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Article

Paper Mill Sludge as a Substitute Material in Paving Blocks for a Sustainable Waste Management Approach

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A B S T R A C T

This study evaluates the use of Paper Mill Sludge (PMS) waste as a partial replacement for fine aggregate in paving block production, focusing on compressive strength and economic feasibility. PMS was incorporated at 0%, 5%, 10%, 15%, and 20% of the total fine aggregate weight. Compressive strength tests followed the Indonesian National Standard (SNI 03-0691-1996), accompanied by production cost analysis. The results showed that 5% PMS achieved the highest compressive strength of 264.23 kg/cm², about 7.7% higher than the control 258.71 kg/cm², meeting the SNI quality class B (K200) standard. Meanwhile, 10% PMS reduced production costs by 6–8% while still satisfying the minimum requirement for K200 paving blocks (category B). This demonstrates a clear trade-off between mechanical performance and cost efficiency, where 5% PMS ensures maximum strength, while 10% PMS provides adequate strength with economic benefits. At lower levels, PMS fibers improved cement–aggregate bonding and reduced voids, whereas higher dosages (>10%) disrupted hydration and lowered strength. Practically, PMS utilization offers the paving block industry a sustainable and cost-effective alternative that reduces reliance on natural aggregates, supports waste valorization, and aligns with SNI standards for applications such as parking lots.

1. Introduction

Pulp and paper mills contribute significantly to the global economy, but they also generate large volumes of solid waste that can pollute the environment. Paper mill sludge (PMS), the primary by-product of wastewater treatment in paper mills, typically consists of cellulose fibers, inorganic fillers such as kaolin and calcium carbonate, and residual chemical additives (Singh et al., 2018). Managing PMS is challenging due to its high volume and complex organic–inorganic composition. In Indonesia alone, the pulp and paper industry produces an estimated 1.5–2 million tons of PMS annually, much of which is still managed through landfilling or incineration (Wahyuningsih, 2020). These disposal methods not only contribute to greenhouse gas emissions, soil contamination, and environmental burdens, but also require substantial additional costs for transportation, land use, and waste treatment, thereby reducing the economic efficiency of paper mills (Tawalbeh et al., 2021).

Globally, construction and demolition waste accounts for more than 35% of total solid waste in the European Union, prompting the development of advanced recycling practices that include sludge utilization in cementitious composites. Similarly, Japan has implemented recycling policies encouraging the use of industrial by-products, including paper sludge, in construction materials to reduce environmental impacts (Turner et al., 2022). These examples highlight the urgency for Indonesia to transform PMS management into a more sustainable practice. Utilizing PMS as a partial substitute in paving blocks not only reduces waste and disposal costs but also increases the market value of sludge, moving toward a zero-waste industry model. This strategy directly supports Environmental, Social, and Governance (ESG) principles by combining environmental protection, economic efficiency, and social responsibility within the pulp and paper sector (Gholami et al., 2022).

Paving blocks, also called concrete bricks or cone blocks, are a type of cement-based building material used to cover or harden ground surfaces. Paving blocks consist of a mixture of Portland cement or other types of hydraulic binder, water, and aggregate, with or without other materials that enhance the quality of the concrete brick (Agyeman et al., 2019). Paving blocks can be used for various purposes, from simple ones to those that require special specifications as a covering material and for hardening the ground surface.

Paving blocks are modular concrete units widely applied for pedestrian pathways, residential roads, and public spaces due to their practicality and durability (Siregar et al., 2022). In Indonesia, their use has become increasingly common, particularly in urban areas such as sidewalks and squares in provincial and district capitals. However, despite the broad adoption of paving blocks, the production process remains highly dependent on natural aggregates, which raises environmental and economic concerns. Limited studies have explored the potential of industrial by-products, such as Paper Mill Sludge (PMS), as alternative materials in paving block production. Addressing this gap, the present research investigates PMS as a partial replacement for fine aggregate, focusing on both mechanical performance and economic feasibility to support sustainable construction practices.

One promising use is as a filler or as a partial replacement for fine aggregate in paving block production. The cellulose fraction can act as a filler, aiding the bonding between aggregate particles, and the inorganic mineral content of PMS, such as $CaCO_3$ and silica, has properties that can improve certain physical properties in non-structural concrete. Previous studies have shown that mix workability can be improved with a certain amount of PMS, porosity can be reduced, and waste management aspects can offer additional value. However, there are still research gaps that require further investigation regarding the optimum proportion, its effect on mechanical properties, and the long-term durability of paving blocks (Hamid et al., 2019; Namarak et al., 2018).

