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Research Article

From Waste to Sustainable Pavements: Performance Evaluation of Eggshell and Green Mussel Shell Ash as Partial Cement Substitutes in Paving Blocks

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Abstract

This study investigates the potential use of eggshell ash and green mussel shell ash as partial cement substitutes in the production of paving blocks intended for pedestrian pavement applications. The research aims to support sustainable construction practices by reducing cement consumption while maintaining adequate mechanical performance. An experimental method was adopted by incorporating the biowaste ashes into paving block mixtures at substitution levels of 2.5%, 5.0%, and 7.5% by weight of cement, with conventional paving blocks used as control specimens. Laboratory testing was conducted in accordance with Indonesian National Standards to evaluate aggregate physical properties, compressive strength at curing ages of 7 and 28 days, and water absorption behavior. The results show that paving blocks containing eggshell and green mussel shell ash achieved compressive strength values that met and, in some cases, exceeded the minimum requirement for pedestrian pavements. The optimum mixture was observed at a substitution level of approximately 5%, where the 28-day compressive strength surpassed the target design strength of 20 MPa, despite a minor reduction in early-age strength at 7 days. Water absorption values remained within acceptable limits, indicating that the inclusion of biowaste ash did not negatively affect durability-related performance. These findings highlight that calcium-rich biowaste materials can be effectively utilized as sustainable cement substitutes in non-structural paving applications. The study contributes to the advancement of circular economy strategies in the construction sector by promoting waste valorization, minimizing environmental impact, and offering an eco-friendly alternative for pedestrian infrastructure development.

Keywords: *Cement; Circular; Eggshell Ash; Green Mussel Shell Ash; Sustainable Paving Bloks*

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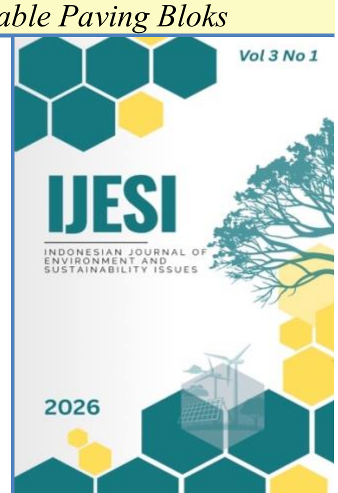

INTRODUCTION

Paving blocks are widely used in contemporary construction, particularly for pedestrian pavements and non structural infrastructure. Their popularity is driven by ease of installation, flexibility in layout, and adequate performance under light to moderate loads. Despite their non structural role, paving blocks are produced in large quantities and therefore consume substantial amounts of Portland cement. Cement production is known to be energy intensive and a major contributor to global carbon dioxide emissions [1], [2], [3]. The environmental footprint associated with cement use has encouraged researchers to explore alternative and supplementary cementitious materials [4], [5], [6]. Material selection in paving block manufacturing strongly influences compressive strength, dimensional stability, and durability against weather exposure. Poor material composition can result in premature deterioration and reduced service life. For pedestrian applications, paving blocks must meet minimum strength and durability requirements specified by technical standards [7], [8], [9]. These requirements make paving blocks a suitable platform for testing innovative and sustainable material substitutions. Compared to structural concrete, paving blocks allow greater flexibility in mix design. This flexibility enables the incorporation of alternative materials without excessive safety risks. Therefore, paving blocks represent an effective entry point for sustainable construction material development.

In parallel with concerns over cement consumption, the accumulation of biowaste has emerged as a significant environmental issue. Eggshell waste generated from households, restaurants, and food industries is produced in large quantities worldwide [10], [11], [12], [13]. Most eggshell waste is discarded without systematic recycling or valorization [14], [15]. This practice contributes to environmental pollution and inefficient resource use [16], [17]. From a materials perspective, eggshells consist predominantly of calcium carbonate. Calcium carbonate is one of the principal constituents involved in Portland cement chemistry. Consequently, eggshell waste has attracted attention as a potential supplementary cementitious material. In addition to eggshells, green mussel shell waste is abundantly generated in coastal regions and seafood markets. Green mussel shells contain high levels of calcium oxide and calcium carbonate. These compounds are essential for cement hydration and strength development. Uncontrolled disposal of mussel shell waste can create environmental and sanitary problems. Utilizing these wastes in construction materials offers both environmental and ecNumerous studies have investigated eggshell powder or ash as a partial replacement for cement in concrete and mortar systems.

