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RESEARCH ARTICLE

Optimizing the Use of Recycled Drinking Water Treatment Sludge in Paving Block Production

Reza Eka Putra[a], Andes Ismayana[b], Heriansyah Putra[c]

[a] Natural Resources and Environmental Management Science Study Program, IPB University, IPB Baranangsiang Campus, Bogor, 16129, Indonesia

[b] Department of Agroindustrial Engineering, Faculty of Agricultural Technology, IPB University, IPB Dramaga Campus, Bogor, 16680, Indonesia

[c] Department of Civil and Environmental Engineering, Faculty of Agricultural Technology, IPB University, IPB Dramaga Campus, Bogor, 16680, Indonesia

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ABSTRACT

Drinking Water Treatment Sludge (DWTS) recycling is a solution for handling waste sludge by making paving blocks. This paper analysis the optimization of the mechanical performance, durability, and cost production of the paving block incorporating recycled DWTS as a replacement for fine aggregate. Three paving block mixes were produced, and the replacement of sand aggregates by DWTS aggregate was mixed into different percentages by weight with variations in the water-to-cementitious ratio (w/c). The mechanical performance and durability significantly decreased, falling well below the quality criteria, with the addition of DWTS increasing by over 40%. The obtained result indicated that DWTS could be used as an adequate replacement for sand aggregate that met the optimum level in the paving block containing 40% sludge with w/c 0.8 could achieve a 28-day compressive strength of 11.64 MPa, a density of 1,866.27 kg/m³, a water absorption of 12.61%, and a wear resistance of 0.077 mm/minute. It was the optimal replacement value that met the quality requirements for Class D (park). It has utilization of DWTS in paving block could help develop the appropriate technology and increase production cost efficiency to 7.73% equivalent 72,697.82 IDR/m³ paving block, thus significantly resulted in product meets technical reliability and low-cost.

Introduction

Population growth is directly proportional to the increase in water consumption, resulting in more residual sludge being produced by each water treatment plant. The total Drinking Water Treatment Sludge (DWTS) generated in water treatment plants can reach up to 100,000 tons per year [1,2]. DWTS sourced from all precipitates produce coagulation, flocculation, sedimentation, and filtration processes, such as suspended materials or colloids, coagulant residuals, and aluminium [3,4]. The disposal of DWTS by transportation and landfilling methods has become a potential hazard and environmental issue, such as pollution impacts, detrimental to human health, and reduced availability of landfills, because the quality of sludge contains aluminium salts, iron salts, colloidal, and suspended impurities adsorbed onto hydroxide precipitates, and the hydroxide precipitates removed from the raw water mainly constitute the solids present in the sludge. DWTS are commonly characterized by high concentrations of Total Organic Carbon (TOC) and inorganic compounds such as aluminium sulphate or poly-aluminium chloride, which cause pollution, are detrimental to human health, and reduce landfill availability [5–7]. The high aluminium concentration of DWTS by 19.6–28.5% or 1.4–2 mg/L is commonly obtained as a coagulant residue from water treatment plants in municipalities; therefore, sludge disposal to land is challenging. Thus, the disposal of DWTS to land sites has inhibited plant growth due to phosphorus fixation, decreased soil acidity, decreased photosynthesis and transpiration rates, and decreased nutrient absorption [4,8–10].

Corresponding Author: Reza Eka Putra rezaekaputra@apps.ipb.ac.id Natural Resources and Environmental Management Science Study Program, IPB University, IPB Baranangsiang Campus, Bogor, Indonesia.

DWTS was utilized as a substitute for the sand aggregate of paving blocks, which can improve environmental benefits, such as the efficiency of natural resource use, absorption of greenhouse gases, prevention of displacement environment and waste production, implementation of sustainable construction, and compensation for the restriction of sand aggregates [3,11,12]. These conditions associated with the highest sand aggregate usage as a component of construction material were estimated to be over 60–75%; this phenomenon is implicated with increasing aggregate consumption globally of ±40,000,000,000 tons in 2014 compared to ±21,000,000,000 tons in 2007, and global aggregate consumption will rise by more than ±60,000,000,000 tons per annum in 2030 [13–17]. However, sand as a concrete filler is categorized as a non-renewable resource [17]. Sand aggregates are extracted from hard-rock sources using drilling and blasting mechanisms [18]. Mining activities of sand aggregates impact the topography and composition of sediments and commensurate non-renewable resource depletion and siltation of the water surface. Thus, recolonization of mining areas occurs slowly and has detrimental environmental impacts [19,20]. Sand extraction might contribute to many health problems, such as lung cancer, which is attributed to high silica exposure levels of above 25 $\mu g/m^3$ [21]. The dust emission released from the crushing phase in sand extraction could also form Total Suspended Particulate (TSP), containing 60%, 6%, and 2% of particulate matter <10 mm, particulate matter <2.5 mm, particulate matter <1 mm within the range of 1–650 $\mu g/m^3$, respectively [22]. The emission was proportional to the addition of conventional materials. Thus, the use of recycled materials lowers emissions. However, it significantly reduces the performance feasibility as the amount of recycled material increases [23]. The Sustainable Development Goal (SDG) 12 promotes sustainable consumption and production, including the massive development of sustainable materials. For example, replacing sand with DWTS in construction materials can solve the problems of natural resource depletion and environmental management. This has improved the exploration of recycling options for sludge waste, and their purpose represents a potential for enhancing production efficiency and reducing environmental pollution [16,24–27].

