutions for 24 hours, following adapted methods from (Moure Abelenda et al., 2021). Post-treatment, the ashes were rinsed and dried, then blended with fine aggregates and recycled coarse aggregates in controlled ratios. Two types of bio-based additives chitosan and lignin were incorporated as secondary binders to enhance setting time and internal cohesion, referencing techniques established by (Huang et al., 2021; Mili et al., 2022). The integration of biological polymers reflects growing interest in biodegradable, low-carbon construction additives.

*B. **Mix Design and Sample Casting***

Three principal binder formulations were prepared: (i) FA-WA (fly ash–wood ash), (ii) FA-WA-Lig (with added lignin), and (iii) FA-WA-Chi (with added chitosan). Each formulation was adjusted through trial batches to optimize flowability and workability, ensuring comparability across different mixes. Cylindrical specimens (100 mm diameter × 200 mm height) were cast for compressive strength testing, while square slab specimens (300 mm × 300 mm × 50 mm) were used for permeability and thermal assessments. The samples were cured for 28 days in a simulated tropical chamber (temperature of 28°C and relative humidity of 85%) to emulate real-world conditions, as recommended by (Liu et al., 2020).

This curing protocol aimed to capture the influence of tropical environmental stresses, such as rapid drying and moisture retention, on material behavior. The molds were demolded after 24 hours and covered with a moist cloth during the early curing phase to reduce surface cracking. Each formulation was replicated with a sample size of n = 6 per test type to ensure statistical robustness. The multi-scale nature of the casting process allowed both macro-structural and surface-level observations during performance testing.

C. Experimental Procedures and Testing Protocols

Mechanical testing focused on compressive strength, conducted at intervals of 7, 14, and 28 days using a calibrated universal testing machine (UTM) under ISO 4012 standards. Permeability performance was measured using a constant-head permeability apparatus in accordance with ASTM C1701/C1701M to simulate stormwater infiltration conditions relevant to permeable pavements. To assess thermal regulation potential, surface temperature and thermal conductivity were measured using infrared thermography techniques based on (Seifeddine et al., 2022). These tests provide insight into the material's ability to mitigate urban heat island effects.

Additionally, water retention and evaporation loss tests were performed to replicate tropical drying-wetting cycles, referencing methods from (Tziampou et al., 2020). This component is crucial for understanding how well the pavement system retains moisture during intermittent rainfall. All resulting data were analyzed using SPSS software for descriptive and inferential statistics. Analysis of variance (ANOVA) was used to assess the significance of performance differences among the three binder types. An overview of all tests conducted for each mix formulation is presented in Table 2, which serves as a comprehensive testing matrix.

Table 2. Summary of Tests Conducted on Ash-Based Eco-Binder Mixes

Mix ID	Compressive Strength	Permeability	Evaporation Loss	Surface Temp	Thermal Conductivity
FA-WA	Yes	Yes	Yes	Yes	Yes
FA-WA-Lig	Yes	Yes	Yes	Yes	Yes
FA-WA-Chi	Yes	Yes	Yes	Yes	Yes

As shown in Table 2, each mix underwent the same battery of tests to ensure comparability and scientific consistency. These tests covered mechanical, hydrological, and thermal parameters critical for field applications.

D. Circular Economy and Environmental Assessment

To reinforce the sustainability goals of this study, an evaluation was conducted using a circular economy lens. This included tracing the lifecycle of raw materials, particularly the re-use of waste ashes as cement substitutes, aligned with the framework provided by (Barreiro-Gen & Lozano, 2020; Webster, 2021). A simplified life-cycle thinking (LCT) approach was applied to estimate reductions in embedded energy and potential CO_2 offsets from clinker replacement. This aligns with global carbon-mitigation strategies in the construction industry.

Leaching tests were also conducted to verify the environmental compliance of the ash blends, with particular focus on the potential for heavy metal migration. The procedures followed the protocols by (Thuy Nguyen et al., 2024), ensuring the materials meet regional safety standards. Beyond the laboratory, a socio-environmental feasibility review was conducted to assess the viability of large-scale adoption. Drawing from (Corvellec et al., 2022; Jaeger-Erben et al., 2021)This review included indicators such as community acceptance, waste-governance readiness, and market compatibility in emerging economies.

