Effect of coconut shell ash substitution on compressive strength, wear resistance and water absorption in paving blocks

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Abstract

Waste refers to leftover material generated from production processes, industrial activities, or other human activities, often considered discarded due to its lack of economic value. Coconut shell waste is one such material that has not been optimally utilized, and it often accumulates without adequate disposal. However, coconut shell ash, which contains silica, can potentially enhance the compressive strength of paving blocks. This study investigates the effect of coconut shell ash substitution on the compressive strength, wear resistance, and water absorption of paving blocks. The tests were conducted in accordance with SNI-03-0691-1996 standards, including compressive strength, wear resistance, and water absorption tests. Coconut shell ash was substituted at percentages of 5.5%, 7.5%, 9.5%, 11.5%, and 13.5% by weight of cement. The paving blocks were tested at 28 days. The mixture used a 1:3 ratio of cement to sand, with the sand comprising equal parts Merapi and Progo River sand to balance their different grain characteristics—Merapi sand being angular and sharp, and Progo River sand being fine and round. The compressive strength, wear resistance, and water absorption of normal paving blocks were found to be 36.925 MPa, 0.085 mm/min, and 2.132%, respectively. The highest optimal performance was achieved at 9.5% coconut shell ash substitution, yielding a compressive strength of 40.450 MPa, wear resistance of 0.086 mm/min, and water absorption of 2.349%, meeting the quality category A standard for roads.

Introduction

In the current era of globalization, prefabrication technology in Indonesia has advanced rapidly. Among these technologies, paving blocks have become a popular choice for ground surface pavement layers due to their ease of maintenance, workability, and straightforward installation. As a form of prefabricated construction material, paving blocks are typically made from a mixture of Portland cement (or similar hydraulic materials), water, and fine aggregate, with or without additional materials, provided these do not compromise quality (SNI 03-0691-1996). Common applications include parking lots, sidewalks, parks, pedestrian paths, and neighborhood roads.

As noted by Arman et al. (2023), paving blocks serve as a durable and environmentally friendly alternative to asphalt and concrete for soil pavement and road surfaces. They are favored not only for their environmental benefits but also for their cost-effectiveness, superior compressive strength, water absorption properties, and wear resistance. Sembiring (2017) further emphasized the advantages of paving blocks, highlighting their excellent water absorption capacity, which helps maintain soil balance.

Waste management is a critical issue that demands attention from all sectors. With a population of 261.89 million, Indonesia faces an increasing waste problem, generating 65 million tons of waste annually (BPS, 2018). This figure is expected to rise as the population grows. Waste can be broadly categorized into organic and inorganic types. Organic waste, which comes from the remains of living organisms, includes materials such as coconut shells. According to Alfiyah et al. (2022), coconut shells are a byproduct of coconut processing after the extraction of coconut meat. Despite their abundance, coconut shells remain underutilized. To address the accumulation of this waste, this study investigates the potential of transforming coconut shell waste into ash for use in paving block production, presenting a novel approach to waste reduction and sustainable innovation.

When coconut shell waste is combusted, it produces coconut shell ash, an organic material that can be utilized in the manufacturing of paving blocks. Coconut shell ash is rich in silica, a compound known for enhancing compressive strength. The primary components of paving blocks—cement, sand, and water—contain key chemical compounds such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and H_2O. Ferric oxide (Fe_2O_3) plays a crucial role in improving material strength due to its high crystallinity and strong intermolecular tensile forces. Mahmudi and Puspita (2010), as cited in Hambali (2013), suggested that polyethylene, commonly used in paving blocks, can reduce water absorption. Given the properties of coconut shell ash, particularly its silica content, its inclusion in paving blocks could enhance both compressive strength and water absorption performance, further improving the material's overall quality.

