

Utilization of Metal-Layered Plastic Packaging Waste and Eggshell Powder as Partial Substitution Materials in Paving Blocks

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ABSTRACT

This study aims to evaluate the use of metal-coated plastic packaging waste (WMP) and eggshell powder (ESP) as partial substitution materials in the manufacture of environmentally friendly paving blocks. The method used is an experimental approach in the laboratory with variations of WMP of 5%, 10%, and 15% as aggregate substitutes, and ESP of 5% as cement substitutes. The test specimens were molded using a hydraulic press machine and tested based on SNI 03-0691-1996 standards for compressive strength, water absorption, resistance to sodium sulfate solutions, and impact tests. The results showed that the combination of WMP and ESP was able to improve the mechanical performance of paving blocks, especially in the variations of WMP 10% and ESP 5%, which produced optimal compressive strength and low water absorption. This study contributes to the development of sustainable construction materials and supports sustainable development goals (SDGs). The practical implications of this research transform difficult-to-recycle plastic waste into cost-effective construction products, promoting resource conservation, a circular economy, and sustainable development goals.

KEYWORDS *eco-friendly construction, egg shell powder, paving block, plastic waste, WMP*



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INTRODUCTION

The escalating global plastic crisis represents one of the most pressing environmental challenges of the 21st century, with far-reaching implications for ecosystems, human health, and climate stability. According to the Organisation for Economic Co-operation and Development (OECD, 2023), global plastic production is projected to reach approximately 1.1 billion tons by 2060, tripling current levels, with plastic waste generation expected to follow a similar trajectory. This alarming trend is compounded by the fact that only 9% of plastic waste is currently recycled globally, while the remainder accumulates in landfills, oceans, and natural environments, creating persistent pollution that takes centuries to degrade (UNEP, 2024). In developing nations, where waste management infrastructure remains inadequate, the environmental burden is particularly severe, necessitating urgent innovation in both waste reduction strategies and circular economy applications (Nayanathara Thathsarani Pilapitiya & Ratnayake, 2024).

The rapid advancement of science and technology has led to the continuous discovery of materials capable of surpassing the limitations of conventional ones. Among these, plastic has emerged as a material that has significantly transformed various aspects of human life due to its advantageous characteristics, including low density, flexibility, durability, and cost-effective production. In 2022, global plastic production was estimated at 400.3 million tons, with projections indicating a continued upward trend in the coming years (Nayanathara Thathsarani Pilapitiya & Ratnayake, 2024). This trend is particularly evident in developing countries such as Indonesia, where practicality and efficiency are highly prioritized in daily activities (Manullang, Prasetya, Kusumadewi, & Zakaria, 2021; Roberts, Sander, & Tiwari,

2019).

However, the escalating consumption of plastics has been accompanied by a parallel increase in waste generation, particularly from plastic types that are difficult to recycle. According to data from the National Waste Management Information System (SIPSN) of the Ministry of Environment and Forestry (MoEF), between 2019 and 2023, Indonesia experienced a 49.6% increase in waste generation, equivalent to an additional 3.4 million tons annually. Of the total waste generated, 36.33% remains unmanaged, with plastics constituting the second-largest proportion at 19.27% and exhibiting an annual growth rate of 0.86%. This situation underscores the urgency of developing innovative waste management strategies and alternative applications for plastic waste to mitigate its environmental impact (Aiguobarueghian, Adanma, Ogunbiyi, & Solomon, 2024; Alaghemandi, 2024).

One type of plastic of particular concern is food packaging waste with a metal coating, known as Waste Metallized Plastic (WMP). This type of waste is commonly found in food and beverage products, but it is very difficult to recycle because it generally consists of multilayer plastic composed of a mixture of materials such as resins, additives, and metal layers, and is often contaminated with residual packaging contents (Norton, 2020). The complexity of these materials presents a major challenge for current waste management systems. Therefore, it is necessary to develop alternative solutions that enable direct recycling or utilization of such waste, one of which is its application in the construction sector, particularly as an additive material in paving block production (Pizon, Matyskova, Hornakova, Gołaszewska, & Kratosova, 2025; Sakthibala, Vasanthi, Hariharasudhan, & Partheeban, 2025).

Paving blocks are construction materials used as ground surface coverings in various applications, such as roads, sidewalks, and parking areas, and are typically produced from a mixture of cement, sand, and other aggregates (Handayasari, Artiani, & Putri, 2018). In recent years, several studies have explored the utilization of plastic waste as a substitute for natural aggregates in paving block manufacturing. For example, Sari & Nurkhaerani, (2025) demonstrated that non-economical plastic waste, including multilayer plastics, can be used as aggregate substitutes in paving block production. Their results showed that paving blocks containing plastic waste met the required compressive strength standards and exhibited low water absorption, indicating potential for environmentally friendly construction applications. Similarly, Tambunan et al., (2024) examined the mechanical properties of multilayer composite paving blocks, revealing that material composition significantly influences compressive strength. Their research also highlighted potential construction applications and identified directions for further investigation, such as formulation optimization and social acceptance. Vicarneltor et al., (2024) investigated the use of multilayer plastic packaging waste (MLP) and Low-Density Polyethylene (LDPE) as base materials for paving blocks through the hot press method, reporting that the inclusion of plastic improved both compressive strength and density.

Although these studies have shown promising results, research specifically focusing on the application of WMP in paving blocks remains limited. Few studies have evaluated the influence of WMP proportions on the mechanical properties and durability of paving blocks, particularly as aggregate substitutes. For instance, a study using metal-coated packaging waste as fiber reinforcement reported improvements in tensile strength and flexural performance. Similar work by Mohammadhosseini et al., (2020) and Safayenikoo (2022) demonstrated that Utilization of Metal-Layered Plastic Packaging Waste and Eggshell Powder as Partial Substitution Materials in Paving Blocks

the inclusion of metal-coated packaging waste fibers in concrete mixtures enhanced the bending toughness of concrete.

