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Performance Assessment of Paving Blocks with Tannery Sludge as a Partial Cement Replacement

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ABSTRACT

The construction industry faces increasing pressure to adopt more sustainable practices, particularly in reducing the environmental impact of cement production, which is responsible for significant CO_2 emissions and the depletion of natural resources. One promising strategy is to partially replace cement with industrial waste materials that possess cementitious properties. This study examines the potential of tannery sludge, a hazardous byproduct of the leather tanning process, as a partial substitute for cement in the manufacturing of paving blocks. The sludge contains valuable oxides such as CaO, Al_2O_3, and Fe_2O_3, which can contribute to the binding characteristics required in concrete applications. An experimental approach was conducted to evaluate the performance of paving blocks containing 0%, 1%, 3%, and 5% tannery sludge by weight of cement. Tests included compressive strength, wear resistance, water absorption, resistance to sodium sulfate, and chemical composition analysis using X-ray fluorescence (XRF). The results revealed that all sludge-containing mixtures maintained compressive strength values exceeding the minimum threshold for class B paving blocks, making them suitable for moderate-load applications such as parking areas and pedestrian pathways. Wear resistance results placed all specimens in class A, indicating high surface durability. However, increased water absorption was observed with higher sludge content, potentially due to the porous nature of the sludge. The sodium sulfate resistance test highlighted the need for further enhancement, as weight fluctuations indicated vulnerability in chemically aggressive environments. XRF analysis confirmed the compatibility of the sludge composition with cement standards. In conclusion, tannery sludge demonstrates technical feasibility as a sustainable alternative to cement in the production of paving blocks. Its use offers environmental and economic advantages, though further research is needed to optimize performance and ensure long-term durability under various conditions.

1. Introduction

Paving blocks have become increasingly popular as a surface material for pedestrian pathways, driveways, and urban pavements due to their numerous functional and aesthetic advantages. These advantages include ease of construction, simplified maintenance, and strong resistance to mechanical stresses such as static loads, dynamic forces, and impact loads. Additionally, paving blocks provide enhanced adaptability to differential settlement conditions, making them suitable for a wide range of soil types and terrains. The interlocking design and voids between units allow for better water infiltration, effectively reducing surface runoff and mitigating floods. This permeability also enhances groundwater recharge and promotes better soil health. Furthermore, paving blocks are known for their long-term durability, modularity, and visual appeal, making them a sustainable and cost-effective choice in modern infrastructure development [1].

In recent years, a substantial body of research has been dedicated to exploring the partial replacement of cement in concrete and paving block production, driven primarily by mounting environmental and economic concerns. The cement industry is widely recognized as a significant

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contributor to greenhouse gas emissions, with global estimates indicating that cement manufacturing accounts for approximately 7% of total CO_2 emissions. This alarming statistic has sparked interest in using alternative materials, primarily industrial by-products and waste substances, as more sustainable substitutes to mitigate the environmental footprint associated with traditional cement production. Despite growing awareness of its environmental impact, cement remains the second most widely consumed material on Earth, after water, and its use continues to rise in parallel with the expansion of infrastructure and urban development. In the context of paving blocks, which have gained widespread popularity for their ease of installation, durability, and aesthetic value, the demand for cement as a key binding agent between sand and water is also increasing. This sustained reliance on cement underscores the urgent need to identify and develop viable replacement materials that can maintain performance standards while contributing to the construction industry's sustainability objectives [2].

Cement manufacturing is a resource-intensive process that significantly contributes to the emission of greenhouse gases, particularly carbon dioxide (CO_2), thereby exacerbating the issue of global climate change. In addition to its environmental impact, cement production also places considerable pressure on natural resource reserves, including the extensive extraction of limestone, clay, and fossil fuels. This dual impact regarding emissions and resource depletion raises serious sustainability concerns and highlights the need for more environmentally responsible alternatives in the construction industry [2], [3], [4]. Therefore, reducing the reliance on cement in the production of paving blocks presents a promising strategy to achieve multiple sustainability goals simultaneously. Manufacturers can significantly decrease carbon emissions associated with cement production by minimizing cement usage, thereby contributing to global efforts to mitigate climate change. Additionally, this approach supports the conservation of finite natural resources, such as limestone and fossil fuels, which are heavily exploited in the cement industry. Beyond environmental advantages, partial cement substitution may also reduce production costs, making paving block manufacturing more economically viable, particularly in regions with limited access to conventional construction materials [5]. One potential strategy to address these challenges is to use alternative materials that can partially or fully replace cement in construction applications. These materials may include industrial by-products, agricultural waste, or other naturally occurring substances with cementitious or pozzolanic properties. By exploring and validating such alternatives, the construction industry can reduce its dependence on traditional cement, thereby promoting more sustainable building practices while simultaneously addressing issues related to waste management and resource scarcity [6]. The successful implementation of alternative materials as partial replacements for cement can play a crucial role in fostering a more sustainable built environment and promoting healthier living conditions for future generations. Such efforts mitigate the environmental impact of cement production and contribute to the efficient management of industrial and agricultural waste. Numerous studies have investigated the viability of incorporating various waste-derived materials, including fly ash, bottom ash, silica fume, rice husk ash, and ground granulated blast-furnace slag, into the production of paving blocks. These materials have demonstrated promising results, often achieving comparable mechanical strength, durability, and overall performance to conventional cement-based mixtures. Furthermore, their use enhances circular economic practices within the construction sector by diverting waste from landfills and reducing the consumption of virgin raw materials, aligning with broader environmental stewardship and sustainable development goals.