Previous research has explored the effects of adding coconut shell ash on the compressive strength of paving blocks. Zhafirin (2012) investigated the use of coconut shell ash as an additive in varying percentages—2.5%, 5%, 7.5%, 10%, and 12.5% by weight of cement—and found that each increase in coconut shell ash content improved both the dry and wet compressive strength, as well as the flexural strength of the paving blocks. At 10% coconut shell ash, the optimum dry compressive strength reached 268.84 kg/cm², while the wet compressive strength was 215.24 kg/cm², and flexural strength measured 27.99 kg/cm². Water absorption tests indicated an optimum value at 12.5%, with a result of 15.99%. A decrease in water absorption is associated with increased compressive strength, as lower absorption signifies a more water-resistant material. Saputra and Bachtiar (2017) also noted that paving blocks with low porosity, and thus higher waterproofing, are more durable and robust.

Given these findings, further research is required to assess the effects of coconut shell ash as an additive based on the SNI 03-0691-1996 standard, focusing on key factors such as compressive strength, wear resistance, and water absorption. This study will employ a broader range of coconut shell ash substitution levels—0%, 5.5%, 7.5%, 9.5%, 11.5%, and 13.5% by weight of cement—to determine the optimal substitution rate for achieving high-quality paving blocks, in accordance with SNI 03-0691-1996 standards.

In this study, a combination of coarse, angular Merapi sand and fine, rounded Progo River sand was used to enhance the compressive strength of paving blocks. A cement-to-sand ratio of 1:3 (with 1.5 parts Merapi sand and 1.5 parts Progo River sand), along with varying levels of coconut shell ash substitution, was tested to assess its impact on the overall quality of the paving blocks.

This research aims to investigate the effect of substituting coconut shell ash on the compressive strength, wear resistance, and water absorption of paving blocks. Additionally, the study seeks to determine the optimal percentage of coconut shell ash needed to achieve the highest paving block quality. The expected benefits of this research include:

1. Serving as a reference for the advancement of construction technology,
2. Providing insights into the use of coconut shell ash to enhance paving block properties, and
3. Contributing to environmental sustainability by reducing coconut shell waste.

The potential impact on environmental sustainability could inspire further research and development in this field, emphasizing the important role of researchers, construction professionals, and environmentalists in driving these advancements.

Research method

Research flow

In this research, initial trials for producing paving blocks were conducted using rectangular molds with dimensions of 20 cm x 10 cm x 6 cm, applying a cement-to-sand ratio of 1:3 using Merapi sand. However, the compressive strength did not meet the desired quality standards. In a subsequent trial, paving blocks of the same rectangular shape (20 cm x 10 cm) but with an increased thickness of 8 cm were produced, using Progo River sand and a cement-to-sand ratio of 1:2. Despite this modification, the compressive strength still fell short of the planned quality specifications. Figure 1 presents a 20 cm x 10 cm x 6 cm paving block test specimen.

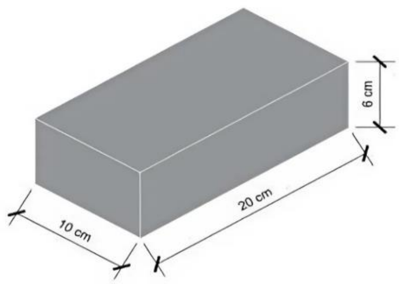

Figure 1. Paving block with 6 cm thickness

In the third trial, paving blocks with dimensions of 20 cm x 10 cm x 8 cm were produced using Merapi sand with a cement-to-sand ratio of 1:3. While the planned compressive strength was not fully achieved, there was a significant improvement due to the increased thickness. Ultimately, this study produced rectangular paving blocks with dimensions of 20 cm x 10 cm x 8 cm, using a mixture of Merapi sand and Progo River sand with a cement-to-sand ratio of 1:3. This combination successfully achieved the target compressive strength of 35-40 MPa, classifying the paving blocks as quality A. Figure 2 illustrates the 20 cm x 10 cm x 8 cm paving block test specimen.

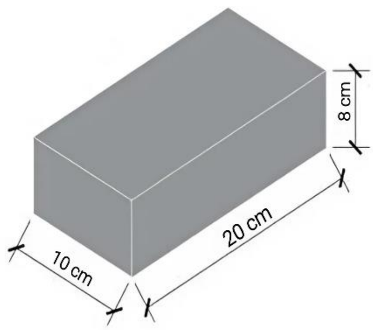

Figure 2. Paving block with 8 cm thickness

A series of trials using different types of sand without the substitution of coconut shell ash resulted in varying compressive strengths. The summarized results of these trials are presented in Table 1.