Nevertheless, the development of truly environmentally friendly paving blocks requires a comprehensive approach that addresses not only aggregate substitution but also the replacement of binding materials such as cement. In this context, efforts to reduce carbon emissions in the construction industry have encouraged the use of sustainable alternative materials, one of which is eggshell powder (ESP) as a partial substitute for cement. ESP contains a high concentration of calcium carbonate (CaCO_3) and has the potential to partially replace cement in mortar or paving block mixtures. Beng Wei et al., (2020) reported that mortars with 5% ESP achieved a compressive strength of 26.64 MPa, higher than the control specimens (25.52 MPa). Furthermore, Jhatial et al., (2022) found that ESP replacement can reduce both carbon emissions and production costs, with total carbon emission reductions ranging from 3.86% to 11.60%.

However, the combined use of WMP and ESP in a single paving block mixture has not been widely studied, particularly in relation to mechanical performance, cost efficiency, and environmental impact. This research is therefore expected to contribute to the development of sustainable construction materials while supporting the achievement of the Sustainable Development Goals (SDGs).

The primary objective of this research is to evaluate the feasibility and performance of paving blocks incorporating WMP and ESP as partial replacements for natural aggregates and cement, respectively. The anticipated benefits of this research extend to multiple stakeholders: for waste management authorities, it offers a scalable solution for valorizing difficult-to-recycle plastic waste; for the construction industry, it provides cost-effective alternatives to conventional materials while meeting sustainability commitments; for policymakers, it generates evidence to support regulations promoting circular economy principles; and for the academic community, it contributes empirical data and theoretical insights that advance the frontier of sustainable construction materials research. Ultimately, this study supports the United Nations Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by demonstrating practical pathways toward waste reduction, resource efficiency, and low-carbon construction practices.

METHOD

This study employed an experimental laboratory approach, beginning with the quality assessment of fine aggregates obtained from Binjai, North Sumatra, with the results presented in Table 1. The mechanical performance of paving blocks was then evaluated by incorporating Waste Metallized Plastic (WMP), a multilayer metal-coated plastic packaging waste, which was shredded using a crushing machine in accordance with SNI 03-6820-2002. The shredded material was subsequently sieved to pass through a No. 4 (4.75 mm) sieve for use as a partial aggregate replacement. In addition, Eggshell Powder (ESP) was used as a partial cement replacement. The ESP was sieved through a standard 75-micron (No. 200) sieve to obtain a uniform particle size; a specification chosen to increase the surface contact area and maximize the reactivity of ESP with cement during the hydration process. The characteristics of WMP

are presented in Table 2, while the chemical composition of ESP, determined through X-ray Fluorescence (XRF) analysis at UPT Laboratorium Terpadu Universitas Sumatera Utara, is shown in Table 3. Test specimens were prepared in various mixture variations, incorporating WMP at proportions of 5%, 10%, and 15%, and ESP at a fixed proportion of 5%. The composition parameters of the specimens are presented in Table 4. The specimens were fabricated manually using a hydraulic press molding machine. Mechanical and durability evaluations included compressive strength testing, water absorption measurement, and sodium sulfate resistance testing in accordance with SNI 03-0681-1996, as well as drop weight impact testing following ACI 544.2R-89. Additionally, microstructural analysis was conducted using Scanning Electron Microscopy (SEM) to examine the internal structure of the paving blocks. A material cost analysis was also performed, excluding other production-related expenses such as labor, distribution, and heavy equipment costs. The test results were subsequently analyzed to determine the influence of material composition on the quality of paving blocks and production cost efficiency, thereby providing an alternative environmentally friendly construction material that supports sustainable plastic waste management.

Table 1. Fine Aggregate Quality Test Results from Binjai, North Sumatra

No.	Testing	Result		Standard	Information
1	Sand Gradation	3,19	1,5 – 3,8	SNI 03-1968-1990	Aggregate of coarse size
2	Specific Gravity (SSD)	2,713	1,6 – 3,3	SNI 03-1970-1990	Qualify
3	Silt Content	1,345%	≤ 5%	SNI 03-4141-1996	Qualify
4	Water Absorption	0,771%	0,2 – 2%	SNI 03-1970-1990	Qualify

Table 2. XRF Test Results of Eggshell Powder (ESP)

Formula	Concentration (%)
CaO	96,26
Al ₂ O ₃	3,40
SrO	0,08
K ₂ O	0,05
Fe ₂ O ₃	0,04
CuO	0,01
MnO	0,01
MgO	0,00
TiO ₃	0,93
MnO	0,00
SiO ₃	0,00

Based on Table 2, X-ray Fluorescence (XRF) analysis indicates that the primary component of eggshell powder (ESP) is calcium oxide (CaO), with a concentration of 96.26%, representing the dominant constituent. The exceptionally high CaO content positions ESP as a potential calcium source in construction materials, particularly in the formation of binding compounds such as calcium silicate hydrate (C–S–H), which is primarily responsible for the development of mechanical strength in cement- or concrete-based materials. In addition to CaO, ESP contains small quantities of other oxides, including Al₂O₃ (3.40%), SrO (0.08%), K₂O (0.05%), and Fe₂O₃ (0.04%). Although present in minor proportions, these elements can contribute to supplementary material properties, such as enhanced resistance to chemical attack or improved microstructural density.

While XRF results indicate that ESP contains no detectable SiO₂, its use is nonetheless explored in this study because the high CaO content allows for secondary reactions with silica from cement or fine aggregates, enabling the limited formation of C–S–H compounds. Moreover, the focus of this research encompasses sustainability, material efficiency, and the utilization of locally available waste. These considerations render ESP a viable cement substitute for investigation, despite its theoretically low reactivity, addressing the demand for inexpensive and abundant alternative materials to support carbon emission reduction efforts in the construction sector.

Table 3. WMP Characteristics

Quality	Value	Reference
Resin Type	Polypropylene	Mohammadhosseini et al., (2020)
Plastic Types	LDPE	Mohammadhosseini et al., (2020)
Density Range (gr/cm ³)	0,915 – 0,945	Mohammadhosseini et al., (2020)
Thickness (mm)	0,07	Mohammadhosseini et al., (2020)
Tensile Strength (Mpa)	600	Mohammadhosseini et al., (2020)
Elongation (%)	8 – 10	Mohammadhosseini et al., (2020)
Melting Temperature (°C)	150	Tene Jomo Kenyatta et al., (2019)
Sealing Temperature (°C)	40	Tene Jomo Kenyatta et al., (2019)
Drying Time	2 hours at 79°C	Tene Jomo Kenyatta et al., (2019)
Water Absorption	0.002% weight in 24 hours	Tene Jomo Kenyatta et al., (2019)

Based on Table 3, the density of this type of plastic ranges from 0.915 to 0.945 kg/m³, which is significantly lower than the density of natural aggregates (2.713 kg/m³).