The growing need to mitigate environmental impacts has increased interest in utilizing industrial waste in construction materials. Among these, tannery sludge presents a unique opportunity due to its chemical composition and abundance in regions with a high concentration of leather industries. Transforming this hazardous waste into a valuable construction resource reduces environmental burdens and supports the principles of a circular economy. Therefore, exploring the feasibility of tannery sludge as a cement substitute in paving blocks aligns with ecological sustainability and material innovation goals. Leather tanning waste can be utilized as a substitute for cement. Leather tanning converts readily damaged rawhide into more durable processed leather using a chromium (Cr) compound tanner. The leather tanning industry produces considerable waste, particularly from the wastewater treatment process conducted at the production facilities. One of the primary by-products of this process is tannery sludge, a semi-solid material that poses significant environmental challenges. Due to its low biodegradability and inability to effectively absorb water, tannery sludge is highly persistent in the environment. When disposed of in conventional landfills, this waste material may require up to 65 years to fully decompose, leading to long-term accumulation and potential contamination of soil and groundwater resources. The difficulty in managing this type of waste underscores the urgent need for innovative and sustainable disposal or reuse strategies, particularly those that can convert sludge into a valuable resource for other industrial applications, such as construction materials [7].

Tannery sludge is known to contain a complex composition of both organic and inorganic constituents, including a significant proportion of mineral elements that are commonly found in construction materials. Chemically, the sludge typically comprises 10–30% calcium (Ca), 2–10% nitrogen (N), 0.2–3% chromium (Cr), 0–12% iron (Fe), and 0–6% aluminum (Al). These components vary depending on the specific tanning processes and chemicals used in the treatment plant. Calcium and iron compounds indicate that tannery sludge may exhibit cementitious or pozzolanic behavior, whereas the chromium content raises environmental concerns due to its potential toxicity. Using tannery sludge in construction applications requires careful characterization to ensure performance and environmental safety [8]. If not correctly managed, tannery sludge poses a significant risk of environmental contamination due to hazardous elements, heavy metals such as chromium, and excess nutrients like nitrogen. Improper disposal or uncontrolled leaching of these substances can lead to soil degradation, groundwater pollution, and adverse effects on surrounding ecosystems. Therefore, effective treatment, stabilization, or repurposing of this waste is essential to minimize its ecological footprint and comply with environmental protection standards [9], [10], [11], [12], [13].

Given that tannery sludge poses environmental disposal issues due to the presence of heavy metals, its beneficial use in construction could contribute to a circular economy. Furthermore, studies have shown that the oxide composition in tannery sludge aligns with that of cementitious materials, suggesting its potential as a functional binder. Iron and aluminum content in tannery sludge can substitute oxides in cement, such as lime (CaO) 60-66%, silica (SiO) 16-25%, aluminum (Al_2O_3) 3-8%, and iron (Fe_2O_3) 1-5% [9]. Previous research by S. Wiryodiningrat (2010) investigated the use of tannery sludge as a partial replacement for fine aggregate in the production of paving blocks, demonstrating its potential to contribute to the physical properties of the resulting material positively.

Existing research has primarily focused on its use as a fine aggregate, offering limited insights into its cementitious properties and binding performance. However, despite this early exploration, a notable gap remains in the literature regarding the feasibility of using tannery sludge as a substitute for cement. Given the presence of mineral oxides such as CaO, Al_2O_3, and Fe_2O_3 within the sludge compounds commonly found in conventional cement, further investigation is warranted to evaluate their performance as a binding agent.

To date, no comprehensive study has assessed the mechanical and durability performance of paving blocks with cement partially replaced by tannery sludge. This research aims to fill that gap by evaluating the physical, mechanical, and chemical properties of paving blocks with varying proportions of sludge and comparing their performance against national standards.

