



MANUFACTURING OF PAVING BLOCKS FROM RED BRICK WASTE AND WATER TREATMENT SLUDGE FROM PERUMDAM TIRTA WIJAYA KABUPATEN CILACAP

Khairullah Aji Izzudin¹, Ilma Fadlilah², Nur Indah Wardani³

¹Diploma 4 Study Program in Environmental Pollution Control Engineering, Cilacap State Polytechnic

²Diploma 4 Study Program in Industrial Chemical Engineering Technology, Cilacap State Polytechnic

Correspondence Email (Author) : khairullahaji@gmail.com

Received: 31-10-2025

Accepted: 13-11-2025

Published: 30-04-2026

Keywords:

Red brick, sludge, paving block, waste, drinking water

ABSTRACT

Construction waste such as broken red bricks and sludge from drinking water treatment is still an environmental problem that has not properly managed. This research aims to recycle both types of waste into paving blocks as a way to support sustainable development and reduce environmental pollution. The research was carried out by mixing cement, sand, water, red brick waste, and water treatment sludge from PERUMDAM Tirta Wijaya Kabupaten Cilacap, with five different composition variations. The production process included mixing, molding, drying, curing, for 28 days, and testing the paving block quality based on the SNI 03-0691-1996 Paving Block standard. The parameters tested were compressive strength, water absorption, abrasion resistance, and resistance to sodium sulfate (Na_2SO_4). In addition, chemical analysis of the sludge was done using X-Ray Fluorescence (XRF) instrument. The results showed that the paving block with a composition of 75% red brick waste and 25% sludge had the best performance and met the D quality classification based on SNI 03-0691-1996 Paving Block, with a compressive strength of 10.54 MPa and water absorption of 8.81%.

1. INTRODUCTION

The rapid expansion of the global construction sector has significantly increased the demand for building materials, especially in developing countries, while also escalating construction and demolition (C&D) waste generation (Mohajan, 2025; Zanelli et al., 2021). Clay red bricks remain one of the most widely used construction materials due to their affordability, durability, and favorable thermal behavior (dos Reis et al., 2020; Mohajan, 2025). However, intensive construction and demolition activities produce large volumes of mineral C&D waste, in which masonry and brick fractions constitute a major component; in several regions, ceramic products (including bricks and tiles) contribute a substantial share of CDW and are often landfilled, causing land occupation, soil disturbance, and environmental degradation (D'Angelo et al., 2021; Wang et al., 2020; Zanelli et al., 2021). Studies report that C&D waste can represent 25-40% of total solid waste, and brick-based fractions can be a significant portion of this stream depending on building typology and demolition practice (Dubale et al., 2023; Zhu & Zhu, 2020). Improper disposal of red brick waste and other mineral

residues leads to land take, depletion of landfill capacity, and associated impacts such as quality degradation, resource depletion, and increased greenhouse gas emissions (Mohajan, 2025; Wang et al., 2020; Zanelli et al., 2021).

The reuse of brick waste as a secondary aggregate or powder fits well within circular economy strategies in construction (He, Shen, et al., 2021; Wong et al., 2018; Zhu & Zhu, 2020). Crushed brick can partially replace natural aggregates in concrete and paving blocks; due to its porosity, replacement levels are usually kept low (often $\leq 25-30\%$) to avoid significant loss of strength and durability (He, Shen, et al., 2021; Wong et al., 2018). When finely ground, brick powder is rich in $\text{SiO}_2\text{-Al}_2\text{O}_3$ and exhibits clear pozzolanic activity, forming additional C-S-H and related hydrates, which can enhance later-age strength and refine pore structure (He, Shen, et al., 2021; Kryzhanovskiy et al., 2025; Likes et al., 2022; Wu et al., 2024). Reviews report optimal cement replacement by brick powder typically around 5-20%, where mechanical performance is maintained or improved and CO_2 emissions are reduced (He, Shen, et al., 2021; Kryzhanovskiy et al., 2025; Wong et al., 2018; Wu et al., 2024).

In parallel, drinking water treatment sludge (WTS/DWTS), a by-product of coagulation, flocculation, and sedimentation, is produced in large quantities and is still predominantly landfilled, raising long-term environmental concerns (De Carvalho Gomes et al., 2019; He et al., 2024; Mattoso et al., 2024). WTS often contains residual coagulants, metal oxides and fine solids, but is also rich in silica-alumina phases and can show pozzolanic behavior after drying, grinding, and sometimes calcination (Arsh et al., 2025; De Carvalho Gomes et al., 2019; He et al., 2024; He, Yang, et al., 2021). WTS has been successfully incorporated into bricks, cement, concrete, and paving blocks, generally with limited dosage: $\approx 5\text{-}10\%$ as cement or sand replacement in concrete, or $\leq 10\%$ in ceramic bricks, without major loss of strength (Arsh et al., 2025; De Carvalho Gomes et al., 2019; Erdogmus et al., 2021; He et al., 2024; Liu et al., 2020; Mattoso et al., 2024). Higher WTS contents typically increase porosity and water absorption, leading to reduced mechanical strength and durability, so optimization of replacement level is critical (Ahmad et al., 2024; Arsh et al., 2025; De Carvalho Gomes et al., 2019; Erdogmus et al., 2021; He et al., 2024; Liu et al., 2020).