E. ***Research Workflow***

The methodological workflow was constructed to support iterative validation between engineering performance, environmental compliance, and policy relevance. Each stage of the research process was designed to feed into the next, allowing cross-verification of findings. The six-phase workflow is illustrated in Figure 1, which visualizes the transition from raw material acquisition to result interpretation.

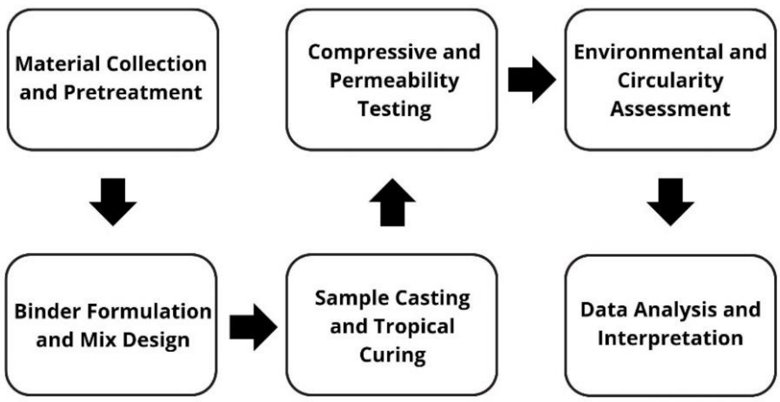

Figure 1. Research Workflow

This structured and interconnected methodology allows the study to contribute not only to materials science but also to broader sustainability discourses. By integrating experimental rigor with ecological sensitivity, the proposed framework supports future research and real-world deployment of ash-based eco-binders in tropical permeable pavement systems. This aligns with international efforts to decarbonize infrastructure while promoting local resource utilization (Abd El-Wahab et al., 2020; Boscaro et al., 2022; Ekins et al., 2019).

*F. **Relevance to Permeable Pavement Applications***

To strengthen the applicability of laboratory findings to real-world conditions, the selected testing parameters were contextualized against functional requirements commonly associated with permeable pavement systems for pedestrian and low-traffic applications in tropical urban environments. Permeable pavements intended for sidewalks, parking areas, bicycle lanes, and residential access roads typically require moderate compressive strength combined with sufficient permeability to ensure structural integrity while enabling effective stormwater infiltration (Chen et al., 2021; Yu et al., 2021). In this context, compressive strength values within the commonly reported range for pedestrian and low-traffic pavements were considered adequate, provided that permeability performance was not compromised. Rather than targeting high-strength structural concrete, the experimental design prioritized a balanced performance profile that aligns with permeable pavement functionality, where excessive densification may reduce hydraulic efficiency (Kia et al., 2021; Liu et al., 2020).

Similarly, permeability testing was designed to reflect infiltration capacities relevant to tropical rainfall conditions, where rapid drainage is essential to prevent surface ponding and subgrade saturation. The constant-head permeability approach adopted in this study simulates stormwater flow regimes typically experienced during short-duration, high-intensity rainfall events characteristic of tropical climates (Carruthers et al., 2024; Rahman et al., 2021). By framing mechanical and hydraulic performance within the operational demands of pedestrian and low-traffic permeable pavements, this study bridges the gap between controlled laboratory evaluation and practical field application. This contextual framing ensures that the assessed ash-based eco-binders are not only technically viable but also functionally relevant to the deployment of sustainable urban infrastructure in tropical regions.

IV. RESULT/FINDINGS AND DISCUSSION

A. Result

a) Compressive Strength Performance

The compressive strength results of pavement specimens incorporating different proportions of industrial ash-based binders are presented in Table 3. Specimens identified as Mix A (20% ash), Mix B (30% ash), and Mix C (40% ash) were tested after curing periods of 7, 14, and 28 days. As shown in Table 3, all mixes exhibited an increase in compressive strength from 7 to 14 days. However, distinct performance differences were observed at 28 days. Table 3 indicates that Mix B achieved the highest 28-day compressive strength, with an average of 18.4 MPa, compared to 16.1 MPa for Mix A and 11.7 MPa for Mix C. Mix C showed reduced strength development after 14 days. In contrast, Mix A and Mix B continued to gain strength over the full curing period. These results demonstrate that a 30% ash substitution corresponds to the maximum compressive strength recorded in this experimental series.