Table 4. Material Composition for Paving Block Production

Specimen Code	Weight (kg)				Water (kg)
	Cement		Added		
	<i>PCC</i>	<i>ESP</i>	<i>Sand</i>	<i>WMP</i>	
Control (0% waste)	0.957	-	1.914	-	0.431
P5ES5W	0.909	0.048	1.818	0.033	0.409
P5ES10W	0.909	0.048	1.723	0.066	0.409
P5ES15W	0.909	0.048	1.627	0.098	0.409
Total	3.685	0.144	7.082	0.197	1.658

Table 4 presents the material composition for a single test specimen with dimensions of 20 × 10 × 6 cm. The control specimen contains 0% waste, while P5ES5W, P5ES10W, and P5ES15W correspond to mixtures containing 5% ESP with 5%, 10%, and 15% WMP, respectively.

RESULT AND DISCUSSION

Compressive Strength Test Results

The compressive strength test of the paving blocks was performed on specimens with a minimum curing age of seven days, which were cut into cubic forms with a loading surface area corresponding to the specimen thickness. Prior to testing, the top and bottom surfaces were

not treated with gypsum or sulfur; instead, they were manually leveled using a flat concrete grinder to ensure parallelism and full contact with the loading platens of the testing machine. Grinding was carried out until both surfaces exhibited a flatness deviation of less than 1 mm, in accordance with the tolerances commonly applied for non-standard concrete specimens, as illustrated in Figure 1. The compressive strength test was conducted using a compression testing machine at the Concrete Technology Laboratory, Department of Civil Engineering, Faculty of Civil Engineering, Universitas Sumatera Utara. The load was applied progressively until the specimen reached ultimate failure, in compliance with the relevant testing standards.



Figure 1. Surface Grinding Process and Cubic Test Specimen of Paving Block

Each country generally has its own technical standards for classifying the quality of paving blocks. For example, in Indonesia, the classification is regulated under SNI 03-0691-1996, whereas other countries adopt different standards, such as ASTM C936 in the United States, BS 6717 in the United Kingdom, EN 1338 in Germany, and AS 3979 in Australia. Paving blocks are available in various strength grades and usage classifications, as determined by these international standards, as presented in Table 5.

The differences in compressive strength requirements between SNI and international standards are primarily due to variations in functional needs, environmental conditions, and design approaches. SNI 03-0691-1996 specifies a minimum compressive strength of 10–20 MPa, which is tailored to light traffic conditions and the stable tropical climate of Indonesia, where extreme freeze–thaw cycles do not occur. Under such conditions, paving blocks with a compressive strength below 20 MPa can still perform optimally without premature degradation. Consequently, the values set by SNI are adapted to local conditions and practical field requirements.

In contrast, countries such as the United States and those in Europe require a compressive strength exceeding 25 MPa, reflecting considerations for heavy traffic loads and extreme weather conditions. International standards typically place greater emphasis on long-term durability. Furthermore, cost efficiency and the availability of local materials also contribute to the more adaptive nature of the Indonesian standard. Thus, despite having lower strength requirements, SNI remains relevant and suitable for national construction needs.

Table 5. Classification of Paving Blocks According to Various National Standards

Country/Standard	Compressive Strength (MPa)	Water Absorption (%)	Wear Resistance (max)	Common Applications
Indonesia (SNI 03-0691-1996)	A: ≥ 40 , B: ≥ 20 , C: ≥ 15 , D: ≥ 10	A: 3, B: 6, C: 8, D: 10	A: 0.09 mm/min, D: 0.219 mm/min	A: Highway, B: Parking, C: Sidewalk, D: Park
America (ASTM C936)	≥ 55 (min individual 50)	≤ 5 (max 7)	≤ 0.02 g/cm ² (ASTM C418)	Heavy traffic areas, ports
England (BS 6717)	≥ 50 (min individual 45)	Not specified	Class A2: loss of $\leq$ thickness 23 mm (<i>Wide Wheel Abrasion test</i>) Class A1: not tested (no performance data)	Industrial areas, heavy roads
Europe (EN 1338)	≥ 50 (min individual 45)	≤ 6 (max 7)	Volume loss ≤ 23 mm ³ (<i>Wide Wheel Abrasion test</i>)	Pedestrian area, light to moderate traffic
Australia (AS 3979)	≥ 50 (min individual 45)	Not specified	Volume loss ≤ 23 mm ³ (<i>Wide Wheel Abrasion test</i>)	Type A: heavy, Type B: light
India (IS 15658:2006)	M30–M50 (30–50 MPa)	≤ 6 (max 7)	Thickness loss: ≤ 2 mm (wet and dry abrasion test)	Pedestrian, local road, light industry
Sri Lanka (SLS 1425:2011)	Type 1: ≥ 25 MPa Type 2: ≥ 35 MPa Type 3: ≥ 50 MPa	≤ 6 (max 7)	Thickness loss: ≤ 2 mm (wet and dry abrasion test)	Type 1: pedestrian; Type 2: light traffic; Type 3: heavy traffic.

In the compressive strength tests for all variations, the quality classification of the paving blocks was determined according to SNI 03-0961-1996, as presented in Table 6. The average compressive strength values shown in Figure 2 indicate that the control paving block achieved 25.37 MPa. For the P5ES5W variation (containing 5% ESP and 5% WMP), the average compressive strength decreased to 15.60 MPa, representing a reduction of 38.50%. Nevertheless, this value still satisfies the requirements for category C paving blocks, which have a minimum threshold of 17 MPa. For the P5ES10W variation (10% WMP), the average compressive strength further declined to 11.79 MPa, a reduction of 53.54% compared to the control, falling within category D. Finally, the P5ES15W variation (15% WMP) recorded the lowest value, 10.40 MPa, corresponding to a 59.01% decrease from the control, and also classified as category D.