The findings of this study confirm that using tannery sludge as a partial cement replacement in paving blocks is technically feasible and offers clear environmental and economic benefits. This approach reduces greenhouse gas emissions, conserves natural resources, and supports effective hazardous waste management. Moreover, it aligns with circular economic principles by converting industrial waste into valuable construction material. With further research to improve long-term durability and chemical resistance, this strategy has strong potential to support sustainable construction and waste utilization.

2. Methods

To comprehensively evaluate the technical feasibility of utilizing tannery sludge as a partial substitute for cement in paving block production, a structured experimental research approach was adopted, integrating both quantitative analysis and laboratory-based material testing. This methodology encompassed preparing paving block specimens at a controlled laboratory scale, preceded by detailed characterization of the raw materials and a series of standardized performance evaluations.

The materials used in this study included Ordinary Portland Cement (OPC), natural sand as fine aggregate, and tannery sludge obtained from a local leather processing facility. Before specimen fabrication, each component underwent rigorous testing to determine its physical and chemical suitability for inclusion in the mix design. Once validated, the paving block specimens were cast with varying proportions of tannery sludge (0%, 1%, 3%, and 5% by weight of cement) and subsequently subjected to a 28-day curing period to ensure proper hydration and strength development.

Post-curing, the specimens were evaluated using a range of performance tests to assess their structural and durability characteristics. These tests included compressive strength testing in determining load-bearing capacity, wear resistance testing to assess surface durability, water absorption measurements to evaluate porosity, sodium sulfate resistance testing to examine chemical durability, and X-ray fluorescence (XRF) analysis to identify the chemical composition of the final product. These assessments provided a comprehensive understanding of material behavior and its potential applicability in sustainable construction practices.

To ensure the reliability of the results, all materials underwent preliminary testing in accordance with the Indonesian National Standards (SNI). The OPC used was classified under SNI 2049:2015 and met the physical and chemical requirements of SNI 7064:2014, including fineness, setting time, compressive strength, and SO_3 content. The water used in this investigation is sourced from the Institut Teknologi Garut Civil Engineering Laboratory. Cement testing was performed in accordance with SNI 2049:2015, and test results data were collected from the Quality Assurance and Research Division Laboratory. The fine aggregate (sand) sourced from Cilopang, Garut, was tested for grain size distribution, specific gravity, water absorption, and moisture content, in accordance with SNI 03-2461-2022. Tannery sludge obtained from Sukaregang in Garut was air-dried for 48 hours before being sieved to a uniform size and characterized using X-ray Fluorescence (XRF) to determine elemental composition (Figure 1). The XRF test was performed to determine the concentration of components in the tannery sludge.

Twelve paving block specimens were produced for this study, with each of the four mix variations, containing 0%, 1%, 3%, and 5% tannery sludge by weight of cement, represented by three identical samples to ensure consistency of results and statistical relevance. The mix design was maintained consistently across all batches, with the only variable being the proportion of tannery sludge used to substitute for the cement content. This approach ensured that any observed changes in mechanical or durability performance could be attributed directly to the presence of the sludge.

The mixing process was conducted manually to ensure uniformity and prevent material segregation. The fresh concrete mixtures were then cast into standardized steel molds with internal dimensions of 20 × 10 × 6 cm, shaped to produce compact rectangular paving blocks. After casting, the specimens were compacted manually to eliminate trapped air and ensure optimal density and homogeneity.

Figure 1. Tannery sludge

Following demolding, all specimens were subjected to a standardized curing regime for 28 days under controlled environmental conditions. The curing process included initial shade curing for 24 hours to prevent rapid moisture loss, followed by daily water spraying and storage at ambient temperature to facilitate hydration and promote strength development. This controlled curing period was crucial for simulating real-world practices and achieving reliable performance outcomes. The curing process was conducted in two phases to ensure optimal hydration and strength development of the paving block specimens. In the initial phase, all samples were placed in a shaded environment for the first 24 hours after casting to prevent excessive moisture loss due to direct sunlight exposure, which could compromise early-age strength gain. This was followed by seven days of moist curing, during which each specimen was sprayed with water daily to maintain a consistently high surface moisture level and promote continuous hydration of the cement.

After the moist curing phase was completed, the specimens were transferred to a well-ventilated area at ambient room temperature, where they remained for the remainder of the 28-day curing period. During this final phase, the blocks were regularly doused with water, at least once per day, to maintain internal moisture levels and prevent premature drying, which could negatively impact the structural integrity of the samples.