Based on this background, this study specifically aims to evaluate the potential use of Paper Mill Sludge (PMS) as a partial replacement for fine aggregate in paving blocks by assessing its effects on compressive strength, water absorption, and wear resistance, alongside an economic feasibility analysis. The novelty of this research lies in its focus on PMS utilization in the Indonesian context, where limited studies have explored its integration into paving block production under the SNI 03-0691-1996 framework. Unlike previous works that primarily addressed physical performance, this study combines mechanical evaluation with cost analysis, offering a practical contribution for sustainable construction and waste valorization.

2. Literature Review

2.1 Characteristics and Composition of Paper Mill Sludge

Paper mill sludge (PMS) is a solid waste generated from wastewater from the pulp and paper industry. It consists of a mixture of residual cellulose fibers, inorganic mineral particles, and residual process chemicals. PMS requires drying before use as a construction material due to its high moisture content (around 60–80%) when wet (Siregar et al., 2022). PMS typically ranges between 4-6%, which comes from wood fiber fragments that are not fully bonded to the paper sheet (Govindan & Kumarasamy, 2023).

In addition, PMS contains inorganic minerals such as $CaCO_3$, kaolin, and silica in concentrations of 20–40%. These minerals function as fillers during the papermaking process. In addition to residual adhesives, other organic materials such as lignin and hemicellulose are also found in small amounts, along with chemical residues such as aluminum sulfate (alum), polyelectrolytes, bleaching agents such as hydrogen peroxide or chlorine dioxide, and other binding agents (Tawalbeh et al., 2021).

PMS has a low specific gravity and is a fine, gray to brownish sludge. Its high mineral content allows it to be used as a filler in concrete or paving block mixes. However, its organic fraction requires further processing to improve the material's long-term stability, such as through thermal curing or stabilization. Previous studies have shown that, although the pozzolanic properties of PMS are relatively low, its ability to fill the pores of the cement matrix can increase the mixture's density and reduce its porosity. Due to its properties, PMS is well-suited for use as an environmentally friendly substitute for fine aggregate or filler in paving blocks. Furthermore, it can also be used as a sustainable solution for paper industry waste management (Govindan & Kumarasamy, 2023; Tawalbeh et al., 2021).

2.2 Application of Industrial Waste in Construction Materials

To reduce the use of natural resources and minimize environmental impact, the use of industrial waste as an alternative material in construction has become a major focus. Fly ash, blast furnace slag, red mud, and cement kiln dust are some types of waste that have been widely used to replace cement or aggregate in concrete and non-structural concrete products. Al-Kheetan (2022) reported, with proper proportioning and processing, the use of wastes can improve the mechanical properties of concrete and its wear resistance, in addition to increasing its sustainability.

The chemical and physical characteristics of waste determine its suitability as a construction material. Given that its mineral content, such as calcium carbonate and silica, can act as fillers to fill the pores of cement mixtures, and its cellulose fibers can increase the material's cohesiveness, waste paper (WSP) has comparable potential in this situation. However, pretreatment is crucial before use in concrete products such as paving blocks, as the high organic content in WSP must be controlled to avoid long-term quality degradation.

Given this material's ability to reduce the use of primary natural resources and reduce the amount of waste generated by the paper industry, research in various countries has focused on the use of paper mill sludge (PMS) as a substitute or additive in paving block production. PMS can be used as a filler or fine aggregate in a concrete matrix due to its rich content of $CaCO_3$, cellulose fibers, and silica and alumina mineral fractions. Studies have shown that the physical, mechanical, and durability properties of the final product can be significantly influenced by the addition of PMS to the paving block mixture (Subashi De Silva & Priyamali, 2022). Research conducted by Lumingkewas et al. (2023) found that using PMS up to 20% as a cement substitute can improve the workability of the mixture and reduce the density of paving blocks. However, if the dosage exceeds this limit, a small decrease in compressive strength occurs. This is in accordance with the Indian standard IS

15658:2006 for medium-grade paving blocks, Djamaluddin et al. (2020) found that by using PMS between 10 and 15% of the total weight of the mixture, compressive strength could be maintained. In addition, Singh et al. (2018) investigated the modification of PMS through a calcination process to increase pozzolanic reactivity. The findings showed that, compared to untreated PMS, the compressive strength increased by up to 12%.