Table 1. A series of trial results

Sand type	Cement and sand ratio	Thickness (cm)	Compressive strength (MPa)
Merapi sand	1:3	6	22.97
Progo River	1:2	6	21.07
Merapi sand	1:3	8	30.60
Merapi sand & Progo river	1:3	8	36.19

A total of 120 paving block specimens were produced, including 20 normal specimens and 20 specimens for each variation of coconut shell ash substitution (5.5%, 7.5%, 9.5%, and 11.5%). All specimens were created using a grade A mix with dimensions of 20 cm x 10 cm x 8 cm. They were immersed in water for 28 days before undergoing comprehensive testing for compressive strength, wear resistance, and water absorption.

Fine aggregate

The fine aggregates used in this study were sourced from Mount Merapi and the Progo River. Each aggregate was tested to ensure compliance with standards for grain gradation, moisture content, specific gravity, bulk density, and mud content.

Portland cement

The cement used in this study for manufacturing paving blocks is Portland cement (PC) of the brand 'Tiga Roda.' According to SNI 15-2049-2015, Portland cement is a fine powder with adhesive and cohesive properties that serves as a binding material. The cement reacts with water to bind aggregate grains, forming a solid mass and filling the air voids between them. Tjokrodimuljo (2007), as cited in Purnomo and Hisyam (2014), noted that Portland cement is a crucial and widely used binding material in construction. When mixed with water, cement forms a paste, which, when combined with sand, creates cement mortar. The addition of gravel or broken brick to this mortar results in concrete. The chemical properties of Portland cement significantly influence its quality, and this research aims to provide a comprehensive understanding of these properties. The chemical composition of Portland cement, based on its compound structure, is summarized in Table 2, which presents a comparison of oxide composition and content.

Table 2. Oxide content of Portland cement

Oxide	Content (%)
Calcium (CaO)	60-65
Silica (SiO_2)	17-25
Alumina (Al_2O_3)	3-8
Ferric (Fe_2O_3)	0.5-0.6
Magnesium (MgO)	0.5-0.4
Sulphur (SO_3)	1-2
Sodium (Na_2O+K_2O)	0.5-1

Coconut shell ash as pozzolan

Coconut shell, a complex and durable outer layer of the coconut fruit, typically has a thickness of 3-6 mm. This hardness is primarily due to its silica content (SiO_2). Coconut shell ash is obtained through the combustion of these shells. The appearance of the coconut shell ash is illustrated in Figure 3.

Figure 3. Coconut Shell Ash

The chemical composition of coconut shells includes various components such as cellulose, pentose, lignin, ash, extractive solvents, anhydrous uronate, nitrogen, and water. Typically, coconut shells account for 15-19% of the total weight of a coconut. Table 3 presents the chemical composition of coconut shell ash (Adeala et al., 2020).

Table 3. Composition of coconut shell ash

Composition	Percentage (%)
SiO_2	7.65
$AI2O_3$	1.50
Feo3	7.47
MnO	0.21
CaO	43.25
P_2O_5	1.85
K_2O	32.05
TIO_2	3.53
V_2O_5	16.19
SO_3	0.45
C_UO	9.57
ZnO	0.10
Rb_2O	0.21
SrO	0.19
Re_2O_7	0.04
OsO_4	0.04

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Mixture composition

This study utilized cube-shaped paving block specimens with the following dimensions for various tests:

- Compressive Strength Testing: 8 cm x 8 cm x 8 cm (120 specimens total, with 10 specimens per variation).
- Wear Resistance Testing: 5 cm x 5 cm x 2 cm (total of 5 specimens per variation).
- Water Absorption Testing: 20 cm x 10 cm x 8 cm (total of 5 specimens per variation).

The paving blocks were manufactured using a mixture of fine aggregates (1.5 parts Merapi sand and 1.5 parts Progo River sand), cement, and coconut shell ash. Table 4 displays the details of the 20 test specimens and four additional safety test specimens.