The majority of these studies focus on compressive strength, workability, and early-age performance [need citation]. Separate research has examined mussel shell waste in various forms, including ash, powder, and aggregate replacement. These investigations often emphasize durability, microstructural properties, or lightweight concrete applications [18], [19], [20]. Research on paving blocks incorporating waste materials has also increased in recent years. However, most paving block studies rely on single waste materials rather than combined biowaste systems. Water absorption behavior, which is critical for durability in pedestrian pavements, is frequently underreported [21], [22]. The interaction between multiple calcium-rich wastes in paving block matrices remains poorly understood. Optimal substitution levels that balance strength and durability are not consistently identified across studies [23], [24], [25]. Many investigations emphasize mechanical performance without explicitly linking results to circular economy objectives [26], [27], [28]. As a result, the sustainability implications of waste-based paving blocks are often only partially addressed. These limitations highlight the need for integrated studies that combine performance evaluation and environmental relevance.onomic advantages.

Previous studies have widely explored the use of eggshell powder or eggshell ash as a partial cement replacement in various cementitious systems, including high-strength concrete, mortar, self compacting concrete, and geopolymer concrete, with primary emphasis on mechanical performance and workability characteristics [29], [30], [31], [32]. Similarly, mussel shell waste has been investigated either as ash, powder, or aggregate replacement in lightweight concrete, foamed concrete, and non-structural concrete applications, focusing on durability, microstructural behavior, and strength development under controlled conditions [33], [34], [35], [36]. In parallel, research on concrete paving blocks has predominantly addressed the incorporation of agricultural residues, industrial by-products, or plastic waste as cement or aggregate substitutes, often prioritizing compressive strength and environmental assessment while employing single waste materials [37], [38], [39], [40]. However, despite the extensive body of literature on eggshell-based and seashell based cement replacement, there remains a notable lack of studies examining the combined use of eggshell ash and green mussel shell ash as partial cement substitutes specifically in paving block applications, particularly with respect to both compressive strength development and water absorption performance relevant to pedestrian pavements. Moreover, limited attention has been given to identifying optimal substitution levels that balance mechanical performance and durability while explicitly linking material performance to circular economy and waste valorization principles. This gap highlights the need for a systematic experimental investigation into the synergistic effects of calcium-rich biowaste materials in sustainable paving block production.

This study aims to evaluate the feasibility of using eggshell ash and green mussel shell ash as partial cement substitutes in paving block production. The research focuses on paving blocks intended for pedestrian pavement applications. Compressive strength development at different curing ages is systematically investigated. Water absorption characteristics are examined to assess durability related performance. Several substitution levels are evaluated to determine their influence on material behavior. Conventional paving blocks without waste substitution are used as reference specimens. Laboratory testing is conducted in accordance with established material characterization standards. The study seeks to identify an optimal substitution level that meets technical requirements. Attention is given to maintaining functional performance while reducing cement consumption. The combined use of two calcium-rich biowastes is expected to reveal potential synergistic effects. Environmental benefits are considered through the perspective of waste valorization and resource efficiency. Ultimately, this research aims to support sustainable and circular approaches in pedestrian infrastructure development.

METHODS

Research Design, Duration, and Location

This research adopted a controlled experimental design to evaluate the effects of eggshell ash and green mussel shell ash as partial cement substitutes in paving block production. The experimental approach was selected to allow systematic comparison between conventional paving blocks and modified paving blocks incorporating biowaste materials at different substitution levels. The study was conducted over a period of five months, encompassing proposal preparation, material collection and processing, laboratory testing, data analysis, and manuscript preparation. All experimental activities were carried out in the Civil Engineering Laboratory, where environmental and testing conditions were maintained consistently to ensure repeatability and reliability of results.

Materials Preparation and Characterization

The primary materials used in this study included natural fine aggregate (sand), Portland cement, superplasticizer admixture, eggshell ash, and green mussel shell ash. Eggshell waste and green mussel shell waste were collected from local sources and subjected to a preparation process prior to use. The wastes were thoroughly cleaned to remove organic residues and impurities, dried to eliminate moisture content, and subsequently processed into ash through controlled heating. The resulting ash was sieved to obtain a uniform particle size suitable for cement substitution. This preparation ensured that the biowaste materials exhibited consistent physical characteristics and could be effectively incorporated into the cementitious matrix.