Paving blocks are used as alternative construction materials (roads, parking areas, pedestrian and bicycle paths, parks), which either partially or entirely use waste material [28,29]. However, recycled paving blocks are mainly manufactured using aggregate materials categorized as hazardous waste, such as metallurgical sludge waste, including slag, scale, dust from blast furnaces, steel, and sintering, which can contaminate soil and groundwater [30]. DWTS is categorized as a non-hazardous waste because its heavy metal content fulfills the USEPA requirements [31]. The physicochemical properties of sludge are composed of SiO_2 55–64%, organic compounds Al_2O_3 20–23%, Fe_2O_3 5–11%, CaO, MgO, Na_2O, K_2O, $NaAlSi_3O_8$, and $CaCO_3$, with an absorption capacity of 6.9–9.7%, density of 0.98–1.35 g/cm^3, and bulk density of 518–726 kg/m^3, thus sludge is suitable for application in fine aggregates [2,25,27,32,33]. The DWTS achieved an effective sludge replacement ratio of 5–20% with an aggregate-to-cement ratio of 1:3 for producing paving blocks, and it was found that the compressive strength was 4.13–52 MPa, water absorption was 4.2–7.7%, and the abrasion index was 11.91–12.42 [3]. Similar studies highlighted the addition of sludge 12.5–100% to replace sand aggregate with a w/c ratio of 0.95–26, it can generate a compressive strength of 0.3–0.6 MPa [34]. DWTS is a potential substitute for sand aggregates in paving blocks to achieve optimum conditions at 28 days [35]. The novelty of this study is that the effect of recycled DWTS as a partial replacement of fine aggregate was investigated at different percentages (0%, 20%, 40%, 60%, 80%, and 100%) by weight and variations in the water-to-cementitious ratio (w/c) of 0.4, 0.8, and 1.2 on the mechanical performance and durability of the paving block were measured using the parameters of compressive strength, density, water absorption, and wear resistance. This study aimed to analyze the optimization of the mechanical performance and durability of paving blocks and the cost benefit of incorporating recycled DWTS as a partial replacement of the fine aggregate of the paving block.

Materials and Methods

This study was classified as experimental research and laboratory observations focused on the recycled optimization of DWTS in the water treatment plant of Water Company XYZ, located in the Administrative Municipalities of Central Jakarta, Indonesia.

Materials

The materials used to produce the paving blocks in this study were cement, water, sand aggregates, and DWTS aggregates. The cement used was locally produced Portland Pozzolan Cement, following SNI 15-2049-2004 [36]. Groundwater was used as the water source. Locally produced sand from Cimangkok Village in

Sukabumi was screened using a number 8 sieve (4.75 mm) before use as a sand aggregate. The DWTS aggregate used was obtained from a drinking water processing plant located in Jakarta, which treated Jatiluhur Lake water and had a capacity of 3,200 LPS (liters per second). The DWTS aggregate was processed by milling using a Los Angeles Machine and sieving of the DWTS with a sieve of No. 16 (1.18 mm) to obtain sludge in powdered form, and then dried at a temperature of approximately 105 °C for 24 h via oven drying. Thus, the DWTS resulted in a lower moisture content and a finer form. The physical parameters of the sand and DWTS aggregates, such as specific gravity, absorption, bulk density, and fineness modulus, were analyzed following Indonesian standard codes for testing aggregate samples. Meanwhile, the chemical composition of the DWTS, such as metal oxide compounds, was determined using X-ray Fluorescence (XRF) [2,3].

Mix Design

Table 1 lists three series of mixture proportions. The mixtures are referred to as series paving block I (PBI), series paving block II (PBII), and series paving block III (PBIII), with water-to-cement ratios (w/c) of 0.4, 0.8, and 1.2, respectively. The aggregate–cement ratio was 3:1. The sand aggregate was substituted with DWTS in partial or complete percentages, with the addition of DWTS contents varying from 0% to 100% by weight. This condition considers the high water absorption of the sludge [34].

Table 1. Mix proportions (wt%) of paving block.