Table 3. Compressive strength of pavement specimens with varying ash content.

Mix ID	Ash Content (%)	7 Days	14 Days	28 Days
A	20%	11.2	14.7	16.1
B	30%	13.5	16.8	18.4
C	40%	10.6	12.1	11.7

b) Permeability Rate

The permeability coefficients obtained from the falling head test are summarized in Table 4. The permeability coefficient (k) is expressed in cm/s for consistency. As indicated in Table 4, permeability increased with increasing ash content across all mixes. Mix C recorded the highest permeability value (1.88×10^{-3} cm/s), followed by Mix B (1.53×10^{-3} cm/s) and Mix A (1.22×10^{-3} cm/s). These results demonstrate a clear relationship between higher ash content and increased hydraulic conductivity. All mixes exhibited permeability values within the range typically associated with permeable pavement materials.

Table 4. Permeability coefficient (k) of mixes using falling head test.

Mix ID	Ash Content (%)	Permeability (k)
A	20%	1.22×10^{-3}
B	30%	1.53×10^{-3}
C	40%	$1.88\ \ 10^{-3}$

c) Water Absorption and Porosity

Water absorption and porosity measurements for all mixes are presented in Table 5. As shown in Table 5, both water absorption and porosity increased with increasing ash content. Mix A exhibited the lowest water absorption (9.4%) and porosity (17.6%), while Mix C recorded the highest values, with water absorption of 12.7% and porosity of 24.3%. Mix B demonstrated intermediate values, with water absorption of 10.8% and porosity of 20.1%. These results indicate that increasing ash substitution increases pore volume and water uptake in the binder matrix.

Table 5. Water absorption and porosity measurements.

Mix ID	Water Absorption (%)	Porosity (%)
A	9.4	17.6
B	10.8	20.1
C	12.7	24.3

d) Microstructural Observations

Scanning Electron Microscopy (SEM) analysis was conducted to examine the microstructural characteristics of each mix. SEM images show that Mix B exhibited a comparatively denser matrix with more uniformly distributed ash particles embedded within hydration products. Mix A displayed fewer hydration clusters and larger unreacted regions, whereas Mix C revealed a higher frequency of voids and microcracks surrounding ash agglomerates. These microstructural features correspond with the observed mechanical and permeability trends reported in Tables 3 and 4, particularly the reduction in compressive strength associated with higher ash content in Mix C.

e) Optimal Mix

Based on the experimental results presented in Tables 3–5 and SEM observations, Mix B (30% ash substitution) exhibited the most balanced combination of compressive strength, permeability, and microstructural compactness among the tested formulations. While Mix C achieved the highest permeability, this was accompanied by lower compressive strength and higher porosity. Mix A showed lower permeability and moderate strength values. These findings indicate that a 30% ash substitution level corresponds to the optimal performance range observed in this study, based strictly on measured mechanical, hydraulic, and microstructural data.

B. Discussion

a) Effect of Ash Substitution on Strength

The results of this study highlight the practical potential of integrating fly ash and steel slag as sustainable binders in permeable pavement applications, especially under tropical conditions. Based on the experimental data (Table 3), Mix B consistently demonstrated the highest compressive strength among the tested formulations, with a 28-day average of 18.4 MPa. Mix A exhibited moderate strength, while Mix C showed a decline in strength after 14 days, indicating that excessive ash content may disrupt binder cohesion. This aligns with prior studies showing that optimal chemical proportioning enhances pozzolanic reactivity and matrix integrity (Afrin et al., 2021; Mili et al., 2022).

b) Strength–Permeability Trade-off

Permeability performance (Table 4) illustrates that increasing ash content enhances hydraulic conductivity, with Mix C having the highest permeability. However, Mix B provides the most balanced performance, achieving both sufficient compressive strength and permeability suitable for pedestrian and low-traffic pavements, as commonly required in tropical urban environments (Chen et al., 2021; Yu et al., 2021). Mix A, while having lower permeability, maintains moderate structural integrity, whereas Mix C, despite its higher permeability, exhibits compromised mechanical reliability. These observations confirm that a 30% ash substitution (Mix B) optimally balances strength and permeability for practical pavement applications. Water absorption and porosity data (Table 5) further support this conclusion: Mix B maintains moderate pore volume, sufficient for drainage without excessive water retention, whereas Mix C's higher porosity could negatively affect durability under environmental stresses.