Table 4. Admixture composition

Code	Cement (gr)	Sand Merapi (gr)	Sand Progo River (gr)	Coconut Shell Ash (gr)
V0	22726.86	34090.29	34090.29	0
V1	22726.86	34090.29	34090.29	1249.97
V2	22726.86	34090.29	34090.29	1704.51
V3	22726.86	34090.29	34090.29	2159.05
V4	22726.86	34090.29	34090.29	2613.58
V5	22726.86	34090.29	34090.29	3068.12

Note:
V0= normal paving block.
V1= 5.5% coconut shell ash substitution,
V2= 7.5% coconut shell ash substitution,
V3= 9.5% coconut shell ash substitution,
V4= 11.5% coconut shell ash substitution,
V5= 13.5% coconut shell ash substitution.

Compressive strength

Compressive strength testing is conducted to determine the maximum load that the paving block specimen can withstand. The compressive strength (f^c) of the paving block can be calculated using the following equation:

$$\sigma = \frac{P}{A} \qquad (1)$$

Note:

σ = compressive strength (N/mm^2),
P = compressive load (N), and
A = compressive area (mm^2).
The setup for the compressive strength test is illustrated in Figure 4.

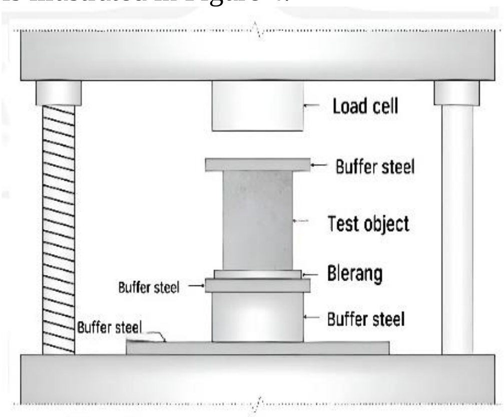

Figure 4. Experimental setup for the compressive strength

Wear resistance

Wear resistance testing can be interpreted as the erosion of the test object's surface layer due to friction. Eq. 2 is used to calculate the wear resistance test on paving blocks.

$$D = 1.26\ G + 0.0246 \qquad (2)$$

Note:
D = wear (mm/minute), and
G = weight loss/wear time (grams/minute).

Water absorption

Water absorption testing measures a material's ability to absorb or retain water. Testing water absorption in paving blocks determines the amount of absorbed water, as referred to in Eq. 3.

$$DSA = \frac{A-B}{B} x\ 100\% \qquad (3)$$

Note:
DSA = water absorption (%),
A = wet weight block paving (gr),
B = paving block weight dry (gr).

Results and discussion

Analysis of Merapi fine aggregate

As mentioned above, both sand quarries have different material characteristics. For this reason, in the early stages of research, fine aggregate testing was conducted on both sand types: Merapi sand and Progo River sand. The test type consisted of fine aggregate gradation, specific gravity, water absorption, solid volume weight, loose volume weight, and sludge content.

Based on the test results presented in Table 5, the fine aggregate of Merapi sand meets the SNI requirements. Furthermore, the research results categorize Merapi sand as Zone II (2), classified as medium sand.

Table 5. Merapi fine aggregate sand test

Test type	Merapi sand	Specification interval	Satisfied code
Fine aggregate gradation	2.64 gr/cm^3	2.5 - 2.7	ok
Specific gravity	2.68 gr/cm^3	-	ok
Water absorption	3.20%	-	ok
Solid volume weight	1.89 gr/cm^3	-	ok
Loose volume weight	1.64 gr/cm^3	-	ok
Sludge content	4.40%	maks 5%	ok

The research results show that Merapi sand falls into the Region II (2) medium sand category. The fine aggregate sieve analysis of Merapi sand is presented in Figure 5.