Series	Item	Material			Amount of sample
		Cement	Aggregate	w/c ratio	
Series I (w/c ratio = 0.4)	PBI-0% DWTS	25%	75% sand	0.4	2
	PBI-20% DWTS	25%	60% sand + 15% DWTS	0.4	2
	PBI-40% DWTS	25%	45% sand + 30% DWTS	0.4	2
	PBI-60% DWTS	25%	30% sand + 45% DWTS	0.4	2
	PBI-80% DWTS	25%	15% sand + 60% DWTS	0.4	2
	PBI-100% DWTS	25%	75% DWTS	0.4	2
Series II (w/c ratio = 0.8)	PBII-0% DWTS	25%	75% sand	0.8	2
	PBII-20% DWTS	25%	60% sand + 15% DWTS	0.8	2
	PBII-40% DWTS	25%	45% sand + 30% DWTS	0.8	2
	PBII-60% DWTS	25%	30% sand + 45% DWTS	0.8	2
	PBII-80% DWTS	25%	15% sand + 60% DWTS	0.8	2
	PBII-100% DWTS	25%	75% DWTS	0.8	2
Series III (w/c ratio = 1.2)	PBIII-0% DWTS	25%	75% sand	1.2	2
	PBIII-20% DWTS	25%	60% sand + 15% DWTS	1.2	2
	PBIII-40% DWTS	25%	45% sand + 30% DWTS	1.2	2
	PBIII-60% DWTS	25%	30% sand + 45% DWTS	1.2	2
	PBIII-80% DWTS	25%	15% sand + 60% DWTS	1.2	2
	PBIII-100% DWTS	25%	75% DWTS	1.2	2

Specimens Preparation

The paving-block manufacturing procedure is illustrated in Figure 1. It consists of three phases: mixing, compacting, and curing. The paving blocks were fabricated at a local factory to achieve production feasibility of the paving blocks under actual industrial conditions.

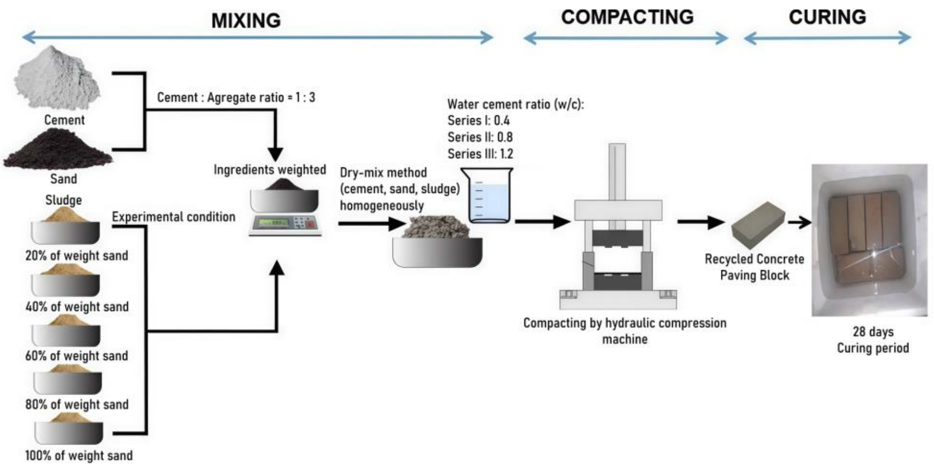

Figure 1. Mixing, compacting, and curing processes used to form paving block specimens.

Mixing phase: Initially, sand, DWTS, and cement were dry-mixed using a manual stirrer in a pan. Subsequently, water was added and mixed to achieve homogeneous conditions [3]. Compaction phase: The mixtures were placed in a batch of 210 mm × 110 mm × 80 mm molds and compacted using a hydraulic compression machine. The paving block specimens were left under ambient conditions for 24 h for initial strength development before curing [37]. Curing phase: The paving blocks were cured in a pond to retain moisture at a humidity (65%) and a temperature (23±2 °C) for a 28-day curing period before conducting the experimental testing, and the ponding method was used to complete the optimum hydration process [3, 38].

Test Methods

The mechanical performance and durability of the paving blocks with DWTS were evaluated using compressive strength, density, water absorption, and wear resistance. Compressive strength, density, and water absorption tests were performed to measure the five mixes after 28-days of curing. The strength, density, and water absorption were characterized by increasing DWTS replacement levels.

Compressive Strength

The compressive strengths of the specimens were tested in accordance with ASTM C140 [39]. A compressive strength test on cubic-shaped specimens (80 mm × 80 mm × 80 mm) was performed using a universal testing machine (UTM); thus, the load was applied until failure. The compressive strength was determined according to Equation 1, where Pmax is the maximum compressive load (N), An is the average net area of the specimen (mm^2), and Fa is the aspect ratio factor.

$$Net\ Area\ Compressive\ Strength, ps\ [MPa] = \frac{Pmax}{An}\ x\ Fa \quad (1)$$

Density

The density of the paving block was determined according to SNI 03-0691-1989 [40]. The density of the specimen was calculated by dividing the weight (W) by the volume (V), as shown in Equation 2 [37]. The standard method requires oven drying at 105 °C to obtain a constant weight before measuring the density.

$$Density\ = \frac{W}{V} \quad (2)$$

Absorption

The water absorption of the specimens was determined according to ASTM C140 [39]. The water absorption tests on the block-shaped specimens (210 mm × 110 mm × 80 mm) were immersed in water for 24 h. All specimens were oven-dried at approximately 110 °C for 24 h until a constant weight was achieved. The absorption percentage was calculated according to Equation 3, where Wd is the oven-dry weight of the specimen, and Ws is the saturated weight of specimen (g).

$$Absorption\ (\%) = \frac{[Ws - Wd]}{Wd} x\ 100 \quad (3)$$

Wear Resistance

The wear resistance of the paving blocks was determined according to SNI 03-0691-1989 [40]. The prepared specimen wear resistance on a block-shaped 50 mm x 50 mm x 20 mm was measured according to Equation 4, where A is the weight difference between before and after wear, BJ is Specific Gravity, L is wear surface area, and W is wear duration.