The performance evaluation of the cured paving blocks was conducted in accordance with the specifications outlined in the Indonesian National Standard SNI 03-0691-1996. The required quality parameters included compressive strength to assess load-bearing capacity, wear resistance to determine surface durability, water absorption to evaluate porosity and permeability, resistance to sodium sulfate to measure chemical durability in aggressive environments, and XRF testing to analyze the chemical composition of the final product.

The mechanical and durability testing of the paving block specimens commenced after a 28-day curing period. For the compressive strength test, three specimens were prepared and tested for each variation of tannery sludge content (0%, 1%, 3%, and 5%) to ensure the accuracy and repeatability of results. This test was conducted in accordance with relevant standard procedures, utilizing a universal testing machine to determine the maximum load-bearing capacity of each block (Figure 2).

The wear resistance test was conducted to assess the abrasion resistance of the surface layer. Specimens with dimensions of 50 × 50 × 20 mm were used, and the test was carried out using a standardized abrasion testing machine (Figure 3). This test is crucial for evaluating the suitability of paving blocks for applications that involve repeated surface contact, such as pedestrian or vehicular traffic.

Full-size paving block specimens were oven-dried at approximately 105 °C for the water absorption test to achieve a constant dry weight. They were then immersed in water for 24 hours, after which the saturated weight was recorded. The percentage of water absorbed was calculated to determine the porosity and permeability characteristics of each block (Figure 4). This parameter is critical in evaluating the long-term durability and resistance to moisture ingress, particularly in outdoor applications.

Figure 2. The compressive strength test

Figure 3. The wear resistance test

Figure 4. The water absorption test

Figure 5. The sodium sulfate resistance test

Table 1. Characteristics of cement

Parameter		SNI 7064:2014
Physical Properties		
Air content (%)	6.0	Max. 12
Blaine (m^2/kg)	468	Min. 280
Autoclave expansion (%)	0.083	Max. 0.8
Compressive strength		
– Three days (kg/cm^2)	180	Min. 130
– Seven days (kg/cm^2)	277	Min. 200
– 28 days (kg/cm^2)	318	Min. 280
Time of setting, Vicat test		
– Initial set (minutes)	148	Min. 45
– Final set (minutes)	259	Max. 375
Early stiffening (%)	75	Min. 50
Chemical Properties		
Sulphur trioxide, SO_3 (%)	1.61	Max. 4.0

The sodium sulfate resistance test (Figure 5) was conducted to evaluate the durability and chemical resistance of the paving blocks when exposed to sulfate-rich environments, such as those commonly found in certain soil conditions. This test simulates long-term sulfate exposure, which can chemically degrade cementitious materials and compromise structural integrity over time.

The procedure involved immersing the specimens in a saturated sodium sulfate solution for 16 to 18 hours. The solution was prepared by dissolving 282 grams of sodium sulfate (Na_2SO_4) powder into 1 liter of distilled water, ensuring complete saturation. [14]. Following the immersion phase, the specimens were oven-dried at 105 ± 2°C for 2 hours and then cooled to room temperature. This soaking and drying cycle was repeated consecutively to replicate cyclic environmental conditions that might occur in natural settings. After the final cycle, each specimen was thoroughly rinsed with clean water to remove any residual sulfate crystals on the surface. The specimens were dried for 2 to 4 hours before final observation and weight measurement.

This test provides valuable insights into the sulfate resistance of the modified paving blocks by observing changes in physical condition and weight gain, both of which can indicate material degradation or salt crystallization within the pores. The results help determine the suitability of the blocks for use in environments where chemical durability is a critical factor.

3. Results and Discussions

3.1 Paving Block's Material Test Results

Cement testing was conducted in accordance with the Indonesian National Standard SNI 2049:2015 to assess its conformity with the required physical and chemical properties for construction applications. The test data utilized in this study were obtained from secondary sources, specifically from the Quality Assurance and Research Division Laboratory, which ensured standardized procedures and reliable measurement outcomes. The detailed characteristics of cement are presented in Table 1. Furthermore, the cement used in this research complied with the specifications outlined in SNI 7064:2014, which define the quality standards for Ordinary Portland Cement. The material met all key parameters, including fineness, setting time, compressive strength at various curing ages, and permissible limits for chemical constituents such as sulfur trioxide (SO_3). This compliance confirms the suitability of the cement for use as a baseline reference in comparative testing with sludge-substituted mixtures.

The results of the sand characterization are presented in Table 2. Based on the testing conducted, the physical properties of the sand, including specific gravity, fineness modulus, and bulk density, fall within acceptable ranges for use in the production of paving blocks. Notably, the water absorption rate of the sand was measured at 1.01%, which is well below the maximum allowable limit of 20%, as stipulated in SNI 03-2461-2022. This indicates that the sand used possesses adequate durability and moisture resistance, making it suitable as a fine aggregate in the concrete mix design. The low absorption value also helps minimize excess water demand in the mixture, supporting consistent workability and strength development during the curing process.