Equipment and Laboratory Tools

Laboratory equipment utilized in this study included trays, a weighing balance with 1 kg precision, an oven for drying materials, mixing containers, cement scoops, measuring cylinders with a capacity of 1000 mL, tamping rods, a sieve shaker, and steel moulds for paving block casting. These tools were selected to support accurate material proportioning, uniform mixing, and standardized specimen preparation. All equipment was calibrated prior to use to minimize measurement errors during experimentation.

Fine Aggregate Testing Procedure

Prior to mix proportioning, the fine aggregate was tested to determine its physical properties in accordance with Indonesian National Standards (SNI). Aggregate characterization is essential to ensure compatibility with cementitious materials and to achieve consistent paving block performance. The tests conducted included particle size distribution, specific gravity, moisture content, and bulk density. The testing procedures and corresponding standards are summarized in Table 1.

Table 1. Procedure for Fine Aggregate Tessting

No.	Test Parameter	Testing Standard	Unit
1	Particle size distribution	SNI 03-1968-1990	%
2	Specific gravity	SNI 03-1970-1990	–
3	Moisture content	SNI 03-1971-1990	%
4	Bulk density	SNI 03-4804-1998	kg/m^3

The results obtained from these tests were used as input parameters for determining the paving block mix design.

Mix Design and Specimen Fabrication

The paving block mixtures were designed to achieve a target compressive strength of 20 MPa (f'c = 20 MPa), which corresponds to the minimum requirement for pedestrian pavement applications. Eggshell ash and green mussel shell ash were used as partial cement substitutes at replacement levels of 2.5%, 5.0%, and 7.5% by weight of cement. A control mixture without biowaste substitution was prepared for comparison. The materials were mixed uniformly to ensure homogeneity before casting. Paving block specimens were cast using moulds with dimensions of 10.5 cm × 21 cm × 7 cm. For each mixture variation, three specimens were produced, resulting in a total of nine specimens for each treatment group.

Curing Process

After casting, the specimens were allowed to set before being demoulded. Subsequently, all paving block specimens were cured by immersion in water to promote proper cement hydration. The curing process was maintained consistently for all specimens to minimize variability in strength development. Proper curing was essential to ensure that the influence of biowaste substitution on mechanical performance could be accurately evaluated.

Testing of Mechanical and Durability Properties

Compressive strength tests were conducted at curing ages of 7 and 28 days to evaluate both early-age and later-age strength development. These testing intervals were selected to capture the influence of biowaste ash on hydration progression and strength gain over time. In addition to compressive strength, water absorption tests were performed to assess durability-related characteristics of the paving blocks. Water absorption behavior is a critical indicator of porosity and long-term performance, particularly for pedestrian pavements exposed to environmental conditions.

Data Analysis and Interpretation

Data analysis involved comparing the compressive strength and water absorption results of paving blocks containing eggshell ash and green mussel shell ash with those of the control specimens. The analysis focused on identifying trends associated with increasing substitution levels and evaluating their impact on mechanical and durability performance. The optimal substitution level was determined based on achieving adequate compressive strength while maintaining acceptable water absorption values. The findings were interpreted in relation to material composition and the potential role of calcium-rich biowaste in enhancing cementitious performance.