$$Wear\ resistance(\%) = \frac{A\ x\ 10}{BJ\ x\ L\ x\ W} x\ 100 \quad (4)$$

Results

Physical and Chemical Characteristics of Fine Aggregate

Table 2 shows the physical properties of the sand and DWTS aggregates. The particle size distributions of the sand and DWTS are shown in Figure 2. The results show that the modulus of fineness of the aggregate. The larger particle size distribution of DWTS (30%) was in the range of 0.6–1.17 mm. The chemical properties of the DWTS were determined by the weight percentage (wt%), as shown in Table 3. X-ray Fluorescence was used to characterize the primary compounds found in the DWTS, including SiO_2 (49.54%), Al_2O_3 (27.70%), and Fe_2O_3 (14.57%). SiO_2 and silicates are the major components of DWTS because of their primary mineralogical content in natural soil [41]. The toxic characteristic leaching procedure (TCLP) results of raw DWTS from the preliminary research showed that the leaching of heavy metals did not exceed the safe limit of Government

Regulation of Republic Indonesia Number 101 Years 2014 concerning the Management of Hazardous and Toxic Waste because the heavy metal concentrations of DWTS are acceptable for direct use in producing recycled paving blocks, as shown in Table 4.

Table 2. Physical properties of sand and DWTS.

Parameter	Sand	DWTS	Standard
Specific Gravity (constant)	2.53	1.60	SNI 1970:2008 [42]
Absorption (%)	2.30	20.12	SNI 1970:2008 [42]
Bulk density (kg/m^3)	1,657	1,305	SNI 03-4804-1998 [43]
Fineness Modulus (constant)	3.06	1.05	SNI 03-1968-1990 [44]

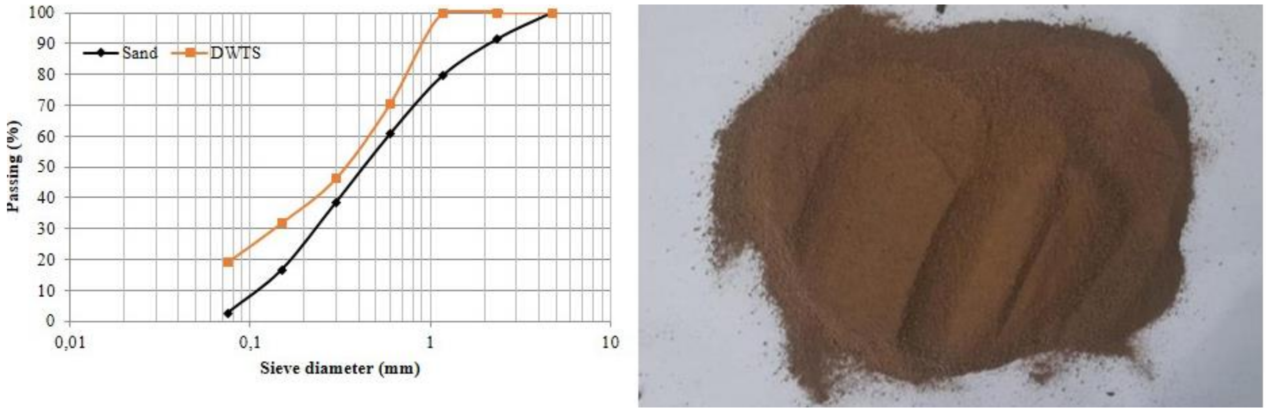

Figure 2. Compared size distribution curves of DWTS represent lighter than sand aggregate.

Table 3. Chemical characteristics of DWTS.

Compound	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO	CaO	K_2O	P_2O_5	SO_3	MnO	Cl
wt%	49.54	27.70	14.50	2.08	1.40	1.37	0.98	0.72	0.43	0.44	0.16

Table 4. Toxic characteristic leaching procedure of DWTS.

Parameter	Pb	Cd	Hg	As	Sb	Mo	Zn	Se	Cu	Ni	Ag	Ba
Result (mg/L)	<0.03	<0.01	<0.0002	<0.0002	<0.0004	<0.06	5.88	<0.0004	0.09	<0.01	<0.006	1.76
Regulatory limit (mg/L)	0.5	0.15	0.05	0.5	1	3.5	50	0.5	10	3.5	5	35

Mechanical Performance and Durability of Paving Block

The mechanical performance and durability of adding DWTS into the paving block were measured using the parameters of compressive strength, density, water absorption, and wear resistance, primarily the fourteen specimens that were able to form. In Series I, of all six mixtures of a specimen prepared with a w/c ratio of 0.4, only four mixtures were able to form a fresh paving block with the sludge addition used to replace sand aggregates in different proportions of 0%, 20%, 40%, and 60%. Meanwhile, two mixtures of paving blocks of Series I prepared with 80% (PBI-80) and 100% (PBI-100) sludge contents could not be formed, as shown in Figure 3.