Hamid et al. (2019) examined PMS as a partial cement replacement at levels of 5%, 10%, and 15%, with compressive strength evaluated against SNI 03-0691-1996. Their study showed that 10% PMS was the most effective, producing a compressive strength of 24.5 MPa (K300) while reducing Portland cement usage by 12% of the total mix. In a related study, Subashi De Silva and Priyamali (2022) also tested PMS at the same levels (5%, 10%, and 15%) and confirmed that 10% PMS yielded the optimal performance, reaching K300 quality and demonstrating both mechanical and material efficiency.

In addition to compressive strength parameters, a number of studies also evaluate aspects of wear resistance (abrasion resistance), water absorption, and environmental sustainability (life cycle assessment). Al-Kheetan (2022) confirms that PMS-based paving blocks not only meet mechanical standards but also have a lower carbon footprint than conventional products. This is because PMS partially replaces clinker-based materials, which have high emission intensity.

A number of studies have looked at factors such as wear resistance (resistance to wear), water absorption, and environmental sustainability evaluation in addition to compressive strength parameters. (Govindan & Kumarasamy (2023) Studies have shown that PMS-based paving blocks not only meet mechanical standards but also have a lower carbon footprint than conventional products. This is due to the fact that PMS replaces some clinker-based materials with high emission intensity. Previous studies have shown that, to achieve performance in accordance with national (SNI) and international compressive strength standards, mixing proportions, waste processing methods (such as drying or calcination), and adjustment of aggregate composition significantly influence the use of PMS in paving blocks. To maximize the potential of PMS in the green building materials industry, an approach that combines environmental sustainability analysis and technical optimization is considered a key strategy.

3. Research Methodology

3.1 Materials and Tools

The main material used in this study is Paper Mill Sludge (PMS) used as a substitute for fine aggregate in the paving block mixture. PMS is obtained from the waste processing unit of the PT. Bukit Muria Jaya paper mill and previously went through a drying process to a water content of <10%. The main binding material is Portland cement type I, in accordance with SNI 15-2049-2004. In accordance with SNI 03-2461-2002, sand with grades is used as fine aggregate. Clean water that meets the construction water standards of SNI 03-2847-2002.

The equipment used includes a precision digital scale (0.01 g), standard paving block mold (200 mm × 100 mm × 60 mm), concrete mixer, concrete press machine (Compression Testing Machine), wear test machine (Abrasion Testing Machine), drying oven, sieve shaker, mixing bucket, shovel, and supporting equipment.

3.2 Research Design

The research employed a laboratory experimental design with variations in the percentage of PMS addition to cement weight: P0 = 0% (control), P1 = 5%, P2 = 10%, P3 = 15%, and P4 = 20%. Each variation consisted of 5 samples for each type of test. PMS was first oven-dried at 105 ± 5 °C until a constant moisture content was reached, then sieved using a 2 mm sieve to ensure homogeneous particle size. The paving block mixture followed a cement-to-sand ratio of 1:4 (by weight), with PMS added according to the treatment percentages. A water–cement ratio (FAS) of 0.4 was applied. All materials were mixed until homogeneous, poured into molds, and compacted using a press machine. After 24 hours, the specimens were demolded and subsequently cured in clean water for 28 days.

For data analysis, compressive strength values were statistically tested using one-way ANOVA to determine the significance of differences between treatments. The analysis was carried out using IBM SPSS Statistics 26 as the primary software, with a significance level set at $p < 0.05$. When significant differences were detected, post-hoc tests (Tukey's HSD) were applied to identify specific treatment groups showing variations.

3.3 Test Analysis

Composition Analysis

Initial testing was carried out on PMS to determine the water content, organic content, mineral content (SiO_2, Al_2O_3, CaO), and particle size, as supporting data for its effect on the paving block mixture.

Compressive Strength

Referring to SNI 03-0691-1996 concerning Paving Blocks, testing was conducted at 28 days using a compressive strength tester. The results were compared with the paving block quality classification based on SNI.

Table 1. Classification of paving block quality (SNI)

Quality	Utility	Compressive Strength (kg/cm2)		Wear Resistance (mm/menit)		Maximum Water Absorption (%)
		Average	Min	Average	Min	
A	Road paving	400	350	0,009	0,103	3
B	Parking lot	200	170	0,130	1,149	6
C	Pedestrian	150	125	0,160	1,184	8
D	City park	100	85	0,219	0,251	10

Water Absorption and Wear Resistance

Referring to SNI 03-0691-1996, with a soaking and weighing procedure to calculate the percentage of water absorption. Wear resistance testing is carried out using an abrasion machine with a certain load and number of rotations, then the volume loss due to wear is calculated.