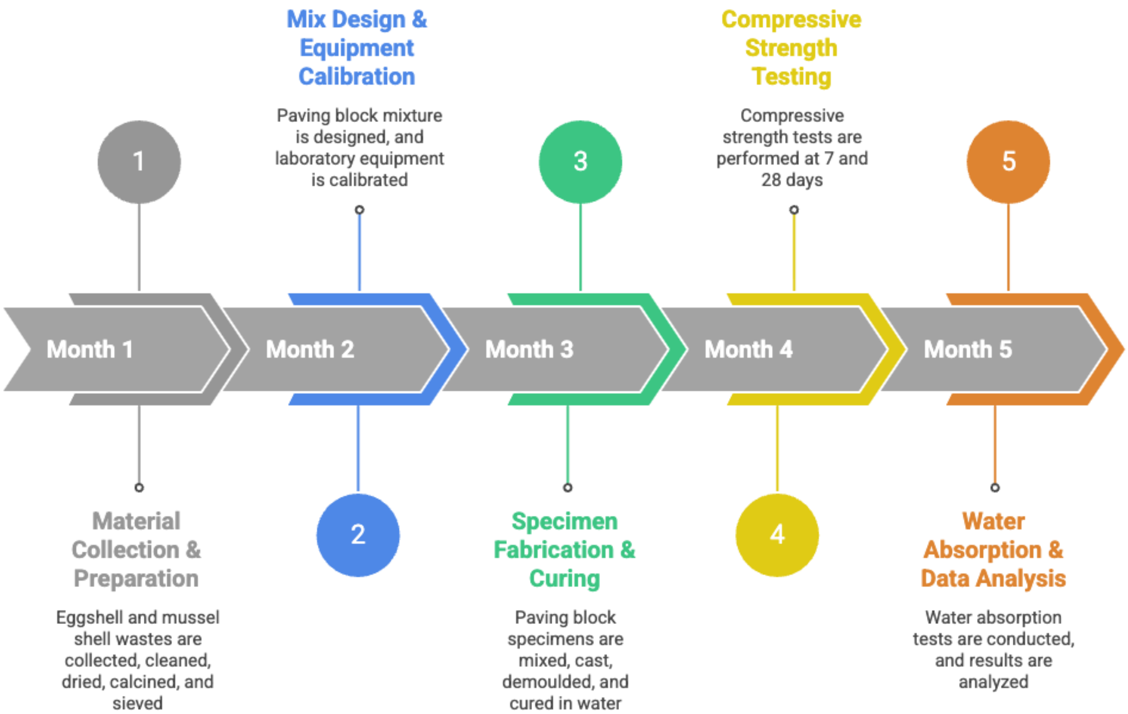

Figure 1. Research Method Flow

RESULT AND DISCUSSIONS

Results

1. **Moisture Content of Fine Aggregate**
   Moisture content testing was conducted to quantify the amount of water contained in the fine aggregate prior to mixing, as this parameter directly affects the effective water content and the water–cement ratio in paving block production. As shown in Table 2, the moisture content obtained from two repetitions was 3.66% and 3.53%, yielding an average value of 3.59%. This indicates that the sand used was not in a fully dry condition and therefore required careful water adjustment during batching to avoid unintended increases in mixing water. The oven-drying procedure and test setup are documented in Figure 2.

Figure 2. Moisture Content Testing Process of Fine Aggregate (Oven Drying Method)

Table 2. Moisture Content Test Results of Fine Aggregate

Parameter	Unit	Test I	Test II	Average
Cup No.	–	1	2	–
Cup weight, W1	g	733	714	–
Cup + wet sample, W2	g	8100	7760	–
Wet sample weight, W3 = W2 − W1	g	7367	7046	–
Cup + oven-dry sample, W4	g	7840	7520	–
Oven-dry sample weight, W5 = W4 − W1	g	7107	6806	–
Moisture content, ((W3 − W5)/W5)×100%	%	3.66	3.53	**3.59**

2. **Specific Gravity and Water Absorption of Fine Aggregate**

Specific gravity and absorption tests were performed to evaluate aggregate density characteristics and pore accessibility, which influence cement paste demand, packing quality, and durability-related behavior. Table 3 shows that the average bulk specific gravity (oven-dry basis) was 2.756, while the saturated surface dry (SSD) specific gravity was 2.780, and the apparent specific gravity was 2.830. These values indicate that the fine aggregate exhibits typical density characteristics suitable for mortar/concrete products. Water absorption values ranged from 0.405% to 1.202%, with an average of 0.804%, suggesting relatively low absorption and limited open porosity of the sand. The testing procedure is documented in Figure 3.

Figure 3. Specific Gravity Testing Process of Fine Aggregate

Table 3. Specific Gravity and Water Absorption of Fine Aggregate

Parameter	Unit	Test I	Test II	Average
SSD sample weight, Bj	g	500.15	500.21	–
Oven-dry sample weight, B2	g	494.21	498.19	–
Container + water, B3	g	1231.81	1231.81	–
Container + sample + water, B1	g	1576.79	1517.83	–
Bulk specific gravity (OD), B2/(B3 + Bj − B1)	–	3.185	2.326	**2.756**
SSD specific gravity, Bj/(B3 + Bj − B1)	–	3.223	2.336	**2.780**
Apparent specific gravity, B2/(B3 + B2 − B1)	–	3.312	2.349	**2.830**
Water absorption, ((Bj − B2)/B2)×100%	%	1.202	0.405	**0.804**

3. Bulk Density of Fine Aggregate

Bulk density testing was conducted under loose and compacted conditions to characterize aggregate packing behavior, which can influence void content and cement paste requirements. As presented in Table 4, the loose bulk density measurements yielded 1.666 and 1.644 kg/dm^3 (average 1.655 kg/dm^3), while the compacted condition yielded 1.680 and 1.677 kg/dm^3 (average 1.680 kg/dm^3). The overall average bulk density reported in the dataset is 1.667 kg/dm^3. The test setup is presented in Figure 4.

