Research Article

Development of Ash-Based Paving Stones Through the Utilization of Industrial Ash Generated During Urban Waste Disposal Processes

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Abstract

With the increase in urban waste and industrial activities, significant quantities of ash are generated from waste incineration plants, cement factories, and energy production facilities. These ash wastes pose critical environmental challenges such as land occupation, soil contamination, and groundwater pollution, making their sustainable management essential. This study aims to utilize industrial ash waste as an alternative raw material in the production of paving stones used in infrastructure applications. Ash-based paving solutions reduce dependence on natural stone and sand resources, contributing to resource conservation; additionally, they help lower environmental impacts by reducing cement consumption and related carbon emissions.

Within the scope of this study, manufacturability, mechanical strength, durability, and environmental performance criteria were evaluated. The results indicate that ash-based paving blocks offer an economical and sustainable alternative to conventional products. This approach enables the transformation of waste materials into value-added products instead of disposal, supporting the development of low-cost and environmentally friendly building materials.

Aligned with European Union environmental policies, this study supports the use of long-lasting, environmentally conscious, and aesthetically favorable products in urban planning and infrastructure applications. The findings demonstrate that industrial ash waste can become a valuable resource for the construction materials industry.

Keywords: Industrial ash, Paving stones, Recycling, Waste management, Sustainability

1. Introduction

The increasing urban population and expanding industrial activities have led to a significant rise in waste generation, particularly in the form of ash residues produced by waste-to-energy plants, power generation facilities, and cement factories. These ash wastes have become a critical environmental concern due to the challenges related to storage, their potential to contaminate soil and water resources, and their long-term ecological impacts. Current sustainable development frameworks emphasize the necessity of recovering and reutilizing such industrial by-products rather than disposing of them.

The international literature includes numerous studies on the use of fly ash in concrete, road base materials, construction blocks, and various binder systems. Research conducted in countries such as India, China, Germany, and the United States demonstrates that ash-based construction materials can exhibit competitive technical properties, including compressive strength, water absorption, freeze–thaw durability, and abrasion resistance.

However, a detailed review of existing studies reveals a lack of systematic research specifically focused on the development of ash-based paving blocks. Although the use of ash in different construction components has been widely discussed, there remains a clear application gap in infrastructure materials, particularly in the context of paving stone production.

This study aims to develop ash-based paving blocks by utilizing industrial ash residues, thereby reducing the consumption of natural resources, lowering carbon emissions, and generating a product with high economic value. Through prototype development and performance testing, an alternative infrastructure material is introduced, addressing a gap in the literature. The study presents an innovative approach for converting waste into economic value and contributes to sustainable infrastructure solutions.

2. Materials and Methods

2.1. Material Preparation

In this study, recycled polymer matrix materials (polyethylene and polypropylene), industrial fly ash and bottom ash, mineral aggregates (sand, quartz), binder resin, and pigments were used. The recycled polymers were collected, cleaned, and mechanically ground to achieve a particle size of at least 10 mm. Industrial ash materials were sieved to obtain an appropriate particle size distribution.

The weight-based proportions of the mixture components were defined as follows:

a) Recycled polymer matrix material: 30–40%

b) Ash (fly ash + bottom ash): 30–40%

c) Mineral aggregates (sand, quartz, gravel): 10–15%

d) Pigment: 1–3%

e) Binder resin: 5–10%

This composition was selected to maximize ash utilization based on the saturation capacity of PE and PP materials while simultaneously meeting requirements for mechanical strength, processability, environmental performance, and aesthetic quality.

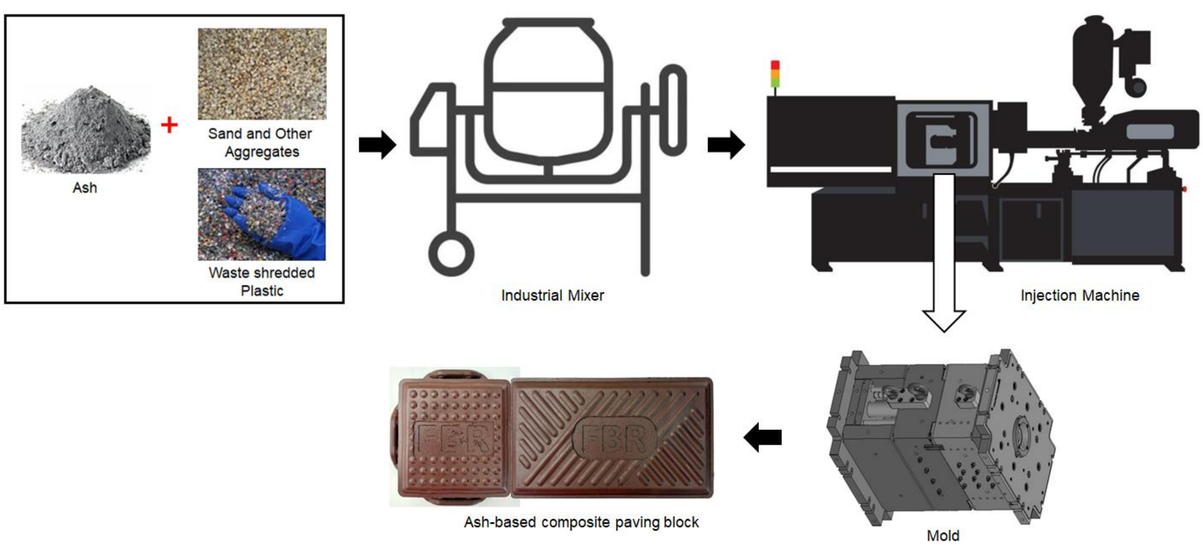

Figure 1: Method for Developing Ash-Based Paving Stones

2.2. Formulation and Mixing

The prepared mineral aggregate and ash mixture was combined with the ground polymer matrix material at the predetermined ratios. All components were placed into a mixing unit and blended for 10–15 minutes at a mixing speed of 50–100 rpm to achieve a homogeneous distribution. Binder resin and pigments were added during this stage. Throughout the process, viscosity and mixture homogeneity were monitored to ensure stable processing conditions.