In Series II, all mixtures prepared in Series II were able to form fresh paving block specimens. In Series II, the mixtures were produced by replacing 0%, 20%, 40%, 60%, 80%, and 100% of the sand aggregate by weight with DWTS with a w/c ratio of 0.8. In Series III, of the six mixtures of a specimen prepared with a w/c ratio of 1.2, only four mixtures were able to form a fresh paving block with DWTS replacement ratios of 40%, 60%, 80%, and 100%. However, the two mixtures with sludge additions of 0% (PBIII-0) and 20% (PBIII-20) were not formed because the amount of water used was generally in excess; thus, the paving block mixtures became aqueous, as shown in Figure 3.

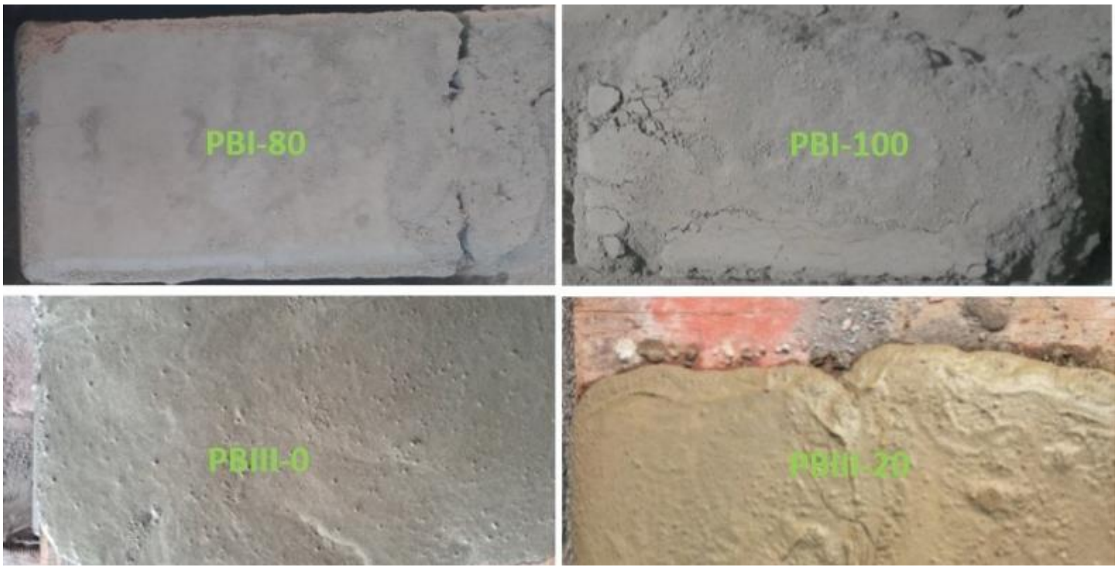

Figure 3. Four mixes unable to form the paving block.

Compressive Strength

The 28-day compressive strength exhibited an inversely proportional relationship with the DWTS content, as shown in the matrix in Table 5. The high additional sludge content decreased the compressive strength of the paving block; thus, the lowest compressive strength for each w/c ratio was demonstrated at the highest replacement ratio of sand by DWTS, when DWTS was used as a 60% replacement of sand in w/c 0.4, 100% replacement of sand in w/c 0.8, and 100% replacement of sand in w/c 1.2.

Table 5. The matrix of compressive strength.

Sludge contain (%)	Compressive strength (MPa)		
	Series I (w/c 0.4)	Series II (w/c 0.8)	Series III (w/c 1.2)
0	11.77	17.25	N/A
20	5.55	21.70	N/A
40	5.11	11.64	10.78
60	3.33	6.20	7.77
80	N/A	5.65	5.25
100	N/A	3.86	4.59

The specimen with an additional sludge at 100% w/c equal to 1.2 (PBIII-100) had a compressive strength of 4.59 MPa, as shown in Figure 4. An observation of the failed cubic specimen PBIII-100 under compression, which is in contrast to the failure of PBII-20 owing to the failure of PBIII-100, indicated that the proportion of aggregate had a higher presence of DWTS, which implies that the samples should have multiplied the local failure caused by lateral stress increases around the pores [17].

Figure 4. Failed cubic specimens under compression.

The compressive strength reached an optimum value when the required water or w/c ratio was increased to the allowable level, accompanied by an increase in the sludge content of the paving block. The water-to-cementitious ratio was varied from 0.4 to 1.2 to achieve the optimal compressive strength for each variation. The results indicated that the water-to-cementitious material ratio was optimized to 0.8 with DWTS replacement ratios of 0%, 20%, 40%, and 80%. Meanwhile, a 100% DWTS replacement ratio requires a water-to-cementitious ratio of 1.2. Therefore, an optimum w/c ratio is required to achieve uniformity in the paving block mixtures and consistency in material performance.