Studies show successful co-firing or co-sintering of WTS with fired clay brick waste to make novel bricks, with systematic testing of density, porosity, water absorption, compressive strength, thermal conductivity, efflorescence, freeze-thaw, and detailed chemical/mineralogical analyses (Erdogmus et al., 2021). Similar work combines WTS with concrete waste in fired bricks or with other construction wastes in clay-free brick blocks.

For paving blocks, WTS has been used mainly as and replacement in concrete paving blocks, with evaluation of compressive strength water absorption, abrasion, sulfate attack and leaching, and in cement paving blocks focusing on mechanical/durability and cost (Putra et al., 2025). DWTS has also been recycled in concrete paving blocks with microstructural and leaching assessment (Liu et al., 2020). However, these works generally use a single waste stream (sludge or construction waste), and while they often include microstructure, they rarely couple two mineral wastes in a paving product or systematically link sludge chemistry (e.g., via XRF) to durability performance.

By jointly valorizing red brick waste and local DWTS in paving blocks strength, water absorption, abrasion, sodium sulfate resistance, and XRF-based sludge chemistry against national standard SNI 03-0691-1996 Paving Block, the study aligns with and extends existing brick/WTS research while addressing the documented lack of integrated physical-chemical assessment for dual-waste paving products (Ahmad et al., 2024; Erdogmus et al., 2021; Liu et al., 2020; Wong et al., 2018).

2. METHOD

This research was conducted in Cilacap from January to May 2025. The experimental site was located at 54

Bakung Street, Sidakaya, South Cilacap. The red brick waste used in this study was sourced from construction debris at the Bukit Panorama Tunggul Wulung Housing Area, Jeruklegi; the material was specifically collected as small, irregular fragments resulting from construction activities. Furthermore, the sludge samples were obtained from the sedimentation tank at the PERUMDAM Tirta Wijaya Kabupaten Cilacap Water Treatment Plant (WTP) in Kunci, Sidareja. This sludge is a residue of the filtration process of raw water sourced from the Citanduy River.

2.1. Materials for Making Paving Blocks

The materials used in this research consisted of varying compositions of red brick waste and water treatment sludge. For each specimen, these materials were mixed with 1 kg of Portland Composite Cement (PCC) as a binder, 1 kg of sieved black sand, and 0.4 L of water.

2.2. Variations of Waste Mix Composition

The composition variations of red brick waste and sludge were prepared in five mixtures with a total weight of 0.6 kg are presented in Table 1.

Table 2. Results of Compound Composition Analysis of Sludge Using XRF (%)

Sample ID	Red Brick Waste (%)	Sludge (%)	Red Brick Waste (kg)	Sludge (kg)
PB-1	100	0	0.6	0.0
PB-2	75	25	0.45	0.15
PB-3	50	50	0.3	0.3
PB-4	25	75	0.15	0.45
PB-5	0	100	0.0	0.6

2.3. Paving Block Manufacturing Process

1. The red brick waste was crushed into smaller particles to ensure a uniform mixture.
2. All materials, including red brick waste, sludge, cement, and sand, were accurately weighed according to the predetermined composition ratios.
3. The dry materials were mixed, and water was added gradually. The mixing continued until a homogeneous consistency was achieved.
4. The mixture was cast into 12 cm cube-shaped molds and compacted to eliminate air voids.
5. The specimens were removed from molds and sun-dried for 24 hours.
6. The final step involved immersing the paving blocks in water for 28 days to allow for optimal cement hydration and maximum strength development.

2.4. Analysis of Sludge Content Using Spectro Xepos X-Ray Fluorescence (XRF)

The chemical composition of the water treatment sludge was analyzed using X-Ray Fluorescence (XRF). The analysis was performed using a Spectro Xepos XRF (Spectro, Germany). The sample preparation involved drying the sludge under sunlight for three days until a constant moisture level was achieved, followed by grinding and sieving to obtain a fine powder. A 5-gram sample of the processed sludge was then placed into a pellet mold. The elemental analysis was conducted for a duration of 10 minutes to determine the concentrations of various oxides and compounds present in the waste material. This analysis was performed as a single measurement, without duplicate or triplicate testing.

2.5. Compressive Strength Test

The compressive strength test was performed on the 28th day using a Compression Testing Machine. Each specimen was placed between the compression plates and loaded at a constant rate until failure. The maximum load at failure was recorded to determine the strength of the paving blocks. This test was performed as a single measurement, without duplicate or triplicate testing. According to SNI 03-0691-1996 Paving Block, the compressive strength is calculated using the following formula :

$$F = \frac{P}{A}$$

Where :

- F = Compressive strength (MPa)
- P = Maximum load at failure (N)
- A = Cross-sectional area of specimen (mm²)