2.3. Shaping and Consolidation

The homogeneous mixture was fed into the extruder system of the injection molding machine and melted within the temperature range of 220–280°C, ensuring full bonding between the polymer phase and the mineral phase. The molten material was injected into paving-block molds. The molds were pressed under a minimum clamping force of 250 tons to optimize material density and mechanical performance. After the injection stage, the products were demolded, and dimensional stability as well as surface integrity were inspected.

Prototype trials showed that a filling time of approximately 10 seconds at 260°C resulted in the best surface quality and homogeneous mold filling. Although 280°C provided shorter filling times, it was not preferred due to increased risk of thermal degradation.

Table 1: Optimum Filling Time and Surface Quality Based on Injection Temperature

Injection Temperature (°C)	Optimum Filling Time (s)	Surface Quality (1 = poor → 5 = excellent)	Notes
220	28	2	Insufficient filling → voids and rough surface.
240	20	3	Filling improves; surface becomes smoother.
260	14	5	Homogeneous filling, smooth surface, low void content.
280	8	4	Fast filling; however, risk of thermal degradation exists.

Table 2: Effect of Mold Clamping Force on Surface Integrity

Clamping Force (ton)	Void Ratio (%)	Surface Roughness Ra (µm)	Surface Integrity Evaluation
150 t	3,5	5,6	Weak – surface contains noticeable pores.
200 t	2,3	3,8	Moderate – improved but lacks full consolidation.
250 t	1,2	2,1	Very good – homogeneous, low void content, smooth
300 t	1	2	Good – slight material flash; mold wear may occur.

2.4. Testing and Standardization

The performance of the fabricated ash-based paving block specimens was evaluated in accordance with the TS EN 1338 standard. Compressive strength tests revealed that the specimens achieved values up to 36 MPa. In water absorption tests, the mass gain of samples immersed in water was monitored, confirming that the water absorption rate remained below 1%. These results indicate the material's durability against environmental exposure.

For microstructural examination, Scanning Electron Microscopy (SEM) was used to analyze polymer–ash interfacial compatibility, particle distribution, and void characteristics. The observations demonstrated that ash particles were uniformly dispersed within the polymer matrix and effectively integrated with the binder phase. Additionally, the internal bonding structure appeared stable, supporting the mechanical and physical performance results.

3. Results

Mechanical, physical, and microstructural tests were conducted to evaluate the performance of the developed fly ash– and recycled polymer–based paving block specimens. Compressive strength tests performed on the produced samples yielded an average value of 36 MPa, which corresponds to approximately 20% higher mechanical performance compared to conventional concrete paving blocks. This outcome indicates that the polymer binder, when combined with mineral additives, forms a strong composite matrix, while the high molding pressure enhances composite density and contributes to the improved mechanical strength.

Water absorption tests revealed a maximum absorption rate of 1%, remaining well below the limits specified in the TS EN 1338 standard. The low absorption level demonstrates that the material exhibits a dense and impermeable structure, supporting long-term durability under outdoor conditions.

Formula optimization showed that the mixture could sustain up to 40 wt.% ash content while maintaining mechanical integrity. Above this threshold, the continuity of the polymer phase was disrupted, leading to weakening of the composite matrix and a reduction in strength values. This limit is considered a critical threshold for achieving an optimal balance among ash, polymer, and aggregate components.

Microstructural analyses indicated that ash particles were well dispersed within the binder phase, with limited interfacial fracture zones and a homogeneous pore structure. Such morphology supports both mechanical strength and long-term environmental durability of the composite material.

4. Discussion and Conclusion

This study evaluated the mechanical and physical performance of composite paving blocks produced from a mixture of recycled polymer matrix, industrial ash, and mineral aggregates. The results demonstrate that the developed samples exhibit superior performance compared to conventional concrete paving blocks. Although previous studies have shown that ash addition improves the strength of cement-based materials, the findings here reveal that combining ash with a polymer matrix enhances strength to an even higher level while significantly improving impermeability. This confirms the structural advantages arising from the polymer–ash synergy.

Unlike most existing research, which focuses predominantly on the use of fly ash in cementitious systems, the binder used in this study is entirely polymer-based, with no cement included. This approach not only reduces the carbon footprint but also minimizes energy consumption during production. The results further indicate that an optimal ash content of 40 wt.% maintains structural integrity, representing a notable advancement in terms of material recovery and sustainability.

Overall, the findings provide a valuable example of transforming industrial waste into high-value structural components and contribute to the field of sustainable material technologies. The study also demonstrates that recycled polymers can be effectively utilized not only in low-load applications but also in structural elements requiring higher mechanical strength. The developed material therefore holds strong potential for future use in urban infrastructure, landscape applications, modular flooring systems, and environmentally responsive design solutions.

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