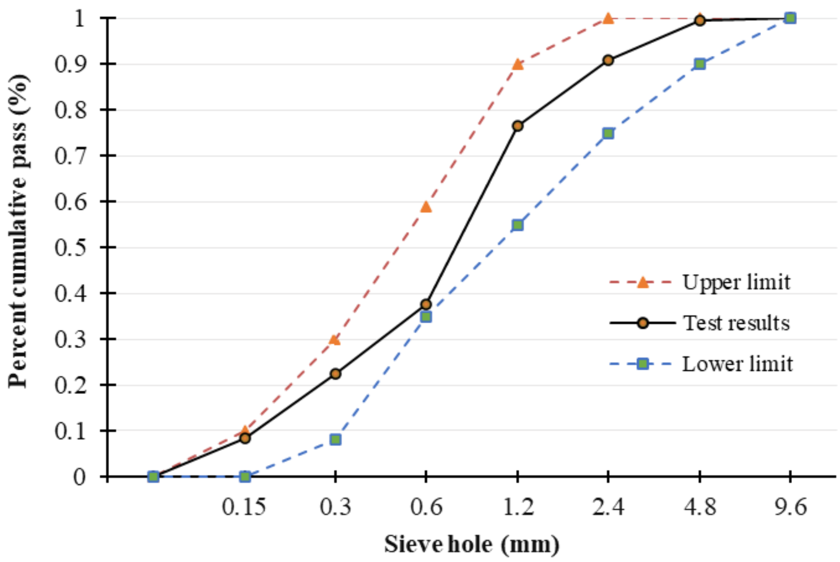

Figure 5. Fine aggregate sieve analysis chart of Merapi sand region II (2)

Analysis of Progo fine aggregate

The fine aggregate testing for Progo River sand followed the same procedures as for Merapi sand, including tests for particle size distribution, specific gravity, water absorption, solid and loose bulk density, and mud content. The test results are shown in Table 6.

Table 6. Fine aggregate testing of Progo River sand

Test type	Progo river sand	Specification interval	Satisfied code
Fine aggregate gradation	2.01 gr/cm^3	2.5-2.7	ok
Specific gravity	2.57 gr/cm^3	-	ok
Water absorption	3.09%	-	ok
Solid volume weight	1.75 gr/cm^3	-	ok
Loose volume weight	1.56 gr/cm^3	-	ok
Sludge content	0.90%	max 5%	ok

The sieve analysis of fine aggregate from the Progo River indicates that it falls into category IV (4) fine sand. The analysis graph is shown in Figure 6.

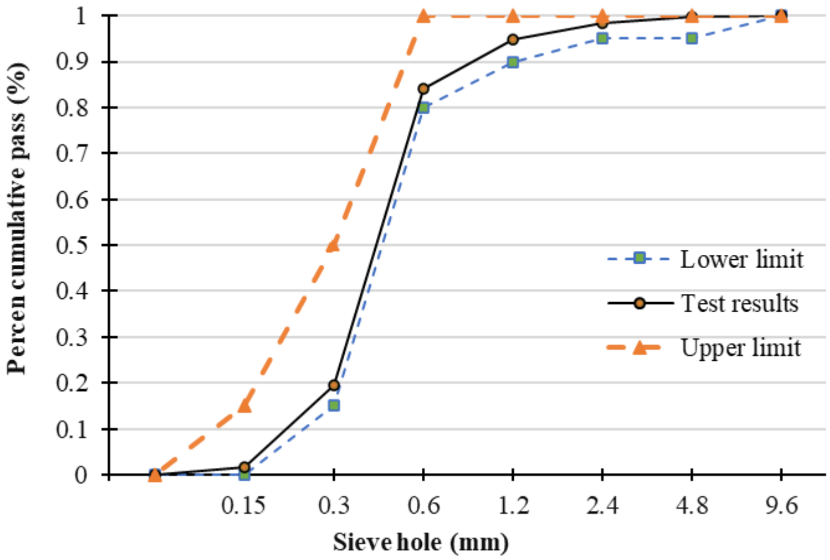

Figure 6. Fine aggregate sieve analysis chart of Progo River region IV (4)

Compressive strength

For compressive strength testing, the specimens were cut into cubes with dimensions of 8 cm x 8 cm x 8 cm. Each variation included 10 test specimens. Table 7 provides a summary of the compressive strength results.