2.6. Water Absorption Test

The water absorption test was conducted to evaluate the porosity and durability of the paving blocks. Each specimen was first submerged in water for 24 hours until saturated. After immersion, the specimens were removed, wiped surface-dry, and weighed to obtain the wet weight (W_w). The samples were then dried in a laboratory oven at a constant temperature of 105 ± 5°C for 24 hours until a constant dry mass was achieved. After cooling, the dry weight (W_d) was recorded. This test was performed as a single measurement, without duplicate or triplicate testing. Based on SNI 03-0691-1996 Paving Block, the water absorption percentage was calculated using the following formula :

$$WA = \frac{W_w - W_d}{W_d} \times 100\%$$

Where :

- WA = Water absorption (%)
- W_w = Wet weight of the specimen (g)
- W_d = Dry weight of the specimen (g)

2.7. Abrasion Resistance Test

The abrasion resistance test was conducted to determine the surface durability of the paving blocks against mechanical wear. Each specimen was cut into dimensions of 5 cm x 5 cm x 2 cm and weighed to record the initial mass. The test was performed using an abrasion testing machine for duration of 3 minutes. After the process, the specimens were weighed again to determine the final mass. This test was performed as a single measurement, without duplicate or triplicate testing. The abrasion resistance (expressed in mm/min) was calculated using the following formula :

$$AR = \frac{\Delta W \times 10}{SG \times A \times t}$$

Where :

- AR = Abrasion resistance (mm/min)
- ΔW = Weight loss before and after testing (g)
- SG = Specific gravity of the paving block (g/cm³)
- A = Surface area of the specimen (cm²)
- t = Testing duration (minutes)

The specific gravity (SG) was determined by dividing the initial weight by the specimen's volume

2.8. Sodium Sulfate (Na₂SO₄) Resistance Test

Based on SNI 03-0691-1996 Paving Block, the sodium sulfate resistance test was performed to evaluate the chemical durability of the paving blocks against salt attack and weathering. Each specimen was submerged in a 25 ml sodium sulfate (Na₂SO₄) solution for 18 hours, followed by a drying process in a laboratory oven at 105°C for 2 hours. This immersion and drying cycle were completed, the specimens were washed with 1 L of barium chloride (BaCl₂) solution, followed by a final rinse with hot water at 50°C to remove residual chemicals. The specimens were then dried at 105°C for another 2 hours. The final physical condition and any signs of disintegration or weight loss were observed and recorded to determine the resistance level. This test was performed as a single measurement, without duplicate or triplicate testing.

3. RESULTS AND DISCUSSION

The analysis of sludge and the paving block tests are presented in the following subsections.

3.1. Analysis of Sludge Composition Using Spectro Xepos X-Ray Fluorescence (XRF)

The results of the compound composition analysis of sludge, using XRF are presented in Table 2.

Table 2. Results of Compound Composition Analysis of Sludge Using XRF (%)

Compound	Content
Silicon Dioxide (SiO ₂)	61.74
Sodium Oxide (Na ₂ O)	16.12
Aluminum Oxide (Al ₂ O ₃)	13.59
Magnesium Oxide (MgO)	7.02
Other Compounds	1.53

Based on the XRF analysis, as presented in Table 2, the sludge samples obtained from the water treatment plant of PERUMDAM Tirta Wijaya Kabupaten Cilacap, specifically at the Kunci Water Treatment Facility in Sidareja District, exhibit a relatively complex composition of inorganic compounds. The dominant constituents are silicon dioxide (SiO₂) at 61.74%, followed by sodium oxide (Na₂O) at 16.12%, and aluminum oxide (Al₂O₃) at 13.59%. In addition, magnesium oxide (MgO) was detected at 7.02%, with other compounds accounting for 1.53%.

The high content of silicon dioxide (SiO₂) indicates that the sludge contains abundant mineral particles, such as sand or clay, which are naturally rich in silica. This may originate from raw water sources, such as rivers or lakes, that transport suspended materials through erosion or surface run off. The sodium oxide (Na₂O) content of 16.12% is considerably high compared to typical sludge compositions (Ahmad et al., 2016; Ciula et al., 2024). This elevated concentration may be associated with the use of chemical coagulants, such as Poly Aluminum Chloride (PAC), which in some commercial formulations contain sodium compounds as stabilizers or to enhance coagulation performance. The high sodium oxide (Na₂O) content can influence the chemical reactivity of materials incorporating sludge as an additive, such as paving blocks, particularly regarding resistance to sodium oxide (Na₂SO₄) (Ahmad et al., 2016). Reactions between sodium oxide and other compounds in cementitious systems may accelerate the formation of expansive sulfate salts, leading to microstructural damage. Furthermore, the significant proportion of aluminum oxide (Al₂O₃) at 13.59% is likely derived from the aluminum-based coagulants, such as PAC, commonly applied in water treatment to agglomerate fine particles into flocs (Ahmad et al., 2016). During this process, not all aluminum precipitates as flocs, and some may remain in the sludge. The magnesium oxide (MgO) content of 7.02% may originate from natural dolomitic lime [CaMg(CO₃)₂], which may have been used in neutralization or stabilization processes (Ahmad et al., 2016; Ciula et al., 2024; Korolev & Zvereva, 2023).