These results indicate that higher waste content in the paving block mixture leads to lower compressive strength. However, at the 5% waste content level, the paving blocks still demonstrated adequate performance, meeting the minimum standard requirements. This downward trend in compressive strength may be attributed to the physical characteristics of waste metallized plastic, which has a lower density compared to natural aggregates. This density is influenced by the type of polymer, as metallized plastics typically consist of multilayer structures made from thermoplastics such as PET, PE, and PP, sometimes coated with metallic layers or other barrier materials (Sari & Nurkhaerani, 2025). According to Mohammadhosseini et al. (2020), the density of waste metallized plastic ranges from 0.915 to 0.945 g/cm³.

Low-economic-value plastic waste tends to form weak aggregates, thereby reducing particle bonding within the mixture (Sari & Nurkhaerani, 2025). This is further exacerbated by the weak interfacial transition zone (ITZ) between the plastic aggregates and the cement paste, which contributes to the reduction in compressive strength. Additionally, the hydrophobic nature of plastic waste aggregates—characterized by their tendency to repel water—hinders the cement hydration process around the ITZ, impairing the bond quality between the cement

paste and aggregates, and increasing the risk of material degradation (Sau, Shiuly, & Hazra, 2024). Another factor contributing to the decline in compressive strength is the smooth surface texture of the plastic, which reduces the mechanical interlock and adhesion between the plastic particles and the cement paste (Fauzan, Zakaria, Nugraha, & Al Jauhari, 2023). Consequently, the resulting paving blocks tend to be more brittle and exhibit lower compressive strength.

Table 6. Compressive Strength Classification of Paving Blocks According to SNI 03-0691-1996

No.	Specimen Code	Maximum Load (N)	Press Cross-Section Area (mm ²)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Paving Block Grade	Condition	
		P	A	P/A			Average (MPa)	Min. (MPa)
1	Control (0% waste)	95000	3600	26,39	25,37	B	20	17,0
		90000	3600	25,00				
		89000	3600	24,72				
2	P5ES5W	56600	3600	15,72	15,60	C	15	17,0
		56200	3600	15,61				
		55700	3600	15,47				
3	P5ES10W	42900	3600	11,92	11,79	D	10	8,5
		42900	3600	11,92				
		41500	3600	11,53				
4	P5ES15W	39100	3600	10,86	10,40	D	10	8,5
		36800	3600	10,22				
		36400	3600	10,11				

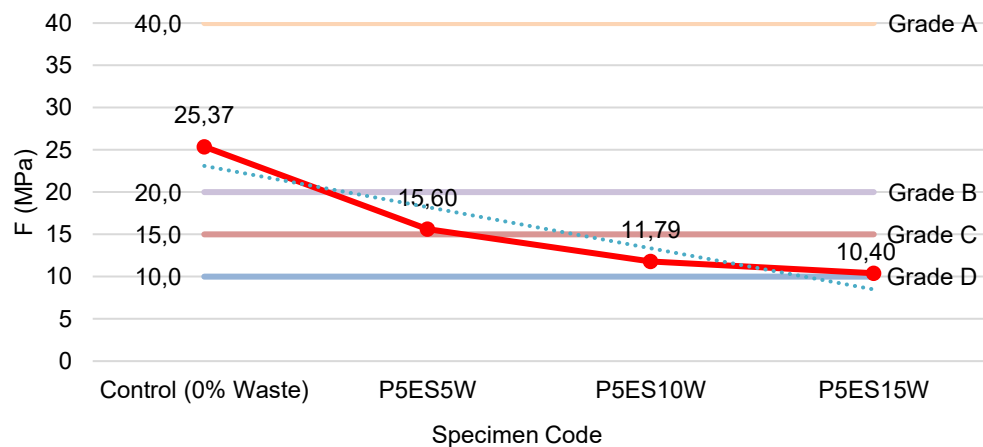


Figure 2. Average Compressive Strength Results

Water Absorption Test Results

Water absorption testing is performed to assess the ability of paving blocks to absorb water after the immersion process. This test is important because the water absorption rate affects the durability of paving blocks against weather exposure and structural deterioration.

The average water absorption value was obtained from five test specimens immersed in water for 24 hours.

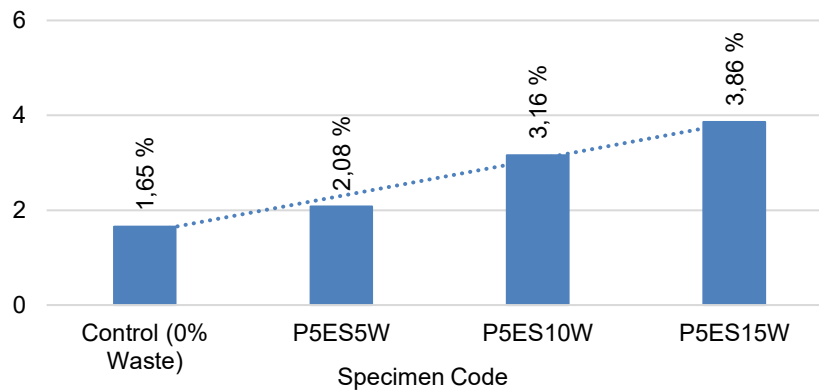


Figure 3. Water Absorption Test Results of Paving Block

Based on the data in Figure 3, the water absorption test results indicate an upward trend as the proportion of waste materials increases in the paving block mixture. Although the overall density decreased, the difference in water absorption between wet and dry conditions became more pronounced in mixtures with higher plastic content. The control paving block recorded an average absorption of 1.65%, a value still comparable to the sand absorption used in this study, which ranges from 0.703–0.839% (Table 1). This suggests that materials predominantly composed of sand have high density and low porosity. In contrast, the mixture with 5% WMP and 5% eggshell powder (ESP) showed an absorption of 2.08%, increasing to 3.16% in the 10% WMP variation, and reaching 3.86% in the 15% WMP variation.

This trend indicates that the addition of waste materials affects the microstructure of the paving block, likely increasing porosity and enhancing water uptake. While this may lead to greater permeability, excessive absorption could reduce durability if it exceeds the limits specified in relevant standards. Therefore, optimizing the waste content is crucial to balancing sustainability benefits with the mechanical and durability performance of the paving blocks.