XRF testing was conducted on the tannery sludge sample to determine the concentration of key chemical elements and to evaluate its potential as a cementitious material. The primary objective of this analysis was to compare the elemental composition of the sludge with that of conventional Portland cement, with a focus on oxides that contribute to the binding properties in cement-based composites [9]. The XRF results revealed the presence of several significant oxides, including iron (Fe) and aluminum (Al) compounds, critical components in ordinary cement. Specifically, the iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3) contents in the sludge suggest that it may partially fulfill the role of cement in the hydration and strength development processes. These oxides are commonly responsible for contributing to the structural matrix in hardened concrete and can potentially enhance durability and resistance characteristics when used appropriately in modified mix designs.

The results of the XRF test on tannery sludge are presented in Table 3 and illustrated graphically in Figure 6, which shows the relationship between energy and the intensity of X-rays emitted by each element.

Table 2. Characteristics of sand

Parameter	
Solid volume weight (kg/lt)	1.73
Loose volume weight (kg/lt)	1.55
Fineness modulus	5.01
Apparent specific gravity	2.61
Bulk specific gravity	2.56
Water absorption	1.01

Table 3. Characteristics of tannery sludge

Element	Content (%)
Al	1.419
Ca	69.767
Cr	9.948
Fe	7.181
Al_2O_3	2.188
SiO_2	7.210
Fe_2O_3	6.334
CaO	66.777
SO_3	3.929

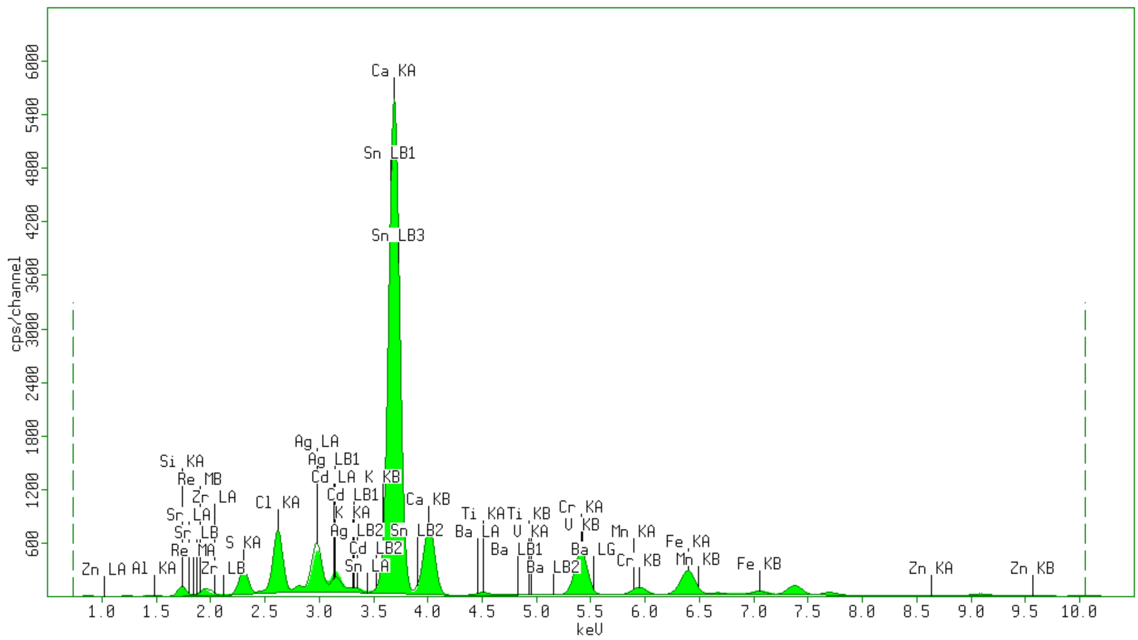

Figure 6. Tannery sludge XRF test results

The chemical composition of tannery sludge includes several elements that, if not properly managed, can potentially contribute to environmental pollution. Among the most critical constituents are calcium (Ca), chromium (Cr), iron (Fe), and aluminum (Al). Based on existing literature and empirical data, typical concentrations of these elements in tannery sludge are reported to be within the following ranges: calcium (10–30%), chromium (0.2–3%), iron (0–12%), and aluminum (0–6%) [8]. As determined through XRF analysis, the elemental composition of the tannery sludge used in this study is consistent with values reported in the previous literature, although some concentrations are notably higher. Specifically, the sludge sample contained 69.767% calcium (Ca), 9.948% chromium (Cr), 7.181% iron (Fe), and 1.419% aluminum (Al).