In general, water treatment sludge is characterized by the presence of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and other metal oxides, resulting both from coagulant usage and suspended solids in raw water. The application of PAC particularly contributes to the elevated sodium and aluminum content in the residual sludge. These chemical characteristics are essential to consider, especially when sludge is to be reused in applications such as construction materials or agriculture.

3.2. Compressive Strength Test

The results of the compressive strength tests conducted on five paving block samples with different composition variations, as illustrated in Figure 1, are presented in Table 3.

Table 3. Compressive Strength Test Results of Paving Blocks

Sample	Composition Ratio of Red Brick Waste : Sludge (%)	Compressive Strength (MPa)	Minimum Compressive Strength Value of Paving Block
PB-1	100 : 0	8.3	8.5 MPa
PB-2	75 : 25	10.54	
PB-3	50 : 50	7.74	
PB-4	25 : 75	7.1	
PB-5	0 : 100	7.8	

Based on Table 3, Paving Block 1, composed of 100% red brick waste (0.6 kg) and 0% water treatment sludge, achieved a compressive strength of 8.3 MPa. This indicates that red brick waste has favourable aggregate properties that contribute to higher structural strength. As a fired ceramic material, red brick possesses surface characteristics that enhance bonding with cement, allowing strong interfacial adhesion (Ramteke et al., 2026; Viranthy Dian Pertiwi et al., 2025).

Paving Block 2, with a composition of 75% red brick waste (0.45 kg) and 25% sludge (0.15 kg), achieved the highest compressive strength of 10.54 MPa. This improvement can be attributed to the sludge acting as a micro-filler, which fills voids between aggregates and improves density and compactness of the paving block (Arsh et al., 2025; Liu et al., 2020; Mojapelo et al., 2025; Rashwan et al., 2020).

In Paving Block 3 (50% red brick waste and 50% sludge), the compressive strength decreased to 7.74 MPa. Although sludge still functions as a filler, the higher proportion disrupts the coarse aggregate structure. Excess sludge tends to increase water content in the mixture, resulting in higher porosity and reduced ultimate strength (Govedarica et al., 2022; Mojapelo et al., 2025; Ospanov et al., 2025; Possan et al., 2024).

Paving Block 4, consisting of 25% red brick waste (0.15 kg) and 75% sludge (0.45 kg), showed a further reduction in strength to 7.1 MPa. The high sludge content leads to dominance of fine particles, which can hinder cement hydration by absorbing water, thus limiting its availability for cement reactions (Arsh et al., 2025; Liu et al., 2020; Mojapelo et al., 2025; Pramuja S et al., 2025).

Finally, Paving Block 5, made entirely of sludge (0.6 kg) without red brick waste, recorded a slightly higher strength of 7.8 MPa. However, the absence of coarse aggregates results in suboptimal load distribution and less stable structural performance (Govedarica et al., 2022; Liu et al., 2020; Possan et al., 2024; Putra et al., 2025).

Overall, the results show that Paving Block 2 meets the Quality D classification of SNI 03-0691-1996 Paving Block, both in terms of compressive strength (minimum 8.5 MPa, with an average around 10 MPa) and water absorption capacity (maximum 10%). Meanwhile, Paving Blocks 1 and 3 meet the water absorption

parameter but fail to meet the compressive strength requirement. Compared to previous studies, the mechanical strength obtained here is relatively lower, as the paving blocks are intended for non-structural applications such as gardens and pedestrian areas. Nonetheless, the combined use of red brick waste and sludge demonstrates technical feasibility and environmental benefits, provided that the material proportions are carefully optimized to meet the SNI Quality D classification.

The fluctuation of compressive strength results, ranging between 7.1 MPa and 10.54 MPa, is attributed to several critical factors. The primary factor is the composition of raw materials, where compressive strength exhibits a negative correlation with the proportion of sludge: higher sludge content leads to lower strength. This is evident from Paving Block 2, where the 75% red brick waste and 25% sludge ratio yielded the highest compressive strength. In addition, variations in mixing and molding processes also played a crucial role, as inadequate mixing and molding precision can lead to reduced compressive strength values.

3.3. Water Absorption Test

The results of the water absorption test conducted on five paving block samples with different composition variations are presented in Table 4.

Table 4. Results of Water Absorption Test of Paving Blocks

Sample	Composition of Red Brick Waste : Sludge (%)	Water Absorption Value (%)	Maximum Average Water Absorption Value
PB-1	100 : 0	6.8	10%
PB-2	75 : 25	8.81	
PB-3	50 : 50	9.42	
PB-4	25 : 75	13.38	
PB-5	0 : 100	15.34	

Based on Table 4, the water absorption values of the five paving block samples vary according to their composition. Paving Block 1 (100% red brick waste and 0% sludge) recorded the lowest absorption value of 6.8%. This can be attributed to the coarse texture and high compressive strength of red brick waste, which enables good bonding with cement. Moreover, red brick primarily consist of silica, which contributes to the formation of calcium silicate hydrate (C-S-H) structures in cement, thereby strengthening the concrete matrix. Consequently, the full utilization of red brick waste yields paving blocks with lower and more ideal water absorption (Pertwi et al., 2025).