Sodium Sulfate Resistance Test Results

Chemical resistance, particularly against sulfate compounds, is a crucial aspect in evaluating the durability of paving blocks used in aggressive environments. Exposure to sulfate solutions can lead to material degradation through chemical reactions that induce expansion, cracking, and surface weathering over time. The evaluation of paving blocks with various WMP and ESP variations was conducted based on the sulfate solution test standard in SNI 03-0691-1996. The test involved immersing two specimens in a saturated Na_2SO_4 solution (28.1 g/100 g water at 25 °C, fully dissolved) for 16 hours, followed by drying for five cycles, to simulate field conditions with high chemical exposure risk. The difference in specimen mass before and after testing was used as the primary indicator to assess the level of resistance to sulfate attack.

The results of the sodium sulfate resistance test are presented in **Table 7**. The control paving block (0% waste) exhibited the smallest change in mass, at 0.12% for both specimens.

This indicates that the material structure remained highly stable and resistant to sulfate solution, with its physical condition remaining intact after testing. The P5ES5W variation (5% ESP and 5% WMP) also demonstrated good resistance, with mass differences of 0.31% and 0.26%, well below the commonly accepted maximum threshold of 1%. This shows that low waste content in the mixture remains relatively stable against sulfate attack. In the P5ES10W variation, the mass differences increased to 0.61% and 0.50%. The highest mass changes were recorded in the P5ES15W variation, at 0.72% and 0.88%. Although these values still meet the sulfate resistance requirement ($\leq 1\%$), they indicate the onset of minor degradation in the paving block structure as the plastic waste content in the mixture increases.

This observation is supported by the visual condition of the paving blocks after undergoing five immersion–drying cycles, as shown in Figure 4, where the specimens were immersed in a Na_2SO_4 solution. Differences in physical condition can be observed among the mixture variations. In Figure 4(a), representing the control sample with 0% waste, the surface of the paving block remains intact and dense, with no significant visible damage. This indicates that conventional paving blocks possess excellent resistance to chemical sulfate attack, characterized by a compact and stable material structure. In contrast, Figure 4(b), representing the P5ES5W variation (5% ESP, 5% WMP), shows a surface that is still relatively good, although slight surface irregularities are noticeable. This suggests that incorporating 5% waste remains within an acceptable range and does not have a significant impact on sulfate resistance. However, in Figure 4(c) for P5ES10W (5% ESP, 10% WMP) and Figure 4(d) for P5ES15W (5% ESP, 15% WMP), the paving block surfaces appear rougher and more porous, with visible indications of more dominant plastic particles on the surface.

Table 7. Results of the Sodium Sulfate Resistance Test on Paving Blocks

Specimen Code	No.	Na ₂ SO ₄ Immersion Test			Condition	Test Specimen Condition (Defect/Good)
		Initial Weight of Test Specimen (gr)	Final Weight of the Test Piece After Soaking and Drying Cycle 5	Weight Difference (%)	Weight Difference (%)	
					$\leq 1\%$	
Control (0% Waste)	1	3372	3368	0,12%	✓	Good
	2	3216	3212	0,12%	✓	
P5ES5W	1	2917	2908	0,31%	✓	Good
	2	3053	3045	0,26%	✓	
P5ES10W	1	2962	2944	0,61%	✓	Good
	2	2794	2780	0,50%	✓	
P5ES15W	1	2921	2900	0,72%	✓	Good
	2	2763	2739	0,88%	✓	

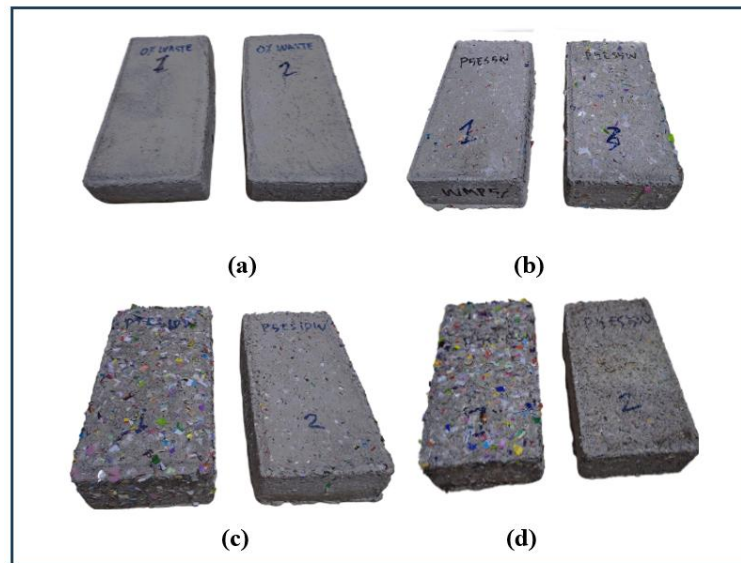


Figure 4. Final visual condition after 5 sodium sulfate cycles: (a) control (0% waste), (b) P5ES5W, (c) P5ES10W, (d) P5ES15W

Drop Weight Impact Resistance Test Results

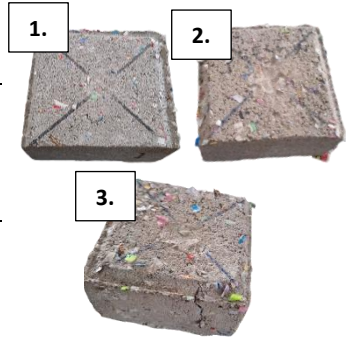
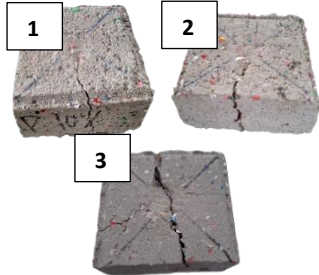
In non-asphalt pavement structures such as paving blocks, in addition to compressive strength and water absorption, resistance to impact loads is also an important aspect in evaluating material performance in the field. In this study, a drop weight impact test was conducted on paving blocks with variations of waste metalized plastic (WMP) and eggshell powder (ESP) mixtures to evaluate the effect of material substitution on impact resistance. The test was performed using a steel ball with a diameter of 60 mm and a mass of 1.115 kg, dropped from a height of 450 mm, repeated 10 times for each specimen. The results were analyzed based on the diameter and depth of the indentation caused by the steel ball, as well as the type of damage observed after each loading stage. The average diameter was calculated from two measurements: d_1 , representing the vertical direction, and d_2 , representing the horizontal direction. The mean value of d_1 and d_2 was used to identify the influence of material composition on the mechanical behavior of the paving blocks under impact loading. The test specimens had a surface area of 10×10 cm.