Figure 4. Bulk Density Testing Process of Fine Aggregate

Table 4. Bulk Density Test Results of Fine Aggregate

Condition	Replicate	Mould weight, W1 (g)	Mould sample, (g)	Sample weight, W3=W2−W1 (g)	Mould water, W4 (g)	Water weight/volume, V=W4−W1 (g)	Bulk density, W3/V (kg/dm³)
Compacted (Padat)	I	2129	7407	5278	5270	3141	1.680
Compacted (Padat)	II	2129	7395	5266	5270	3141	1.677
Average (Compacted)							**1.680**
Loose (Lepas)	I	2129	7362	5233	5270	3141	1.666
Loose (Lepas)	II	2129	7294	5165	5270	3141	1.644
Average (Loose)							**1.655**
Overall reported average							**1.667**

4. **Pericle Size Distribution (Sieve Analysis) of Fine Aggregate**
Sieve analysis was performed to determine the particle size distribution of the fine aggregate and to verify that the gradation falls within acceptable limits for paving block manufacturing. Table 5 presents the retained mass and cumulative passing percentages across sieve sizes, while the gradation curve is illustrated in Graph 1, and the sieve testing process is shown in Figure 5. The cumulative passing results indicate a balanced distribution, with approximately 50.17%

passing the 0.300 mm sieve and 7.91% passing the 0.075 mm sieve, which is consistent with a gradation that supports adequate packing and workable mortar matrices.

Figure 5. Fine Aggregate Sieving Process

Table 5. Sieve Analysis Results of Fine Aggregate

Sieve opening (mm)	Mass retained (g)	% retained	Cumulative retained	Cumulative % passing
4.750	0.00	0.00	0.00	100.00
2.360	47.88	4.79	4.79	95.21
1.180	103.00	10.31	15.11	84.89
0.600	17.77	1.78	16.89	83.11
0.300	329.00	32.94	49.83	50.17
0.150	238.00	23.83	73.66	26.34
0.075	184.00	18.42	92.09	7.91
Pan (Sisa)	79.00	7.91	100.00	0.00
Total	**998.65**	**100.00**	–	–

5. Mix Dedsign Implementation and Specimen Febrication

Following aggregate characterization, paving block mixtures were prepared using a control mix and three substitution levels of combined eggshell ash and green mussel shell ash. The substitution levels corresponded to 2.5%, 5.0%, and 7.5% relative to cement content (as described in the study), operationalized in the dataset as 25 g, 50 g, and 75 g of combined ash addition. Mixing and casting procedures are documented in Figure 6, while the specimen appearance is shown in Figure 7. After casting, specimens were cured and subsequently tested at 7 and 28 days for compressive strength and water absorption.

Figure 6. Mixing Process of Eggshell and Green Mussel Shell Ash into the Paving Block Mixture

6. **Compressive Strength of Paving Blocks**

Compressive strength results for all mixtures are presented in Table 6. At 7 days, the control (normal) paving blocks showed compressive strength values of 22.40, 21.32, and 26.87 MPa, indicating relatively high early-age strength. In comparison, the 25 g substitution group produced 15.85–17.24 MPa at 7 days, while the 50 g and 75 g groups produced 15.91–17.24 MPa and 15.88–16.70 MPa, respectively, reflecting a lower early-age strength relative to the control. The strength distribution at 7 days is visualized in Figure 7.