Paving Block 2 (75% red brick waste and 25% sludge) exhibited a water absorption value of 8.81%. The increase indicates that the addition of sludge begins to influence the porosity of the paving block. Sludge from water treatment contains fine particles, such as sodium oxide (Na₂O) and magnesium oxide (MgO), which are

less stable during hydration reactions and do not form dense structures like coarse aggregates. As a result, the paving block becomes more porous and absorbs more water (Agwa et al., 2020; Detho et al., 2025).

Paving Block 3 (50% red brick waste and 50% sludge) showed a water absorption value of 9.42%. A higher proportion of sludge leads to a looser paving block structure, as the fine particle distribution of sludge interferes with the formation of strong bonds between cement and aggregates. This creates more voids within the structure, thereby increasing water absorption compared to mixtures dominated by red brick (Agwa et al., 2020; Vaithiyasubramanian et al., 2021).

Paving Block 4 (25% red brick waste and 75% sludge) recorded a significant increase in water absorption, reaching 13.38%. This indicates that the paving block structure becomes increasingly porous with higher sludge content. Excessive sludge content promotes the dominance of fine aggregates in the mixture, which tends to create micro-pores during drying and curing. In addition, the high sodium oxide (Na₂O) content in sludge can lead to expansion and micro-cracking during curing, further increasing water absorption capacity. This finding highlights that excessive sludge use compromises the water resistance of paving blocks (Agwa et al., 2020; Detho et al., 2025).

Paving Block 5 (0% red brick waste and 100% sludge) showed the highest water absorption value of 15.34%, representing the maximum porosity among all samples. In the absence of red brick waste as a coarse aggregate, sludge becomes the sole main material, which is less effective in resisting water penetration due to its weak structural strength. The chemical composition of sludge, including high levels of silicon oxide (SiO₂) and sodium oxide (Na₂O), contributes to the reduced density of the paving block structure. As a result, this type of paving block not only absorbs water more easily but is also likely to exhibit lower mechanical strength (Agwa et al., 2020; Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Overall, the water absorption value increases with the addition of sludge in the paving block mixture. This is due to the tendency of sludge to disrupt bonding between cement and aggregate particles, making the paving block structure more porous and less dense. Sludge has a lower specific gravity compared to aggregates such as sand or red brick waste, which leads to the formation of more air voids in the mixture and directly increases water absorption. Moreover, inadequate mixing homogeneity and the manual addition of sludge can create internal air voids, further enhancing porosity and absorption. Optimal water absorption performance was observed in mixtures containing approximately 10% to 50% sludge. Exceeding 50% sludge content result in excessively high absorption. Therefore, the increased water absorption of paving blocks with higher sludge content is a consequence of their more porous internal structure and the physical characteristics of sludge combined with the imbalance in material composition.

3.4. Abrasion Resistance Test

The results of the abrasion resistance test conducted on five paving blocks samples with different composition variations are presented in table 5.

Table 5. Results of Abrasion Resistance Test of Paving Blocks

Sample	Composition of Red Brick Waste : Sludge (%)	Abrasion Resistance Value (mm/minute)	Minimum Requirement for Abrasion Resistance
PB-1	100 : 0	1.962	0.251 mm/minute
PB-2	75 : 25	5.536	
PB-3	50 : 50	1.892	
PB-4	25 : 75	15.769	
PB-5	0 : 100	10.022	

Based on Table 5, Paving Block 1 demonstrated an abrasion resistance value of 1.962 mm/minute, which significantly exceeded the threshold limit of 0.251 mm/minute for Class D quality according to SNI 03-0691-1996 Paving Block. This indicates that the use of 100% red brick waste provides relatively good abrasion resistance. This can be attributed to the hard and coarse-textured nature of red brick waste, which enhances compactness and resistance against friction (Pertiwi et al., 2025).

Paving Block 2 showed a high abrasion value 5.536 mm/minute, indicating reduced abrasion resistance. The addition of 25% sludge likely lowered aggregate quality, as sludge tends to consist of fine and clay-like particles. Furthermore, sludge can disrupt bonding between cement and aggregates, leading to softer paving blocks that are more prone to wear (Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Interestingly, Paving Block 3 recorded an abrasion resistance value of 1.892 mm/minute, slightly lower than that of Paving Block 1. This may be due to a more uniform distribution of sludge and red brick waste particles, which creates a more homogeneous mixture and reduce weak points on the paving block surface. However, despite this improvement, the value still does not meet the Class D standard of SNI 03-0691-1996 Paving Block (dos Reis et al., 2020; Vaithiyasubramanian et al., 2021).

Paving block 4 exhibited a sharp increase in abrasion value, reaching 15.769 mm/minute, indicating that it is highly susceptible to wear. The dominance of sludge (75%) proved to be ineffective, as sludge as low compressive strength and weak bonding properties. The use of sludge exceeding 50% significantly compromises the mechanical structure of paving blocks (Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Paving Block 5, although containing no red brick waste, still recorded a high abrasion value of 10.022 mm/minute. While slightly better than Paving Block 4, it remains far above the acceptable standard. This poor abrasion resistance highlights that sludge alone is

unsuitable as a primary material for paving block production. The absence of coarse aggregates such as red brick waste makes the paving block more vulnerable to frictional forces (Detho et al., 2025; Vaithiyasubramanian et al., 2021).