The exceptionally high calcium content suggests a substantial potential for the sludge to contribute to the binding phase in cementitious mixtures, potentially enhancing compressive strength. However, the elevated chromium concentration—approaching 10%—warrants careful consideration due to its environmental and health implications. These findings highlight the dual nature of tannery sludge, both as a promising alternative material and a substance that requires cautious application and further ecological assessment.

Iron and aluminum in tannery sludge suggest its potential to substitute cement, mainly due to its oxide content, which is also found in Ordinary Portland Cement. Typical cement compositions include lime (CaO) in the range of 60–66%, silica (SiO_2) 16–25%, alumina (Al_2O_3) 3–8%, and iron oxide (Fe_2O_3) 1–5% [9]. In this study, XRF analysis of the tannery sludge revealed the following oxide concentrations: CaO at 66.777%, SiO_2 at 7.21%, Al_2O_3 at 2.188%, and Fe_2O_3 at 6.334%.

Although the Al_2O_3 content is slightly below the typical range found in cement, the CaO and Fe_2O_3 levels are well within or above standard values, indicating a substantial potential for the sludge to contribute to the binding characteristics of the cementitious matrix. The relatively high CaO content supports the hypothesis that tannery sludge can enhance the hydration process and promote the development of compressive strength. Therefore, based on the comparative analysis of its oxide composition, the tannery sludge used in this research is chemically suitable for partial replacement of cement in the production of paving blocks.

In addition to its oxide composition, the chemical compatibility of tannery sludge with cement standards can also be assessed through its sulfur trioxide (SO_3) content. According to the specifications outlined in SNI 7064:2014, the maximum permissible SO_3 content in Ordinary Portland Cement is 4%, as excessive sulfur can adversely affect setting time and long-term durability. The XRF analysis of the tannery sludge used in this study revealed an SO_3 concentration of 3.929%, which falls within the acceptable range defined by the standard.

This finding indicates that, from a chemical standpoint, the sludge does not exceed critical thresholds that would typically disqualify a material from being used in cementitious applications. Therefore, the SO_3 content of the tannery sludge in this research complies with national standards, further supporting its potential suitability as a partial cement substitute in the production of paving blocks.

3.2 Paving Block Test Results

The performance evaluation of the paving block specimens involved a series of standardized tests, namely compressive strength, wear resistance, and water absorption, to assess their mechanical properties and durability under various conditions. These parameters indicate the material's suitability for practical applications such as pedestrian walkways, driveways, and other load-bearing pavements.

The results obtained from each of these tests for the different sludge substitution levels (0%, 1%, 3%, and 5%) are summarized in Table 4, providing a comparative analysis of how the inclusion of tannery sludge affects the overall performance of the paving blocks.

Table 4. Paving block test result

Tannery sludge	Compressive strength (MPa)	Wear resistance (mm/minute)	Water absorption (%)
0%	37.05	0.046	5.63
1%	30.37	0.038	5.77
3%	28.11	0.048	6.61
5%	27.47	0.044	6.96

The compressive strength test results indicate that all paving block specimens incorporating tannery sludge meet the requirements for Class B paving blocks, as defined by SNI 03-0691-1996. Specifically, the compressive strength values for mixtures containing 1%, 3%, and 5% tannery sludge were recorded at 30.37 MPa, 28.11 MPa, and 27.47 MPa, respectively—all of which significantly exceed the minimum threshold of 17 MPa required for Class B paving blocks, typically used in medium-load applications such as parking areas. These results suggest that including tannery sludge, even at a concentration of up to 5%, does not compromise the load-bearing capacity of the blocks.

Regarding wear resistance, the results demonstrate that all paving block variations fall into Class A, representing the highest standard for abrasion resistance. The wear rates for the 1%, 3%, and 5% sludge mixtures were 0.038 mm/min, 0.048 mm/min, and 0.044 mm/min, respectively. Each of these values is well below the maximum allowable limit of 0.103 mm/min specified for Class A, indicating that the surface durability of the blocks remains excellent regardless of sludge content.

The results of the water absorption test revealed a trend of increasing absorption with higher sludge content. The values for 1%, 3%, and 5% sludge mixtures were 5.77%, 6.61%, and 6.96%, respectively. Based on these results, the 1% sludge mixture qualifies as Class B, with a water absorption rate of less than 6%. In contrast, the 3% and 5% mixtures fall into Class C, allowing absorption rates between 6% and 8%. This increase in absorption is likely due to the porous and hydrophilic nature of the tannery sludge, which enhances the material's ability to retain moisture. While the increased absorption may impact long-term durability in specific environments, the values remain within acceptable limits for non-structural paving applications.