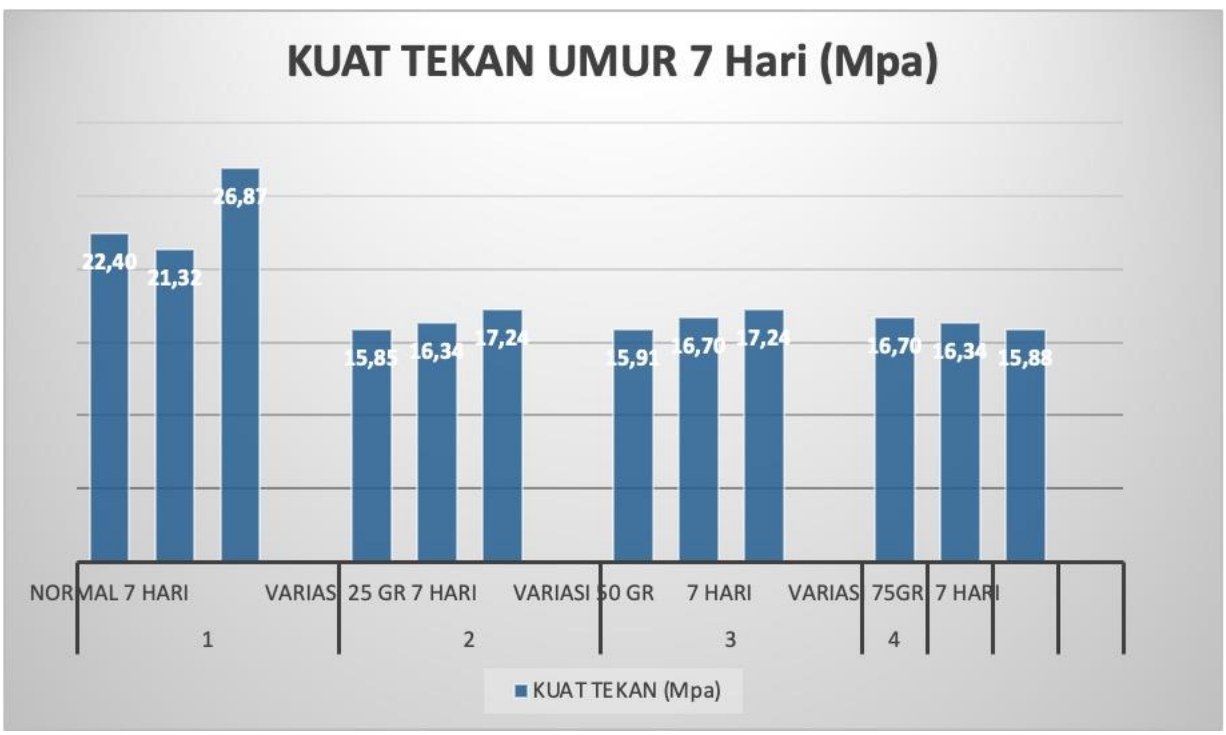

Figure 7. Compressive Strength at 7 Days

The figure presents the 7-day compressive strength results of paving blocks produced with different mixtures, including a control mixture and mixtures containing eggshell and green mussel shell ash substitutions. The control specimen (normal mix) exhibits compressive strength values of 22.40 MPa, 21.32 MPa, and 26.87 MPa, which are higher than those of the modified mixtures, while the specimens with 25 g, 50 g, and 75 g substitutions show compressive strength values ranging approximately from 15.85 MPa to 17.24 MPa, indicating relatively similar performance among the substitution levels. Overall, the results indicate that the incorporation of shell-based ash tends to reduce early-age compressive strength compared with the control mixture, although the values remain within a relatively consistent range across the different substitution variations.

At 28 days, strength development increased for the substituted mixtures, particularly for the 50 g group, which achieved 27.21 and 26.32 MPa (with one replicate at 22.68 MPa), indicating that this mixture delivered the highest later-age strength among all variations. The 75 g group also exhibited improved 28-day strength (24.05–24.49 MPa), while the 25 g group remained around 19.95–20.05 MPa. The 28-day strength patterns are illustrated in Figure 9. Overall, the results suggest that moderate substitution (notably 50 g) supported superior later-age compressive strength compared to both lower and higher substitution levels.