SNI 03-0691-1996 requires the minimum physical properties of the paving block, especially compressive strength, to be divided into four paving criteria: 35 MPa for grade A (roads), 17 MPa for grade B (vehicle parking), 12.5 MPa for grade C (pedestrians), and 8.5 MPa for grade D (parks) [40]. Figure 4 illustrates that the highest compressive strength of 21.7 MPa was achieved in the paving block with a sludge ratio of 20% and w/c of 0.8 (PBII-20), meeting the quality requirements for parking equipment. The maximum replacement ratio of sand by DWTS in the paving block at an acceptable level was 40% and w/c ratios of 0.8 and 1.2 resulted in 28-day compressive strengths of 11.64 MPa and 10.78 MPa, respectively, which are still within the quality requirements limit of the paving block application for vehicle parking. This condition could result from the high porosity of sludge particles and an absorption capacity of 20.12% compared to the sand absorption capacity of 2.12%, implying an increased w/c ratio of paving block mixtures incorporating a high DWTS content.

Density

The density of the paving block decreased with increasing concentration of sludge in the mixture of specimens, as shown in Table 6. The lowest for each w/c ratio was demonstrated at the highest replacement ratio of sand by DWTS, when DWTS was used as a 60% replacement of sand at w/c of 0.4 (1,124.00 kg/m^3), 100% replacement of sand at w/c of 0.8 (1,226.44 kg/m^3), and 100% replacement of sand at w/c of 1.2 (1,232.56 kg/m^3). Density is an indicator of the mechanical strength of a specimen. Specific gravity is a dependent factor that affects the physical properties of fine aggregates, with specific gravities of 2.53 and 1.60 for sand and DWTS aggregates, respectively.

Table 6. The matrix of density.

Sludge contain (%)	Density (kg/m^3)		
	Series I (w/c 0.4)	Series II (w/c 0.8)	Series III (w/c 1.2)
0	1,701.24	1,854.16	N/A
20	1,585.86	2,197.11	N/A
40	1,581.86	1,866.27	1,656.15
60	1,124.00	1,653.88	1,596.15
80	N/A	1,637.60	1,356.59
100	N/A	1,226.44	1,232.56

Water Absorption

The relationship between the DWTS and the water absorption of the specimens is presented in Table 7. The percentage water absorption increased with the increase in the DWTS content for each w/c variation, which demonstrates that the highest water absorption on the DWTS addition up to 100% was between 25% and 17% for w/c of 0.8 and w/c of 1.2, while the sludge addition was 60% for a w/c of 0.4, and the DWTS addition 60% had water absorption of 26% at w/c 0.4.

Table 7. The matrix of water absorption.

Sludge contain (%)	Water absorption (%)		
	Series I (w/c 0.4)	Series II (w/c 0.8)	Series III (w/c 1.2)
0	15.91	8.64	N/A
20	14.82	8.27	N/A
40	18.72	12.61	14.10
60	35.45	15.32	16.28
80	N/A	17.38	17.88
100	N/A	33.65	20.01

Wear Resistance

Table 8 shows the increase in wear resistance with increasing DWTS content. The results showed that the addition of DWTS increased the wear resistance, and the high wear resistance of the specimen had a negative effect on the mechanical performance. This effect appeared to decrease the compressive strength and density of the paving block and increase the wear resistance.

Table 8. The matrix of wear resistance.

Sludge contain (%)	Wear resistance (%)		
	Series I (w/c 0.4)	Series II (w/c 0.8)	Series III (w/c 1.2)
0	0.054	0.063	N/A
20	0.156	0.059	N/A
40	0.098	0.077	0.049
60	0.112	0.151	0.084
80	N/A	0.178	N/A
100	N/A	0.168	N/A

Cost Benefit of Using DWTS

The measured cost-benefit confirmed the potential use of DWTS to produce a low-cost paving block material. Table 9 shows that utilizing the DWTS recycling process and the limitation of sand used as fine aggregate can also effectively reduce the cost of producing the paving block by 3.87–7.73% equivalent to 36,348.91–72,697.82 IDR/m^3 paving block. The obtained results indicated that DWTS could be used as an adequate replacement for sand aggregates and that the optimum level in the paving block could help increase production cost efficiency, thus significantly resulting in a low-cost product.

Table 9. Production cost the paving block specimens meets compliance with SNI 03-0691-1996.

Item	Production cost							
	Cement (IDR/m^3 block)	Sand (IDR/m^3 block)	Sludge (IDR/m^3 block)	Water (IDR/m^3 block)	Electricity (IDR/m^3 block)	Labor cost (IDR/m^3 block)	Equipment cost (IDR/m^3 block)	Total cost (IDR/m^3 block)
Sludge contain 0% and w/c 0.8	540,000	303,482	-	72,000	10,704	10,517	3,170	939,872
Sludge contain 0% and w/c 0.4	540,000	303,482	-	36,000	10,704	10,517	3,170	903,872
Sludge contain 20% and w/c 0.8	540,000	242,786	24,348	72,000	10,704	10,517	3,170	903,523
Sludge contain 40% and w/c 1.2	540,000	182,089	48,695	108,000	10,704	10,517	3,170	903,175
Sludge contain 40% and w/c 0.8	540,000	182,089	48,695	72,000	10,704	10,517	3,170	867,175

Discussion

Physical and Chemical Characteristics of Fine Aggregate

As the observed in the sieve analysis represented the particle size distribution of the fine aggregates was obtained by sieve analysis by screening with a No. 4 (≤4.75 mm), especially particle size range of 1.17–0.6 mm. The sand aggregate was significantly coarser than the DWTS aggregate [3]. Al_2O_3 is a constituent of DWTS sourced from metal-based coagulant residues and is a chemical material widely used to eliminate colloids and metal compounds from the treated water of water treatment plants [45]. Fe_2O_3 or ferric oxide is a chemical compound of ferric sludge collected from the sludge dewatering system of a water processing plant [46].