Economic Analysis

Calculate the production costs of paving blocks for each PMS variation. Compare cost savings under optimum PMS conditions with the control (P0). Calculate the percentage savings and potential added value from utilizing PMS waste.

4. Results and Discussion

The PMS is first added to the mix with graded sand and stirred until evenly mixed. Portland cement is added at the end of the mixing process to ensure the PMS mixture is well-mixed, preventing clumping caused by the addition of Portland cement. This sequence of material addition is important to ensure even distribution of the PMS. Uneven casting can cause clumping, which will reduce the bond between materials and the strength of the paving block.

Figure 1. Sample preparation and casting mixing process

The addition of PMS (Paper Mill Sludge) to the paving block mixture at 0%, 5%, 10%, 15%, and 20% showed significant changes in its physical and mechanical properties. Tests conducted according to SNI 03-0691-1996 and ASTM C936 (Standard Specification for Solid Paving Concrete Blocks). Standards included wear resistance, water absorption, and compressive strength of the paving blocks. The results can be mapped to the paving block compressive strength classification (K).

Composition Analysis

Initial analysis shows that the factory has a high water content (48–55 percent), a high organic solids content (35–40 percent), and a mineral fraction consisting of calcium carbonate ($CaCO_3$), silica (SiO_2), and alumina (Al_2O_3).

Table 2. Paper mill sludge composition analysis

Component	Mean Content (%)	Standard Deviation (±)
CaO	32.50	0.42
SiO_2	28.30	0.35
Al_2O_3	8.70	0.18
Fe_2O_3	6.10	0.15
MgO	4.25	0.10
SO_3	2.85	0.08
K_2O	1.95	0.05
Na_2O	1.25	0.03
TiO_2	0.70	0.02
MnO	0.40	0.01
Loss on Ignition (LOI)	13.00	0.30

The chemical analysis of Paper Mill Sludge (PMS) revealed a dominant composition of CaO (32.5%), SiO_2 (28.3%), and Al_2O_3 (8.7%), along with minor components such as Fe_2O_3, MgO, SO_3, K_2O, and Na_2O. The high CaO content can act as a filler and improve the density of the paving block matrix, while the presence of SiO_2 and Al_2O_3 supports pozzolanic reactions that contribute to mechanical strength development. Additionally, minor oxides such as MgO, Fe_2O_3, and SO_3 influence the physical properties and dimensional stability of the final product. Therefore, the chemical characteristics of PMS provide a strong basis for its potential use as a partial cement substitute in paving block production, offering an environmentally friendly solution without compromising required quality standards. In addition, the high CaCO3 content can function as a filler and increase the density of the paving block matrix. (Subashi De Silva & Priyamali, 2022).

Compressive Strength of Paving Blocks

The compressive strength of paving blocks was tested using a compression testing machine in a horizontal position, consistent with their intended use on the ground surface. Each sample tested had a curing time of 28 days.

Figure 2. Paving block compressive strength testing

Compressive strength testing was conducted on paving blocks with varying PMS additions (Table 2). The results showed that strength increased to an optimal point with the addition of 5% PMS (P1) with a compressive strength value of 264.23 kg/cm2. Meanwhile, the control without PMS (P0) had an average compressive strength value of 258.71 kg/cm2. The CaCO3 filler and cellulose fiber contained in PMS are factors in this increase in compressive strength through the bonds between particles in the paving block components. Visually, P1 appears to be evenly mixed when PMS is mixed in the paving block casting.

Table 3. Paving block test analysis

Sample	Compressive strength (kg/cm2) ± SE	Water Absorption (%) ± SE	Wear Resistance (%) ± SE	Density (g/cm^3) ± SE
P0	258.71 ± 0.42	6.25 ± 0.15	97.50 ± 0.20	2.35 ± 0.02
P1	264.23 ± 0.38	6.40 ± 0.12	96.80 ± 0.25	2.30 ± 0.02
P2	242.20 ± 0.36	6.58 ± 0.14	96.10 ± 0.22	2.21 ± 0.03
P3	192.66 ± 0.40	7.05 ± 0.13	95.00 ± 0.30	2.14 ± 0.02
P4	143.12 ± 0.45	7.85 ± 0.15	90.20 ± 0.28	2.02 ± 0.03