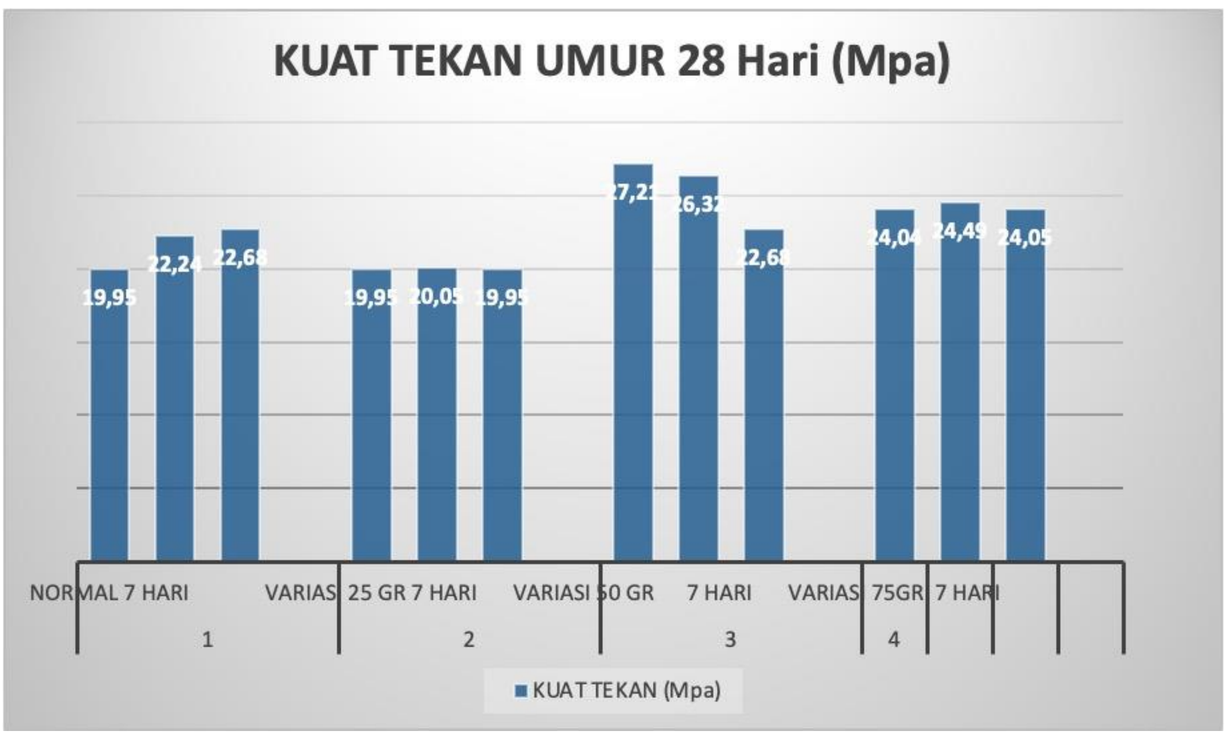

Figure 8. Compressive Strength at 28 Days

Table 6. Compressive Strength Test Results of Paving Blocks

Mix type	Specimen	Weight (kg)	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)
Normal (Control)	1	2.8	22.40	19.95
Normal (Control)	2	2.8	21.32	22.24
Normal (Control)	3	2.8	26.87	22.68
25 g eggshell+mussel ash	1	2.5	15.85	19.95
25 g eggshell+mussel ash	2	2.5	16.34	20.05
25 g eggshell+mussel ash	3	2.6	17.24	19.95
50 g eggshell+mussel ash	1	2.6	15.91	27.21
50 g eggshell+mussel ash	2	2.6	16.70	26.32
50 g eggshell+mussel ash	3	2.5	17.24	22.68
75 g eggshell+mussel ash	1	2.6	16.70	24.05
75 g eggshell+mussel ash	2	2.5	16.34	24.49
75 g eggshell+mussel ash	3	2.5	15.88	24.05

7. Water Absorption of Paving Blocks

Water absorption testing was conducted as a durability-related indicator reflecting pore connectivity and permeability. The results are summarized in Table 7, while the trends are illustrated in Figure 10 (7 days) and Figure 11 (28 days). At 7 days, the control paving blocks showed an absorption value of 3.8447%, whereas the 25 g group exhibited the lowest absorption value (1.7293%), followed by the 50 g group (2.4206%) and the 75 g group (2.4696%). At 28 days, the absorption values for the control and 25 g groups were 3.0280% and 2.8379%, respectively. The 50 g group achieved the lowest absorption value at 28 days (2.0825%), indicating improved densification relative to other mixtures. In contrast, the 75 g group showed the highest 28-day absorption value (4.2314%), suggesting that excessive substitution may have increased pore volume or pore connectivity. Collectively, the absorption results indicate that moderate substitution levels, particularly 50 g, improved the balance between strength and absorption performance, while higher substitution (75 g) may introduce adverse porosity effects.