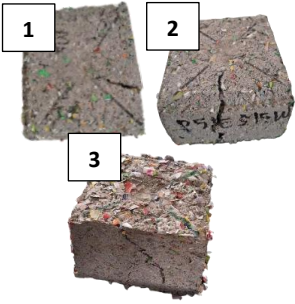
Based on the results of three trials of the paving block impact resistance test, as shown in Table 8, the data indicate that all control samples (0% waste) were able to withstand up to 10 loading stages without cracking, with a maximum damage diameter of 28.00 mm and a maximum depth of 2.80 mm. This condition demonstrates that the control material has a dense structure capable of optimally absorbing impact energy. Meanwhile, the paving block with a composition of 5% WMP and 5% ESP (P5ES5W) still exhibited relatively good performance. Two out of three samples remained intact up to the 10th stage, while one sample experienced cracking to the bottom at the 7th stage. The maximum damage diameter was recorded at 32.50 mm, with a depth of 2.20 mm. These results indicate that with a total waste content of 10%, the paving block still retained impact resistance close to that of the control, although early signs of strength reduction were evident.

At higher waste content, namely P5ES10W, all samples exhibited severe cracking, including side cracks and vertical cracks extending to the bottom. The maximum load stage reached was only the 6th stage, with a damaged diameter of up to 42.50 mm. Similarly, for the P5ES15W mixture, all samples experienced significant cracking as early as the 3rd stage, and the damage diameter increased to 45.00 mm. These findings indicate that with waste content exceeding 10%, the paving block structure becomes brittle and can no longer effectively withstand impact energy.

Overall, it can be concluded that the higher the waste content added to the paving block mixture, the lower its resistance to impact loading. The mixture composition that can still be tolerated and approaches the performance of the control is P5ES5W. In contrast, mixtures with total waste content of 15% and 20% (P5ES10W and P5ES15W) are not recommended, as all samples exhibited severe cracking at low load stages.

Table 8. Drop Weight Impact Test Results and Physical Damage Observations of Paving Blocks with WMP and ESP Mixtures

No	Test Band Code	Load Level	Average Diameter (mm)	Depth (mm)	Condition	Visual
1	Control (0% waste)	10	28.00	2.80	Good	
2		10	24.00	2.30	Good	
3		10	28.00	2.30	Good	
1	P5ES5W	10	31.50	1.90	Good	
2		10	34.00	1.80	Good	
3		7	32.50	2.20	Cracked to the bottom	
1	P5ES10W	6	32.50	2.80	Crack on the top 1 side 4 cm long to the bottom side	
2		6	35.00	1.80	Cracked to the bottom	

3		4	42.50	1.00	Vertical crack to the bottom	
1		4	37.50	4.10	Crack on the top 1 side 4 cm long to the bottom side	
2	P5ES15W	4	39.00	1.90	Crack on the top 1 side 4 cm long to the bottom side	
3		3	45.00	1.20	Cracked to the bottom	

Microstructure Test Results

Scanning Electron Microscope (SEM) observations on the fracture surfaces of paving blocks composed of sand and cement provided essential insights into the microstructural characteristics for evaluating material performance after the compressive strength test, as shown in Figure 5. In Figure 5(a), at 1000 $\times$ magnification, the surface appears rough and non-homogeneous, with irregularly distributed pores indicating the presence of voids caused by suboptimal mixing or compaction processes. Microcracks are also observed propagating along the interface between sand particles and the cement matrix. In Figure 5(b), at 2000 $\times$ magnification, the hydrated cement phases, particularly C-S-H (calcium silicate hydrate), are more apparent, with capillary pores becoming more visible and microcracks propagating subtly. In Figure 5(c), at 5000 $\times$ magnification, the C-S-H texture is more distinct, exhibiting sharper microfibrillar characteristics.

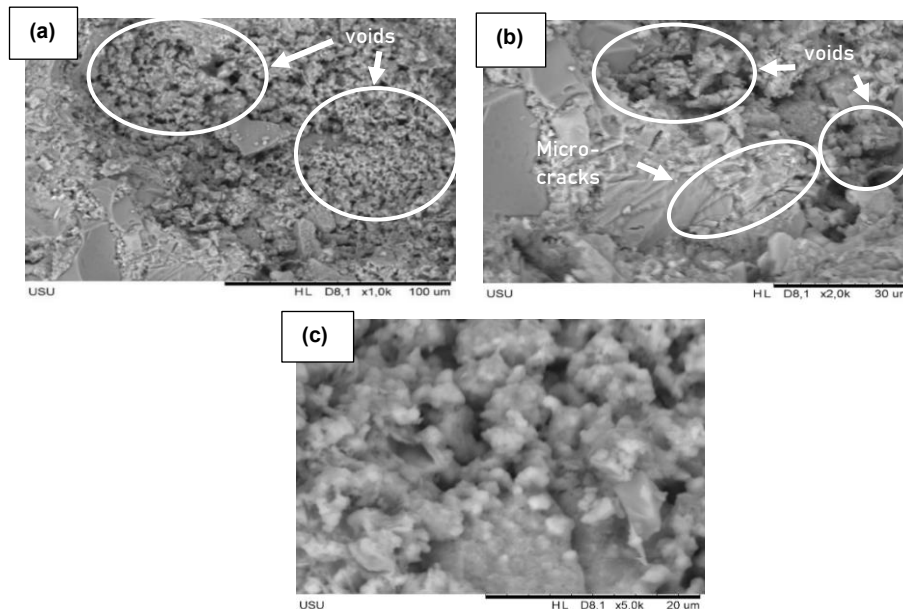


Figure 5. SEM observations of paving blocks without waste at magnifications of (a) 1000 $\times$, (b) 2000 $\times$, and (c) 5000 $\times$