However, in the P2 paving block sample, there was a slight decrease in compressive strength to 242.20 kg/cm2. The decrease in compressive strength was more significant in the P3 and P4 samples, where the strength of the paving block decreased to 143.12 kg/cm2. The decrease in compressive strength in paving blocks is closely related to the increase in the number of micro and macro pores (PMS). The more PMS, the higher the total porosity of the material, so that the distribution of compressive loads becomes uneven and causes stress concentrations in weak areas. This condition makes cracks more likely to occur during compression testing (Farooq et al., 2023). An increase in PMS is usually triggered by the use of materials with light properties or low bonding strength, which reduces the density of the structure. As a result, the bonds between particles become less dense, reducing the ability of the paving block to withstand loads. Technically, each increase in PMS will reduce the material's modulus of elasticity, so that the compressive strength is significantly reduced. (Subashi De Silva & Priyamali, 2022).

The decrease in paving block density is proportional to the decrease in compressive strength due to increased porosity. High porosity due to the lighter and less dense proportion of paper mill sludge reduces the compactness and bonding between particles, resulting in uneven load distribution and triggering damage during compression tests. Therefore, controlling the mix composition is necessary to maintain optimal density and meet SNI standards.

Water Absorption and Wear Resistance

Based on the data in Table 2, it can be seen that increasing the PMS content tends to significantly affect water absorption and wear resistance, which ultimately correlates with a decrease in compressive strength. For example, in composition P1, water absorption is only around 6.40% with a wear resistance of 96.80%, and the compressive strength reaches 264.23 kg/cm2. However, in P4, water absorption increases to 7.85% and wear resistance deteriorates to 90.20%, followed by a decrease in compressive strength to 143.12 kg/cm2. The increase in water absorption indicates higher material porosity due to the reduced amount of active cement and the increase in the pore fraction, so that the bonds between particles are weakened. The decreased wear resistance also reflects the reduced cohesiveness of the cement paste matrix, which accelerates the mechanical degradation of the surface (Lumingkewas et al., 2023). This relationship aligns with the theory that high porosity (as evidenced by water absorption) reduces density and increases wear susceptibility, simultaneously reducing the material's ability to withstand compressive loads. Thus, the combination of increased water absorption and decreased wear resistance due to high PMS is the direct cause of the decrease in compressive strength.

Economic Analysis of PMS Use

The optimal use of PMS based on quality is at an additional amount of 5%. However, if analyzed from an economic perspective, the addition of 10% PMS becomes the optimal point in the use of PMS, considering the quality that is still tolerable. Economically, At the 10% PMS addition level, the use of cement and fine aggregate is reduced significantly compared to the control mixture. For every 1,000 paving blocks sized 20 × 10 × 6 cm, cement savings reach around 30–35 kg. With the market price of cement at Rp 18,500 per 40 kg sack (equivalent to Rp 462.5 per kg), this translates to savings of Rp 13,875–16,188. Additionally, a proportional reduction in fine aggregate use contributes an extra Rp 40,000–45,000 in cost efficiency, bringing the total direct savings to Rp 55,000–61,000 per 1,000 blocks. When calculated against the overall material cost of producing 1,000 blocks (approximately Rp 850,000–900,000), this reduction equals 5–7% cost savings. These savings do not yet include potential reductions in waste management expenses for the paper industry, suggesting that wider adoption of PMS could further strengthen the economic feasibility of this substitution.

5. Conclusion

The compressive strength, water absorption, and wear resistance of paving blocks were significantly affected ($p < 0.05$) by the addition of PMS. The addition of 10% PMS (P2) meets the requirements of SNI 03-0691-1996 K-242, making it suitable for class B applications such as parking lots. Specifically, P2 achieved a compressive strength of 242.20 kg/cm², water absorption of 6.58%, wear resistance of 96.10 mm/min, and density of 2.21 g/cm³. At concentrations of 5–10%, PMS functions as a micro-reinforcement that helps reduce microcracks, whereas additions above 10% decrease strength due to weaker cement–aggregate bonding. From an economic perspective, this composition reduces production costs by approximately ±8%, supporting its potential as a sustainable substitute material in paving block manufacturing. Beyond these findings, industry applications should be explored through pilot-scale production trials to evaluate large-scale feasibility. Furthermore, conducting life-cycle assessment (LCA) and cost–benefit analysis would provide stronger evidence for environmental and economic viability. Future research should also consider durability tests under real field conditions and optimization of PMS processing methods to ensure consistent quality in practical applications.

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