Should be DWTS primarily consist of mineral phases silicon (SiO_2), aluminium (Al_2O_3), iron (Fe_2O_3), which were consequently justified by their chemical structures and functions. The SiO_2 fraction is a component of concrete formulations, and DWTS can be used in concrete as a substitute for sand [47]. Initially, SiO_2 reacts with Al_2O_3 to form kaolinite crystals ($Al_2Si_2O_5(OH)_2$) as the cement content increases, which can increase the interfacial bonding force between the aggregate and the cement matrix of concrete [3]. The utilization of DWTS as an alternative substitute for fine aggregate materials can be categorized as non-hazardous waste and environmentally friendly construction materials [37]. Thus, the leaching test of paving blocks may not be required as an indicator test in the application of DWTS for creating paving blocks.

Mechanical Performance and Durability of Paving Block

The mechanical performance and durability of paving blocks are important parameters that affect their formation of paving blocks. Thus, they are dependent on the curing time and increase in the percentage of DWTS as a partial replacement of sand aggregate. The failure to form paving blocks may be attributed to the difficulty in compacting the fresh paving block because of the high water demand of the sludge, resulting in mixtures of paving blocks becoming too dry and more porous [48]. Therefore, the specimen had weak bonding at the DWTS-cement interface, which prevented the mixtures from obtaining the desired result [3]. The aqueous nature of the paving block indicates that sand aggregates have a less porous structure than DWTS; thus, sand aggregates absorb less water than DWTS [49].

Compressive Strength

As observed in the 28-day compressive strength test indicated the potential of using DWTS particles as a substitute for the sand aggregate could be effective for the DWTS replacement level in the range of 20 to 40% with a w/c ratio of 0.8 to 1.2. Thus, the quality requirement of the paving block was achieved. Meanwhile, the mechanical performance of the specimen, particularly the reduction in the compressive strength, was significant when the DWTS replacement level was above 40%. Thus, the 28-day compressive strength decreased well below the quality requirement. The compressive strength was reduced for the high replacement ratio of sand by DWTS, owing to the inhibited formation of portlandite and Calcium Silicate Hydrate (C-S-H) gel, which was not evenly distributed compared with the specimen with a lower DWTS replacement level, which caused the calcium cation reaction to occur more easily in a more porous solution [3,31]. The sludge content of the paving block affected the compressive strength owing to its correlation with the loss of cohesion between sludge and cement. The increased DWTS content of the paving block mixture inhibits the hydration process of cement owing to the lack of water during the mixing process caused by the oven-dried sludge, which increases the absorption of free water [3]. The surfaces of the paving blocks were mainly covered by small crystalline ettringite, which caused microfractures in the paving block specimen, possibly caused by the penetrating ettringite in C-S-H to complete the filling of the pores [31,50]. Sludge containing organic compounds demonstrated a weaker impact on the bonding interface between the sludge and cement matrix [51].

The 28-day compressive strength was affected by the interfacial surface between the cement and aggregate when the paving block mixtures were compacted using the vibration method, which could result in the water content of the aggregate being transferred to the cement matrix. Thus, this condition is mainly attributed to the high local w/c ratio around the particle, which weakens the interfacial surface between the cement matrix and aggregate [52]. The high water absorption of sludge results in a higher water demand, generating a void in the bonding area between the cement paste and the aggregate, thus reducing the compressive strength of the sludge composite [4]. The raw sludge was treated using a milling process, which transferred kinetic energy to the sludge particles, potentially reducing the particle size and increasing the agglomeration force [53]. The effectiveness of homogenous mixtures and compaction materials has been demonstrated [54]. The fine aggregates agglomerated more easily than the primary particles because they had a larger specific surface area [41]. Similar research highlighted that using sludge composite as an aggregate sand replacement had an absorption capacity of 24%; thus, the required w/c ratio was increased by 0.01 for every 2% increase in sludge [4]. The increased water requirement of the paving block is directly related to the specific surface area of the fine aggregates [55].

Density

As observed in the densitiy test represented the optimum replacement level of DWTS was used as a 20% within w/c of 0.8 (2,197.11 kg/m^3). The mechanical strength of sludge aggregates is affected by size distribution, non-homogenous particle size, irregular shapes, and larger specific surface area [41]. The density and particle size of the powder determine the optimum composition of the suspension according to its microstructural properties [56]. The properties of fine particles with small particles could be attributed to a more straightforward compaction process. Thus, fine particles have a better filler effect. The density generally decreases as the porosity of the paving block increases, and the inverse relationship between the porosity and density is associated with water absorption. Thus, the pores appear significantly larger for the paving block with high water absorption compared to that of the paving block with low water absorption, which is associated with a lower density [57]. The reduction in density is accompanied by relatively increased water absorption in the paving block [58].