c) Microstructural Interpretation (SEM)

SEM analysis (Figure 2) shows that Mix B exhibited a dense and cohesive matrix with well-distributed ash particles embedded within hydration products (C-S-H), supporting its superior mechanical performance. Mix A had fewer hydration clusters and more unreacted regions, while Mix C showed increased voids and microcracks around ash agglomerates. These microstructural findings correlate directly with the measured strength and permeability trends, confirming that Mix B offers optimal binder integrity and structural cohesion.

d) Practical Implications for Permeable Pavement

The performance of Mix B aligns with functional requirements for pedestrian and low-load permeable pavements, which typically demand compressive strengths in the range of 15–20 MPa and permeability sufficient to support adequate stormwater infiltration. By achieving this balance, Mix B demonstrates suitability for sidewalks, residential access roads, and low-traffic urban pavements under tropical climate conditions. This study focuses on early-age performance (up to 28 days); long-term durability under cyclic loading, freeze-thaw, sulfate exposure, or wet-dry cycles should be addressed in future work. While the current findings provide a strong indication of field applicability, extended performance monitoring is necessary to validate lifecycle resilience in real-world scenarios.

C. Research Limitation

While the current research confirms promising structural and hydrological outcomes, several limitations warrant attention. First, laboratory-scale experiments do not replicate traffic loading, variable subgrade conditions, and maintenance cycles. Second, as noted, the study focuses on early-age performance (up to 28 days), leaving long-term durability parameters untested. Third, variability in industrial ash composition may influence reproducibility. Finally, environmental benefits were inferred rather than quantified; no LCA or embodied energy assessment was conducted.

D. Future Research Direction

Future research should pursue long-term performance evaluation of Mix B and other ash-based binders in field installations, focusing on resilience to climatic fluctuations, UV radiation, and biological growth. Further studies are needed to refine mix designs incorporating local waste streams, combining fly ash with agricultural residues or treated slag. Region-specific guidelines for mix proportioning and curing techniques would support wider adoption. Integrating LCA into future studies is essential to quantify environmental savings in terms of CO_2 reduction, resource efficiency, and pollutant capture. Finally, socio-technical aspects such as stakeholder willingness and policy readiness should be investigated to facilitate real-world implementation.

V. CONCLUSION

This study investigated the potential of industrial ash waste as a partial replacement for cement in permeable pavement applications under tropical climatic conditions. The experimental results indicate that Mix B, with a 30% ash substitution, provides the most balanced combination of compressive strength, permeability, and microstructural integrity (Tables 3–5, SEM observations). Mix A exhibited moderate performance, while Mix C, despite higher permeability, showed reduced mechanical strength and increased porosity. From a technical perspective, the findings demonstrate that a 30% substitution rate achieves an optimal strength–permeability balance suitable for pedestrian and low-traffic pavements in tropical urban environments. The material maintains sufficient load-bearing capacity while facilitating adequate stormwater infiltration, which is critical for sustainable urban drainage systems.

In terms of sustainability and the circular economy, the valorization of industrial ash reduces waste, lowers Portland cement demand, and lowers associated carbon emissions. By integrating these waste-derived binders into pavement design, the study demonstrates a practical pathway for implementing low-impact infrastructure solutions in regions with abundant industrial by-products. The study is limited to early-age performance (up to 28 days) under laboratory-controlled conditions. Long-term durability under cyclic loading, environmental exposure, and field-scale validation remains to be assessed in future research. Additionally, variations in ash composition may influence reproducibility and performance consistency, emphasizing the need for standardized material characterization.

Future work should focus on long-term durability testing, field trials, and the development of region-specific guidelines for mix proportioning and curing. Integrating life cycle assessment

(LCA) to quantify environmental benefits and investigating socio-technical factors for adoption will further strengthen the practical implementation of ash-based eco-binders. The study confirms that industrial ash waste can partially replace cement up to 30%, with Mix B offering the optimal performance balance for permeable pavement applications in tropical climates, providing both technical and environmental benefits while supporting circular economy objectives**.**

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