Table 7. Recapitulation of the compressive strength tests for the paving block

Material variation codes	Average compressive strength (MPa)	Quality classification type	Pavement usefulness
V0	36.93	B	Parking area
V1	37.97	B	Parking area
V2	39.13	B	Parking area
V3	40.45	A	Pavement area
V4	34.02	B	Parking area
V5	30.35	B	Parking area

Standard paving blocks achieved a compressive strength of 36.93 MPa, classified as B quality. With the addition of 5.5% coconut shell ash, the compressive strength increased to 37.97 MPa, maintaining B quality. Further increases to 7.5% and 9.5% coconut shell ash resulted in compressive strengths of 39.13 MPa and 40.45 MPa, respectively, still within B quality for 7.5% and upgraded to A quality for 9.5%. However, at 11.5% and 13.5% coconut shell ash, compressive strengths dropped to 34.04 MPa and 30.35 MPa, both returning to B quality. These results indicate that the optimal compressive strength was achieved with 9.5% coconut shell ash, attributed to its silica content, which enhances the strength of the paving blocks.

Wear resistance

The wear resistance test samples must be cut into cubes with dimensions of 5 cm x 5 cm x 2 cm. For each variation, five specimens are tested. Table 8 summarizes the wear resistance test results.

Table 8. Recapitulation of the wear resistance

Material variative codes	Average water absorption (mm/menute)	SNI 03-0691-1996		Paving block usefulness
		Quality class	Minimum wear resistance (mm/menit)	
V0	0.085	A	0.103	Pavement
V1	0.089	A	0.103	Pavement
V2	0.093	A	0.103	Pavement
V3	0.086	A	0.103	Pavement
V4	0.109	B	0.149	Parking pavement
V5	0.118	B	0.149	Parking pavement

The wear resistance test results indicate that as the percentage of coconut shell ash increases, the wear resistance of the paving blocks improves. This improvement is attributed to the fine particles of coconut shell ash, which effectively fill the voids within the paving block, increasing its resistance to wear. The optimal wear resistance is observed at 9.5% coconut shell ash, where the ash fills the spaces efficiently without compromising the structural integrity of the block, thereby enhancing particle cohesion and durability.

Water absorption

Recapitulated results of water absorption testing are presented in Table 9.

Table 9. Recapitulation of the water absorption

Material variation codes	Average Water Absorption (mm/menit)	SNI 03-0691-1996		Paving block usefulness
		Quality class	Maximum average water absorption (%)	
V0	2.132	A	3	Pavement
V1	2.360	A	3	Pavement
V2	2.626	A	3	Pavement
V3	2.349	A	3	Pavement
V4	3.417	B	6	Parking pavement
V5	3.801	B	6	Parking pavement

The higher the percentage of coconut shell ash in the mixture, the greater the water absorption value of the paving block. This is because coconut shell ash, which has smaller pores than cement, influences the overall pore structure of the block. As the percentage of coconut shell ash increases, the paving block's capacity to absorb water also rises. Coconut shell ash contains silica, a pozzolanic material that enhances water absorption. However, at a 9.5% substitution, the water absorption reaches an optimum point. At this level, the air cavities in the paving block are maximally filled by the ash, preventing any excess accumulation and allowing the ash to act effectively as a filler. Consequently, the paving block achieves a watertight structure with minimal further increases in water absorption beyond this point.

Conclusion

The research on paving blocks using coconut shell ash as a substitute for sand presents a promising future with the following potential benefits:

1. Merapi sand alone yields a compressive strength of 22.97 MPa, while Progo River sand achieves 21.07 MPa. However, combining both sands results in a compressive strength of 36.19 MPa, classified as quality B.
2. Standard compressive strength tests show a value of 36.93 MPa, with the highest increase observed at 9.5% coconut shell ash, reaching an impressive 40.45 MPa.
3. The standard wear resistance is 0.085 mm/min, and the 9.5% coconut shell ash variation achieves an optimal wear resistance of 0.086 mm/min.
4. The optimum water absorption is also observed at 9.5% ash, with a value of 2.349%.
5. This 9.5% coconut shell ash variation provides the best results overall, achieving a compressive strength of 40.45 MPa, wear resistance of 0.086 mm/min, and water absorption of 2.349%, qualifying it for quality A roads.

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