However, the reduction in the density of the paving block was explained by the high sludge content, which is likely to have a more porous structure and a higher angularity than sand. Thus, the addition of sludge affects the homogeneity of the paving blocks during compaction, causing a decrease in the cohesiveness of the cement matrix [59]. A higher DWTS content produced a more porous paving block specimen with high water content when the porosity increased owing to the high water content of the specimen [60]. The addition of DWTS content can affect the density of paving blocks, indicating that paving blocks with a higher DWTS proportion showed a decrease in density compared to paving blocks with a higher sand proportion because of the lower specific gravity of DWTS compared to that of sand [47].

Water Absorption

As observed in the water absorption test indicated the optimum replacement level of DWTS was used as a 20% within w/c of 0.8 (8.27%). The addition of DWTS to the specimen enhanced the water absorption, especially for the specimen made with a higher additional DWTS content, effectively increasing the water absorption of the specimen owing to the high specific surface area of the sludge [34,49]. The addition of sludge was highly correlated with water absorption, which also affected the durability of the paving blocks, as the production process resulted in high porosity of the paving block [61]. In fact, the higher water absorption in the specimen was affected by the porous structure, porous volume, porous structure dimensions, and high porosity [62,63]. A higher water absorption has a significant impact on the volume of the specimen being attacked by a solution. Thus, the solution could penetrate the hardened matrix [64]. The porous construction material had a high porosity because of the pore structure and pore size; thus, the condition resulted in an increase in infiltration capacity, such as the pavement permeability as a porous material, which could be used to increase infiltration, storage, and evaporation of water in urban drainage for rainfall-runoff control and reduce flooding [65,66].

Wear Resistance

As observed in the wear resistance test represented the reduction within increased the DWTS replacement level. An increase in wear resistance can affect the hardness and density of a material; thus, when the material is more loaded, it can influence the durability and lifetime of the material [3]. The hardness of the paving block is associated with the Interfacial Transition Zone (ITZ), and the weakened interfacial transition zone between the DWTS and cement matrix could be associated with the bonding, which was a very loose and higher magnification of the sludge-cement interface [3].

Cost Benefit of Using DWTS

Utilization DWTS to replace fine aggregates significantly reduced the production cost. All costs of manufacturing paving blocks are expressed in detail along with the sources of the product life cycle phase, such as raw materials, utilities, personnel, and equipment costs [67]. Potential use of waste materials to produce low-cost construction materials [37]. Figure 5 represents a comparison of the cost and compressive strength.

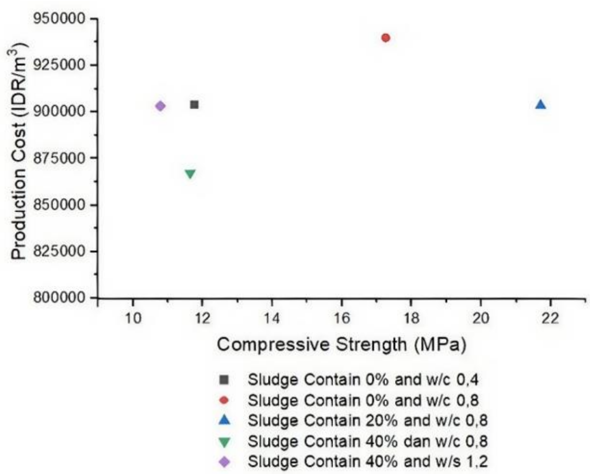

Figure 5. Production cost to compressive strength for each mixed the paving block specimens meet compliance with SNI 03-0691-1996.

A previous study found that replacement of aggregate 25–75% of aggregates with recycled aggregates reduced the production cost by 2.45–7.35% [68]. The obtained results indicated that DWTS could be used as an adequate replacement for sand aggregates that meet the optimum level in the paving block. The DWTS could also help increase production cost efficiency, thus significantly resulting in low-cost products.

Conclusions

The recycling optimization of the DWTS could effectively be used as a fine aggregate of the paving block with a replacement ratio of sand by DWTS 40% with w/c of 0.8 proved to be the optimal replacement value that qualified the quality requirements for park equipment, therefore 28 days compressive strength of 11.64 MPa, density of 1,866.27 kg/m^3, water absorption of 12.61%, and wear resistance of 0.077 mm/minute halves represent the condition of is the optimal treatment. The w/c ratio was adjusted with an increase in DWTS content to achieve cohesion between the DWTS and cement. Meanwhile, the mechanical performance and durability decreased, although the water absorption and wear resistance increased significantly below the quality requirement with an increase in the addition of DWTS by over 40%. The cost benefit of using DWTS could increase production cost efficiency by 7.73% equivalent to 72,697.82 IDR/m^3 paving block. DWTS has potential for recycling as a paving block, which achieve higher technical reliability and lower cost than conventional paving blocks.

Author Contributions

REP: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **AI:** Conceptualization, Methodology, Supervision; **HP:** Conceptualization, Methodology, Supervision, Writing - Review & Editing.

Conflicts of Interest

There are no conflicts to declare.

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