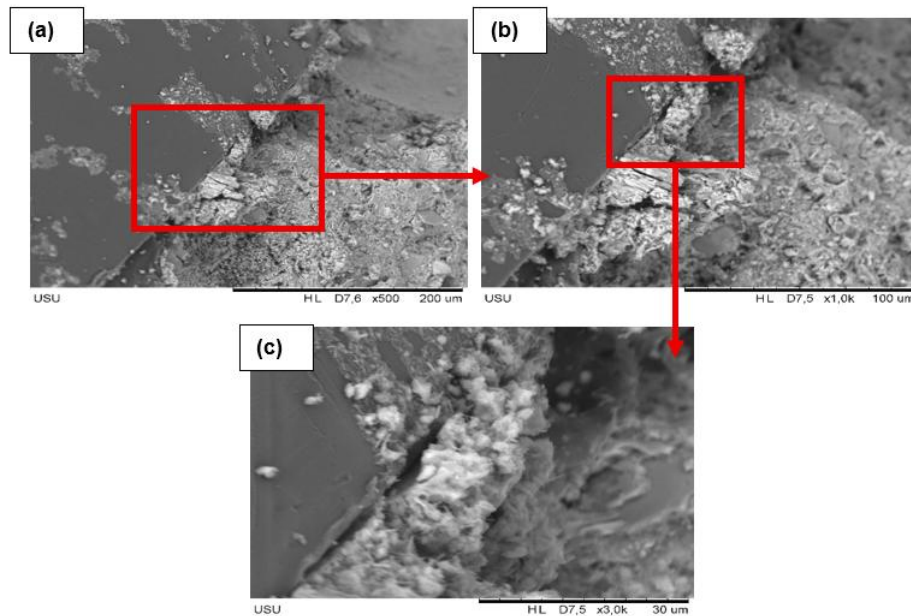


Figure 6. SEM observations of paving blocks with a mixture of WMP and ESP at magnifications of (a) 500×, (b) 1000×, and (c) 3000×

Figure 6 presents the microstructure of paving blocks containing WMP and ESP at magnifications of 500×, 1000×, and 3000×. In Figure 6(a) (500×), WMP appears as flake-like or thin-film fragments substituting for aggregate, partially coating the surface but not fully integrating with the surrounding material, suggesting incomplete plastification during mixing. In Figure 6(b) (1000×), ESP exhibits a layered and porous morphology with a rough surface, while still presenting a low-density transition zone. This becomes more evident in Figure 6(c) (3000×), where ESP shows fibrous and hollow textures, with interphase gaps acting as weak points for microcrack initiation. According to Nandhini & Karthikeyan, (2022), the addition of ESP can aid in filling voids and forming a network of calcium silicate hydrate (C-S-H) minerals during hydration. These findings align with Shcherban' et al., (2022), who stated that ESP's pozzolanic effectiveness is only achieved at specific dosages, while excessive amounts promote particle agglomeration that compromises microstructural compactness. Furthermore, Akhila & Rao, (2023) explained that microstructural changes due to hydration and carbonation reactions can occur gradually, even under constant CO₂ and humidity conditions, particularly when inert components such as WMP are present.

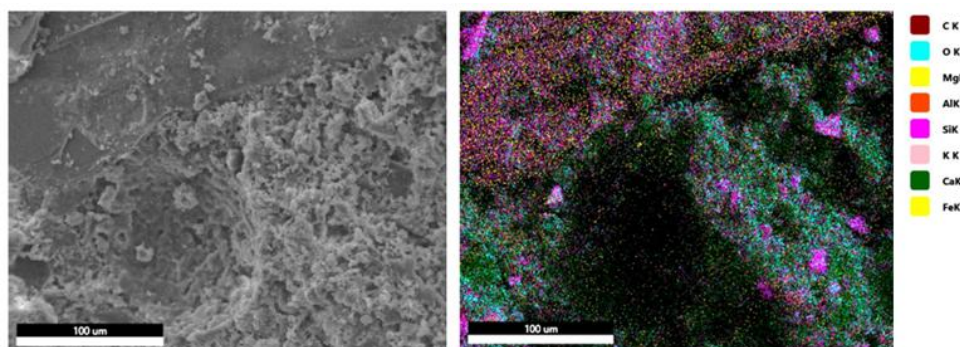


Figure 7. Elemental Mapping of Paving Blocks with WMP and ESP Mixture

Overall, Figure 7 reveals distinct pore formations that could affect compressive strength and water absorption, potentially accelerating material degradation if not optimized. This observation correlates with the water absorption results, where mixtures containing WMP and ESP exhibited higher absorption (3.86%) compared to the control paving blocks without waste (1.65%). Microvoids detected in several images indicate the presence of weak transition zones between ESP particles and the cement matrix, which can serve as initiation points for damage, especially under wet or aggressive environmental conditions.

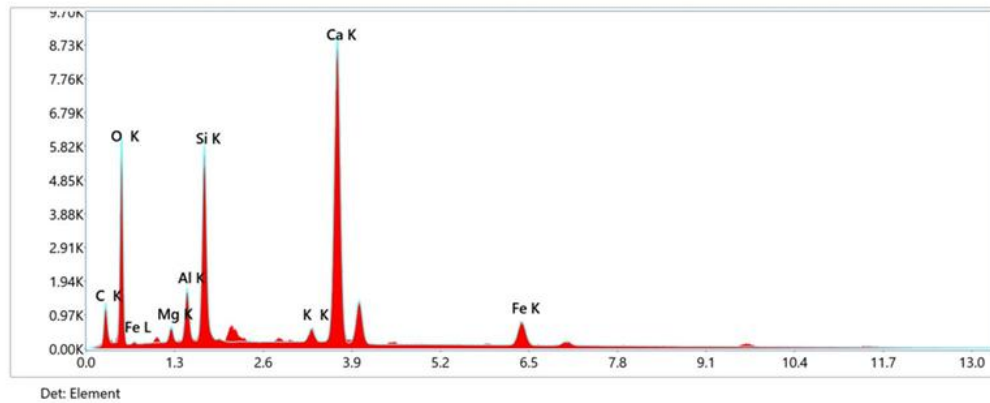


Figure 8. EDX Spectrum of Paving Block Samples Containing Waste Metallized Plastic (WMP) and Eggshell Powder (ESP)

Elemental mapping in Figure 8 shows the predominant distribution of oxygen (O) and calcium (Ca), indicating the presence of CaO and Ca(OH)_2 as major constituents derived from Portland cement hydration and calcium carbonate from ESP. Silicon (Si) is also well distributed, suggesting the presence of silicates from cement and fine aggregates. The significant carbon (C) content (12.29 wt.%) strongly indicates the presence of WMP, which consists of carbon-based organic polymers with thin metallized layers.