3.3 Resistance Test Results for Sodium Sulfate Paving Block

The sodium sulfate resistance test was conducted to assess the durability of the paving blocks under chemically aggressive conditions, specifically in environments containing sulfate ions, which are known to cause degradation in cement-based materials. This evaluation primarily focused on observable physical changes in the specimens and on measuring weight gain, which can indicate the extent of sulfate penetration and salt crystallization within the concrete matrix.

Among the variations tested, the maximum weight increase was observed in the specimen with 1% tannery sludge, while all other specimens also exhibited varying degrees of weight change. These results suggest that incorporating tannery sludge may influence the pore structure of paving blocks and their sulfate permeability, potentially affecting their long-term chemical resistance. The complete results of the sodium sulfate resistance test for each variation are summarized in Table 5, providing a comparative overview of the physical condition and weight changes observed across all sludge content levels.

Table 5. Test results for the resistance of sodium sulfate

Tannery sludge	Physical condition	Weight gain (%)
0%	Good	6.94
1%	Good	15.50
3%	Good	8.08
5%	Good	15.94

3.4 Paving Blocks XRF Test Results

Calcium oxide (CaO) is a principal chemical component in cement, playing a critical role as a binding agent in the hydration process, which ultimately contributes to the strength and integrity of cement-based materials. This study evaluated the CaO content in paving blocks incorporating tannery sludge using XRF analysis. The results revealed CaO concentrations of 50.081%, 53.024%, and 49.568% for the 1%, 3%, and 5% sludge variations, respectively.

Notably, the highest CaO content was observed in the 3% sludge mixture, suggesting that this substitution level optimizes the binder-related chemical composition of the paving block. The elevated CaO concentration at this level closely aligns with the typical CaO content found in Ordinary Portland Cement. This reinforces that 3% tannery sludge can partially replace cement without compromising the material's structural bonding function.

These findings highlight the potential of tannery sludge not only as a filler but also as a chemically active component that contributes to the binding matrix within the paving block. The full results of the XRF analysis for all sludge variations are presented in Table 6.

Table 6. Paving blocks XRF test results

Element	Paving block with tannery sludge			
	0% (%)	1% (%)	3% (%)	5% (%)
Al_2O_3	8.626	8.011	7.093	7.867
SiO_2	29.603	27.075	25.818	26.921
Fe_2O_3	12.443	10.187	9.432	10.722
CaO	44.583	50.081	53.024	49.568

3.5 Paving Block Quality

The overall quality classification of the paving blocks, based on the results of compressive strength, wear resistance, and water absorption tests, was determined in accordance with the criteria set by SNI 03-0691-1996. Each variation of tannery sludge content (0%, 1%, 3%, and 5%) was evaluated against these performance parameters to establish suitability for specific applications, such as pedestrian walkways or vehicular areas.

The comprehensive quality assessment for each variation is summarized in Table 7, providing an integrated view of how the sludge content influences the paving block classification across multiple performance dimensions.

Table 7. Paving blocks quality

Paving block with tannery sludge	Quality based on		
	Compressive strength	Wear resistance	Water absorption
0%	A	A	B
1%	B	A	B
3%	B	A	C
5%	B	A	C

The results obtained from this study reinforce the viability of utilizing tannery sludge as a partial replacement for cement in the production of paving blocks. Across all sludge variations tested (1%, 3%, and 5%), compressive strength values remained above the minimum requirement of 17 MPa as prescribed for Class B paving blocks, supporting their use in medium-duty applications such as pedestrian walkways and parking areas.

Specifically, paving blocks incorporating 3% and 5% tannery sludge were classified as Class B, while the 1% sludge mixture fell into Class C, which is suitable for lighter applications, such as pedestrian pathways. These classifications were based on a combination of compressive strength, wear resistance, and water absorption in accordance with SNI 03-0691-1996. However, it is essential to note that sodium sulfate resistance testing revealed signs of physical degradation in all sludge-containing specimens, raising concerns about the long-term durability of these specimens in chemically aggressive environments.

The poor performance of paving blocks in the sodium sulfate resistance test can be attributed to the high porosity and water absorption associated with increased tannery sludge content. Tannery sludge contains organic matter and fine particles that tend to increase pore connectivity within the concrete matrix. This higher porosity facilitates greater penetration of sulfate ions, which react with calcium hydroxide and other hydration products to form expansive compounds such as ettringite and gypsum. These reactions lead to internal cracking, microstructural degradation, and ultimately mass loss or dimensional instability over time.