The fluctuation of abrasion resistance value, ranging from 1.892 mm/minute to 15.769 mm/minute, is influenced by the inconsistent density and structural conditions of the paving blocks. These variations may be attributed to the absence of a homogeneous wear layer, causing the abrasion testing machine to strike different surface areas with varying hardness due to aggregates of different sizes within the mixture.

3.5. Resistance Test Against Sulfate (Na₂SO₄)

The results of the sodium sulfate (Na₂SO₄) resistance test on five paving block samples with different composition variations are presented in Table 6.

Table 6. Results of Sodium Sulfate (Na₂SO₄) Resistance Test of Paving Blocks

Sample	Composition Red Brick Waste : Sludge (%)	Test Result of Sodium Sulfate (Na ₂ SO ₄)	Evaluation of Sodium Sulfate (Na ₂ SO ₄)
PB-1	100 : 0	Damaged	Good = no cracks and no erosion
PB-2	75 : 25	Damaged	
PB-3	50 : 50	Damaged	
PB-4	25 : 75	Damaged	
PB-5	0 : 100	Damaged	Damaged = presence of cracks or erosion

As shown in Table , Paving Block 1 exhibited minor cracks and was thus categorized as damaged, although no erosion was observed. The composition of 100% red brick waste provides relatively stable material properties against chemical agents such as sodium sulfate solution (Na₂SO₄). Red brick contains high levels of silica and alumina, which are chemically inert and therefore capable of withstanding the expansive reactions caused by sulfate salt crystallization (Detho et al., 2025; Pertiwi et al., 2025).

Paving Block 2 showed slight cracking and minor erosion, also categorized as damaged. Although sludge was introduced, the proportion was relatively small, allowing the mechanical and chemical resistance of the paving block to remain relatively intact. Sludge from water treatment contains chemically active compounds that may react with sulfate ions; however, at 25% proportion, its effect on structural durability was not significant (Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Paving Block 3 still exhibited relatively good resistance but showed more degradation compared to the previous two samples, as indicated by minor cracking and slight erosion, which classified it as damaged. This degradation is likely due to the higher amount of sludge used, which increased the probability of chemical reactions within the pores of the paving block when

exposed to sodium sulfate solution (Na_2SO_4) (Agwa et al., 2020; Vaithiyasubramanian et al., 2021).

Paving Block 4 displayed grater degradation, with visible cracking and significant erosion, particularly at the corners, and was categorized as damaged. The higher sludge content reduced density and compactness, making it easier for sodium sulfate solution (Na_2SO_4) to penetrate the pores and accelerate degradation through internal salt crystallization (Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Paving Block 5 suffered the most severe damage, with multiple cracks and extensive erosion, and was therefore categorized as damaged. This result indicates that sludge from water treatment is unsuitable as the primary material for paving block production, as it lacks adequate bonding strength and chemical resistance. The presence of organic matter and heavy metals in sludge may also contribute to the instability of the structure when exposed to sodium sulfate solution (Na_2SO_4) (Agwa et al., 2020; Detho et al., 2025; Vaithiyasubramanian et al., 2021).

Overall, all five paving block samples were categorized as damaged due to deterioration caused by chemical reactions between their constituent materials and sodium sulfate solution (Na_2SO_4). However, the degree of damage varied depending on the mixture composition. Higher sludge proportions resulted in greater degradation and reduced structural strength after immersion cycles. This may be attributed to the presence of compounds in sludge, such as silicon oxide (SiO_2), sodium oxide (Na_2O), aluminum oxide (Al_2O_3), and magnesium oxide (MgO), which are more vulnerable to sulfate attack, thereby weakening the paving block structure.

4. CONCLUSION

Among the variations of red brick waste and sludge, the mixture that meets the Quality Class D classification of SNI 03-0691-1996 Paving Block for both compressive strength and water absorption test is Paving Block 2, which consists of 75% red brick waste and 25% sludge. The dominance of red brick waste (75%) enhances the compressive strength of the paving block, while the 25% proportion of sludge acts effectively as a filler material. This balance prevents excessive porosity and ensures that sludge does not overly compromise the structural quality of the paving block.