Quantitative EDX results presented in Table 9 and the EDX spectrum in Figure 7 reveal that oxygen (O) is the dominant element, accounting for 46.11 wt.% and 57.30 at.%. Calcium (Ca) is present at 25.52 wt.%, originating from CaCO_3 in ESP and hydrated cement phases. The relatively high carbon (C) content suggests that WMP did not fully integrate or decompose within the cement matrix. Iron (Fe) at 4.80 wt.% likely comes from the metallic coating of WMP, which is reflective and corrosion-resistant. Silicon (Si), aluminum (Al), magnesium (Mg), and potassium (K) represent fractions of minerals from cement and natural aggregates.

In summary, the SEM-EDX analysis indicates that the combination of WMP and ESP results in a microstructural system that remains insufficiently compact, potentially influencing the mechanical properties of paving blocks, particularly their compressive strength and weathering resistance. Nevertheless, the notable presence of Ca and Si continues to contribute to the formation of C-S-H gel, which plays a key role as the primary binding phase.

Table 9. Quantitative Energy Dispersive X-Ray (EDX) Analysis Results of Paving Blocks Containing Waste Metallized Plastic (WMP) and Eggshell Powder (ESP)

Element	Weight %	Atomic %	Interpretation
O	46.11%	57.30%	Generally, from hydrate compounds such as C–S–H (Calcium Silicate Hydrate) and Ca(OH) ₂
Ca	25.52%	12.66%	Dominant from cement and eggshell powder (CaCO ₃). The highest peak → the dominant element.
C	12.29%	20.35%	Strong indications of the presence of WMP – carbon from metallic plastics.
Si	7.41%	5.25%	Indications of the presence of silicate compounds from cement and aggregates.
Fe	4.80%	1.71%	Indications are derived from WMP (metallic metals) or impurity aggregates.
Al	2.26%	1.66%	Components in cement, such as in C ₃ A (Tricalcium Aluminate).
Mg	0.80%	0.65%	Minor elements – likely derived from minor aggregates or minerals.
K	0.81%	0.41%	Potassium minor – possible from the aggregate.

Cost Aspect

One of the most popular installation patterns is the herringbone (zig-zag) pattern, which is considered more stable under load and displacement due to the even distribution of forces between units (SNI 03-0691-1996), as shown in Figure 9. However, this paving block shape does not have geometric interlocking between adjacent sides, relying instead on dimensional accuracy and precision in installation.

In analyzing the cost aspect in this study, a market price approach was used based on prevailing prices in Medan City, North Sumatra, Indonesia, for each material composing the paving block, without considering other production costs such as labor, distribution, or heavy equipment expenses.

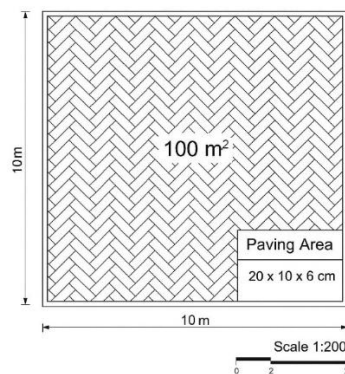


Figure 9. Illustration of Paving Block Installation

PCC (PT Semen Padang)	= Rp. 60,000/bag (40 kg)
	= Rp 1,500/k
Sand	= Rp. 270,000/m ³
	= Rp 99.5/kg ≈ Rp. 100/kg
WMP Waste	= Rp. 0,-
ESP Waste	= Rp. 0,-

Table 10. Estimated Cost of Required Materials

No.	Material	Unit Price (IDR/kg)	Number of materials per piece (Kg)	Price Per Piece (IDR)
A. 0% Waste Paving Block				
1	PCC	1500	0.957	1,435.55
2	ESP	0	0.000	-
3	Sand	99.52	1.914	190.49
4	WMP	0	0.000	-
5	Water	1	0.431	0.43
Total			3.302	1,626.47
B. P5ES5W (Replaced 5% ESP; 5% WMP)				
1	PCC	1500	0.909	1,363.77
2	ESP	0	0.048	-
3	Sand	99.52	1.818	180.96
4	WMP	0	0.033	-
5	Water	1	0.409	0.41
Total			3.217	1,545.14
C. P5ES10W (Replaced 5% ESP; 10% WMP)				
1	PCC	1500	0.909	1,363.77
2	ESP	0	0.048	-
3	Sand	99.52	1.723	171.44
4	WMP	0	0.066	-
5	Water	1	0.409	0.41
Total			3.154	1,535.62
D. P5ES15W (Replaced 5% ESP; 15% WMP)				
1	PCC	1500	0.909	1,363.77
2	ESP	0	0.048	-
3	Sand	99.52	1.627	161.92
4	WMP	0	0.098	-
5	Water	1	0.409	0.41
Total			3.092	1,526.10

Based on the data presented in Table 10, the incorporation of Waste Metallized Plastic (WMP) and Eggshell Powder (ESP) into the paving block mixture demonstrates a notable influence on production costs, compressive strength, water absorption, and sodium sulfate resistance. From a cost perspective, the control specimen (without waste) exhibited the highest unit price at IDR 1,626.47. Partial substitution of aggregates and cement with 5% WMP (P5ES5W) resulted in a reduction to IDR 1,545.14 (representing a 5.0% cost saving), which further decreased to IDR 1,525.10 (6.2% saving) in the P5ES15W mixture.

CONCLUSION

Based on the findings, it can be concluded that the partial substitution of cement with 5% Eggshell Powder (ESP) and aggregates with 5-15% Waste Metallized Plastic (WMP) successfully produces paving blocks that meet specific quality standards (Category C and D according to SNI) for non-structural applications like garden pathways, while reducing direct material costs by up to 6.2%. However, this environmental and economic benefit comes at the expense of mechanical performance, as evidenced by a significant reduction in compressive strength (up to 59.01%), increased water absorption, and diminished impact resistance due to

a weaker interfacial transition zone and higher porosity. For future research, it is recommended to investigate the use of chemical or physical treatments to improve the adhesion between the plastic waste and the cement matrix, explore different particle sizes and types of plastic waste, and conduct long-term field studies to assess the real-world durability and weathering performance of these composite paving blocks under various environmental conditions.

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