Table 7. Water Absorption Test Results of Paving Blocks

Curing age	Mix proportion	Wet mass	Dry mass	Water absorption (%)
7 days	0%	2.701	2.601	3.8447
7 days	25.0%	2.706	2.660	1.7293
7 days	50.0%	2.581	2.520	2.4206
7 days	75.0%	2.614	2.551	2.4696
28 days	0.0%	2.722	2.642	3.0280
28 days	25.0%	2.754	2.678	2.8379
28 days	50.0%	2.598	2.545	2.0825
28 days	75.0%	2.685	2.576	4.2314

The experimental results demonstrate that the incorporation of eggshell ash and green mussel shell ash as partial cement substitutes significantly influences both the mechanical and durability-related properties of paving blocks, with performance strongly dependent on substitution level and curing age. The observed reduction in compressive strength at 7 days for all substituted mixtures suggests a delayed early-age hydration process, which is commonly associated with partial cement replacement by inert or slowly reactive materials. However, the substantial strength gain at 28 days, particularly for the 50 g substitution mixture, indicates that the calcium-rich composition of eggshell and mussel shell ash contributed to continued hydration and matrix densification over time. The high calcium carbonate content of these biowastes likely promoted secondary reactions and improved particle packing through a filler effect, resulting in a denser cementitious microstructure. This behavior explains why the 50 g mixture not only recovered early-age strength loss but surpassed the compressive strength of the control specimens at 28 days. In contrast, the 75 g substitution level showed diminishing returns, suggesting that excessive cement replacement reduced the availability of primary binding phases, leading to less efficient strength development. These findings highlight the importance of optimizing substitution levels to achieve a balance between cement reduction and mechanical performance.

From a durability perspective, the water absorption results further support the existence of an optimal substitution threshold. The lowest absorption values recorded for the 50 g mixture at both 7 and 28 days indicate improved pore refinement and reduced connectivity within the cement matrix, which is consistent with enhanced densification and packing efficiency. Conversely, the increased absorption observed in the 75 g mixture at 28 days suggests the formation of additional voids or discontinuities due to excessive replacement of cementitious material. Collectively, these results contribute to the advancement of knowledge by demonstrating that the combined use of eggshell ash and green mussel shell ash is not merely feasible but can outperform conventional paving blocks when applied at an appropriate dosage. This study extends previous research that primarily focused on single biowaste materials by providing empirical evidence of synergistic effects between two calcium-rich wastes in non-structural concrete applications. Furthermore, the findings support the broader adoption of waste valorization strategies in construction materials, reinforcing circular economy principles while maintaining compliance with technical performance standards for pedestrian pavements.

CONCLUSION

This study demonstrates that eggshell ash and green mussel shell ash can be effectively utilized as partial cement substitutes in paving block production for pedestrian pavement applications without compromising mechanical and durability-related performance. The experimental results confirm that substitution level plays a critical role in determining material behavior, with moderate replacement providing optimal outcomes. Although a reduction in early-age compressive strength was observed at 7 days for all substituted mixtures, significant strength development occurred at 28 days, particularly for the mixture incorporating 50 g of combined eggshell and mussel shell ash, which exceeded the target compressive strength of 20 MPa and outperformed the control specimens. Water absorption testing further revealed that this optimal substitution level produced the lowest absorption values, indicating improved matrix densification and reduced pore connectivity. In contrast, higher substitution levels led to increased porosity and diminished performance, highlighting the importance of dosage optimization. Overall, the findings confirm the synergistic potential of combining two calcium-rich biowaste materials to enhance paving block performance while reducing cement consumption. This research contributes to the development of sustainable construction materials by providing empirical evidence that biowaste valorization can support circular economy principles, minimize environmental impact, and deliver functional paving blocks that meet technical requirements for pedestrian infrastructure.

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AUTHORS CONTIBUTIONS

Randy Setiawan was primarily responsible for the conceptualization of the research, including the formulation of research objectives, experimental design, and overall supervision of the study. He also led the data analysis and prepared the initial draft of the manuscript. Deny Syarani contributed to the development and implementation of the experimental methodology, conducted laboratory testing, and ensured the accuracy and validation of the collected data. Ahmad Muhtadi provided substantial support in material characterization, assisted in data interpretation, and contributed to the critical review and technical refinement of the manuscript. Janne Hillary contributed to the scientific discussion, supported the interpretation of results from an international perspective, and assisted in improving the clarity, structure, and academic quality of the manuscript. All authors reviewed and approved the final version of the manuscript and collectively agreed to be accountable for all aspects of the research, ensuring its integrity and accuracy.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the design, implementation, analysis, or publication of this research. All procedures were conducted independently, and no financial or personal relationships have influenced the outcomes presented in this article.

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