REFERENCES

- Agwa, I. S., Omar, O. M., Tayeh, B. A., & Abdelsalam, B. A. (2020). Study on properties of clay brick incorporating sludge of water treatment plant and agriculture waste. *Case Studies in Construction Materials*, 13, e00397. <https://doi.org/10.1016/j.conbuildmat.2019.117541>
- Ahmad, T., Ahmad, K., & Alam, M. (2016). Characterization of Water Treatment Plant's Sludge and its Safe Disposal Options. *Procedia Environmental Sciences*, 35, 950–955. <https://doi.org/10.1016/j.proenv.2016.07.088>
- Ahmad, T., Ahmad, K., & Alam, M. (2024). Eco-efficient reuse of alum-based water treatment sludge into structural sintering bricks. *Case Studies in Construction Materials*, 20, e03011. <https://doi.org/10.1016/j.jclepro.2016.02.073>
- Arsh, K., Mondal, B. C., & Masum, M. M. H. (2025). Characterization of water treatment sludge and its implications on concrete and cement mortar as a partial replacement of cement. *Construction and Building Materials*, 458, 139454. <https://doi.org/10.1016/j.conbuildmat.2024.139454>
- Ciuła, J., Wiewiórska, I., Kulczycka, J., & Willson, J. (2024). Analysis of the Physical and Chemical Composition of Sludge from the Water Treatment Plant. *Rocznik Ochrona Srodowiska*, 26, 479–492. <https://doi.org/10.54740/ros.2024.045>
- D'Angelo, G., Fumo, M., Rio Merino, M. Del, Capasso, I., Campanile, A., Iucolano, F., Caputo, D., & Liguori, B. (2021). Crushed bricks: Demolition waste as a sustainable raw material for geopolymers. *Sustainability (Switzerland)*, 13(14). <https://doi.org/10.3390/su13147572>
- De Carvalho Gomes, S., Zhou, J. L., Li, W., & Long, G. (2019). Progress in manufacture and properties of construction materials incorporating water treatment sludge: A review. *Resources, Conservation and Recycling*, 145, 148–159. <https://doi.org/10.1016/j.resconrec.2019.02.032>
- Detho, A., Kadir, A. A., Shayuti, A., Rahim, B. A., Ghazouani, N., Mabrouk, A., Elhag, A. B., & Rassem, H. H. (2025). Improvement of engineering properties and environmental impact of fired clay bricks utilizing industry sludge waste. *Scientific Reports*, 15(1). <https://doi.org/10.1038/S41598-025-89147-1>
- dos Reis, G. S., Cazacliu, B. G., Cothenet, A., Poullain, P., Wilhelm, M., Sampaio, C. H., Lima, E. C., Ambros, W., & Torrenti, J. M. (2020). Fabrication, microstructure, and properties of fired clay bricks using construction and demolition waste sludge as the main additive. *Journal of Cleaner Production*, 258, 120733. <https://doi.org/10.1016/j.jclepro.2020.120733>
- Dubale, M., Vasić, M. V., Goel, G., Kalamdhad, A., & Singh, L. B. (2023). Utilization of Construction and Demolition Mix Waste in the Fired Brick Production: The Impact on Mechanical Properties.

- Materials*, 16(1).
<https://doi.org/10.3390/ma16010262>
- Erdogmus, E., Harja, M., Gencel, O., Sutcu, M., & Yaras, A. (2021). New construction materials synthesized from water treatment sludge and fired clay brick wastes. *Journal of Building Engineering*, 42, 102471.
<https://doi.org/10.1016/j.jobbe.2021.102471>
- Govedarica, O., Aškračić, M., Hadnađev-Kostić, M., Vulić, T., Lekić, B., Rajaković-Ognjanović, V., & Zakić, D. (2022). Evaluation of Solidified Wastewater Treatment Sludge as a Potential SCM in Pervious Concrete Pavements. *Materials*, 15(14). <https://doi.org/10.3390/ma15144919>
- He, Z. hai, Wang, B., Shi, J. yan, Rong, H., Tao, H. yu, Jamal, A. S., & Han, X. dong. (2024). Recycling drinking water treatment sludge in construction and building materials: A review. *Science of The Total Environment*, 926, 171513.
<https://doi.org/10.1016/j.scitotenv.2024.171513>
- He, Z. hai, Yang, Y., Yuan, Q., Shi, J. yan, Liu, B. ju, Liang, C. feng, & Du, S. gui. (2021). Recycling hazardous water treatment sludge in cement-based construction materials: Mechanical properties, drying shrinkage, and nano-scale characteristics. *Journal of Cleaner Production*, 290, 125832.
<https://doi.org/10.1016/j.jclepro.2021.125832>
- He, Z., Shen, A., Wu, H., Wang, W., Wang, L., Yao, C., & Wu, J. (2021). Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials. *Construction and Building Materials*, 274, 122113.
<https://doi.org/10.1016/j.conbuildmat.2020.122113>
- Korolev, V. I., & Zvereva, E. R. (2023). Russian experience in the use of chemical water treatment waste in economic activity: prospects for use in the treatment of sewage sludge (review article). *Power Engineering: Research, Equipment, Technology*, 24(6), 47–62. <https://doi.org/10.30724/1998-9903-2022-24-6-47-62>
- Kryzhanovskiy, V., Orlowsky, J., Skocek, J., & Macias Barrientos, M. (2025). Utilization of Brick Powder in Blended Cement Compositions: Rheological, Mechanical, and Microstructural Properties. *Materials*, 18(22).
<https://doi.org/10.3390/ma18225120>
- Likes, L., Markandeya, A., Haider, M. M., Bollinger, D., McCloy, J. S., & Nassiri, S. (2022). Recycled concrete and brick powders as supplements to Portland cement for more sustainable concrete. *Journal of Cleaner Production*, 364, 132651.
<https://doi.org/10.1016/j.jclepro.2022.132651>
- Liu, Y., Zhuge, Y., Chow, C. W. K., Keegan, A., Li, D., Pham, P. N., Huang, J., & Siddique, R. (2020). Properties and microstructure of concrete blocks incorporating drinking water treatment sludge exposed to early-age carbonation curing. *Journal of Cleaner Production*, 261, 121257.
<https://doi.org/10.1016/j.jclepro.2020.121257>
- Mattoso, A. P., Cunha, S., Aguiar, J., Duarte, A., & Lemos, H. (2024). Valorization of Water Treatment Sludge for Applications in the Construction Industry: A Review. In *Materials* (Vol. 17, Number 8). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/ma17081824>
- Mohajan, H. K. (2025). Impacts of Construction and Demolition Waste on Environment: An Overview. *Studies in Social Science & Humanities*, 4(3), 1–5.
<https://doi.org/10.63593/sssh.2709-7862.2025.05.001>
- Mojapelo, K. S., Kupolati, W. K., Burger, E. A., Ndambuki, J. M., Snyman, J., Sadiku, E. R., & Ibrahim, I. D. (2025). Optimising the mechanical properties of concrete for non-structural applications through partial replacement of fine aggregates with wastewater sludge. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-04151-9>
- Ospanov, K., Andraga, D., Alzhigitova, M., Kabylbekov, B., & Mukhanova, G. (2025). Utilization of water treatment plant sludge in concrete mix. *Technobius*, 5(3), 0083.
<https://doi.org/10.54355/tbus/5.3.2025.0083>
- Possan, E., Ramirez, K. G., de Oliveira Andrade, J. J., & Sandoval, G. F. B. (2024). Concrete with Wet and Calcined Water Treatment Plant Waste: Macro and Micro Scale Analysis. *Waste and Biomass Valorization*, 15(5), 2611–2623.
<https://doi.org/10.1007/s12649-023-02311-4>
- Pramujya S, B., Mirdiana, F., Muhammad I, R., & Roesdiana, T. (2025). Analysis of the Effect of Brick Waste on Concrete Compressive Strength. *Journal of World Science*, 4(1), 1798–1811.
<https://doi.org/10.58344/jws.v4i1.1272>
- Putra, R. E., Ismayana, A., & Putra, H. (2025). Optimizing the Use of Recycled Drinking Water Treatment Sludge in Paving Block Production. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan*, 15(4), 710–723.
<https://doi.org/10.29244/jpsl.15.4.710>