Additionally, unlike traditional pozzolanic materials (e.g., fly ash or silica fume), tannery sludge lacks the strong secondary reaction with calcium hydroxide that could otherwise help refine the pore structure and improve chemical resistance. The absence of such pozzolanic action may further explain the observed lack of resistance to chemical attack, especially in sulfate-rich environments.

Compared with alternative binders, such as fly ash and blast furnace slag, tannery sludge demonstrated competitive performance, particularly in maintaining compressive strength. Previous studies have shown that fly ash substitution can lead to 15–30% strength reductions. In contrast, this study found that a 5% sludge replacement maintained a compressive strength of 27.47 MPa, indicating only a moderate decline.

Wear resistance results were consistent across all variations, with each mixture qualified as Class A, suggesting excellent surface durability. This performance is likely attributable to mineral oxides such as Fe_2O_3 and Al_2O_3 in the sludge, which may contribute to microstructural densification. On the other hand, water absorption levels increased with higher sludge content, indicating enhanced porosity and reduced impermeability. This observation aligns with existing literature regarding the hydrophilic nature of sludge-based binders. Nonetheless, all values remained within acceptable limits for non-structural applications.

Regarding chemical composition, the CaO content in sludge-modified paving blocks remained sufficiently high to preserve binding functionality. The peak CaO concentration observed in the 3% sludge mixture suggests an optimal balance between cement replacement and structural integrity.

These findings hold meaningful implications for both the construction industry and environmental management. Using tannery sludge as a partial cement substitute offers a dual benefit: mitigating the environmental impact of cement production while providing a sustainable solution for managing industrial waste. This approach aligns well with circular economic principles and is particularly relevant in regions with concentrated leather manufacturing activities.

Despite the promising results obtained in this study, several limitations should be acknowledged. All experimental procedures were conducted under controlled laboratory conditions, with a focus on short-term curing and performance evaluation. Consequently, the long-term behavior of paving blocks containing tannery sludge, particularly under real-world environmental conditions, such as freeze–thaw cycles, rainfall exposure, UV radiation, and repeated loading, remains uncertain and warrants further investigation.

In addition, the results of the sodium sulfate resistance test revealed noticeable physical deterioration in all sludge-containing mixtures. This suggests a lack of chemical durability, likely due to higher porosity and the absence of significant pozzolanic activity in the sludge. These deficiencies indicate that further formulation improvements are necessary to enhance performance in chemically aggressive environments. Incorporating pozzolanic materials, such as fly ash, silica fume, or nano-silica, may help refine the pore structure, increase chemical stability, and enhance long-term resistance to sulfate attack.

Future research should therefore aim to:

1. Evaluate the field performance of tannery sludge-based paving blocks under various climatic and load conditions over time.
2. Investigate hybrid binder systems combining tannery sludge with other supplementary cementitious materials (SCMs) to enhance both strength and durability.
3. Conduct microstructural and mineralogical analyses (e.g., SEM, XRD, FTIR) to understand hydration products and deterioration mechanisms better.
4. Perform Life Cycle Assessments (LCA) to quantify environmental impacts and compare sustainability metrics with traditional paving materials.
5. Explore the economic feasibility and scalability of implementing tannery sludge-based paving blocks at the commercial level, particularly in regions with high leather industry waste output.

By addressing these research gaps, the integration of tannery sludge as a partial cement replacement can be refined and developed into a viable, eco-friendly construction material, thereby making a meaningful contribution to sustainable infrastructure and industrial waste management.

5. Conclusions

Based on the findings of this study, it can be concluded that incorporating tannery sludge into paving block mixtures demonstrates promising potential as a partial cement substitute. Among the tested variations, the 3% tannery sludge mixture exhibited the highest calcium oxide (CaO) content, indicating an enhanced binding capability comparable to that of conventional cement. As CaO plays a critical role in the hydration process and forming bonds between sand and water, its elevated presence at this level suggests that 3% sludge content provides an optimal balance between substitution and performance.

From a mechanical performance perspective, the paving blocks with 1% tannery sludge achieved Class B quality, making them suitable for moderate-load applications such as parking areas. In contrast, paving blocks incorporating 3% and 5% tannery sludges were categorized as Class C, indicating their suitability for lighter applications, such as pedestrian pathways. This classification is based on the compressive strength, wear resistance, and water absorption criteria defined in SNI 03-0691-1996.

However, the sodium sulfate resistance test results revealed that none of the sludge-containing mixtures fully met durability standards under chemically aggressive conditions. This highlights a limitation on their long-term chemical stability. To overcome this issue, it is recommended that future formulations include supplementary materials, such as pozzolanic additives or nano-silica, to enhance sulfate resistance and ensure compliance with all quality standards for paving block applications.

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