- Ramteke, R. D., Hemrick, J. G., & Mahapatra, M. K. (2026). Microstructure and bonding between calcium aluminate cement-containing gahnite–alumina matrix and refractory aggregates. *Journal of the American Ceramic Society*, 109(1). <https://doi.org/10.1111/jace.70221>
- Rashwan, M. A., Al - Basiony, T. M., Mashaly, A. O., & Khalil, M. M. (2020). Behaviour of fresh and hardened concrete incorporating marble and granite sludge as cement replacement. *Journal of Building Engineering*, 32, 101697. <https://doi.org/10.1016/j.job.2020.101697>
- Vaithiyasubramanian, R., Sriniva, D., & Kanagarajan, A. K. (2021). *Study on Preparation of Brick Blocks by Using Construction Waste and Sludge*. <https://doi.org/10.21203/rs.3.rs-488732/v1>
- Pertiwi, Viranthy Dian, A., Caronge, M. A., & Tjaronge, M. W. (2025). Producing Eco-Friendly Concrete Paving Block Using Waste Refractory Brick Aggregates. *International Journal of Pavement Research and Technology*, 18(6), 1399–1411. <https://doi.org/10.1007/s42947-024-00425-z>
- Wang, Y., Huang, J., Wu, T., Huang, J., & Liu, Y. (2020). Comprehensive utilization study of waste red brick in urban reconstruction. *IOP Conference Series: Earth and Environmental Science*, 514(3). <https://doi.org/10.1088/1755-1315/514/3/032066>
- Wong, C. L., Mo, K. H., Yap, S. P., Alengaram, U. J., & Ling, T. C. (2018). Potential use of brick waste as alternate concrete-making materials: A review. *Journal of Cleaner Production*, 195, 226–239. <https://doi.org/10.1016/j.jclepro.2018.05.193>
- Wu, H., Gao, J., Liu, C., Guo, Z., & Luo, X. (2024). Reusing waste clay brick powder for low-carbon cement concrete and alkali-activated concrete: A critical review. *Journal of Cleaner Production*, 449, 141755. <https://doi.org/10.1016/j.jclepro.2024.141755>
- Zanelli, C., Marrocchino, E., Guarini, G., Toffano, A., Vaccaro, C., & Dondi, M. (2021). Recycling construction and demolition residues in clay bricks. *Applied Sciences (Switzerland)*, 11(19). <https://doi.org/10.3390/app11198918>
- Zhu, L., & Zhu, Z. (2020). Reuse of Clay Brick Waste in Mortar and Concrete. In *Advances in Materials Science and Engineering* (Vol. 2020). Hindawi Limited. <https://doi.org/10.1155/2020/6326178>