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Eco-Pave: Paving Blocks Originating from Construction Waste

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Abstract

Construction waste is a significant contributor to global solid waste, underscoring the need for effective sustainable management strategies. This study aims to assess the quality and environmental impact of paving blocks manufactured from two different sizes of recycled aggregates. Two categories, CA1 (12.5–4.75 mm) and CA2 (37.5–4.75 mm), were used as constituent materials. The paving blocks were assessed based on compressive strength, water absorption, and wear resistance. Experimental results indicate that paving blocks incorporating CA2 recycled aggregates performed better than those with CA1. The tested paving blocks meet grade D standards for garden paving (CA1) and grade C standards for pedestrian pathways (CA2). Additionally, utilizing recycled aggregates from concrete waste enables 48.1% rubble recycling and reduces carbon dioxide emissions by 64.7%, thereby contributing to sustainable waste management.

Keywords: construction waste, recycled aggregates, paving blocks, ecological impact

1. Introduction

Construction waste is a significant global issue, with construction and demolition (CDW) debris contributing substantially to total solid waste generation. In 2012, approximately 3 million tons of construction waste were produced across 40 countries [1]. According to Lopez-Ruiz et al. [2], CDW accounts for 30% to 40% of global solid waste. The rapid increase in waste generation is closely aligned with population growth and is expected to continue rising significantly in the future [3]. Southeast Asia has experienced significant population growth, reaching 650 million people in 2020, with more than half of the population residing in urban areas. In terms of the construction industry's value, the construction and demolition waste generation ratio in Southeast Asia ranks below that of China but surpasses other developed nations [4].

Construction and demolition waste (CDW) in Southeast Asia has received limited attention. Weak law enforcement, combined with a shortage of disposal sites, has led to the illegal dumping of CDW. Consequently, a significant portion of CDW is either disposed of in landfills or dumped illegally, resulting in land scarcity and environmental degradation. If left unaddressed, this issue will escalate, posing more significant risks such as pollution and ecosystem disruption [4-5]. Liu et al. [6] highlighted that waste management behavior plays a crucial role in determining the effectiveness of CDW handling. Therefore, adopting more sustainable waste management strategies is essential for improving recycling efficiency and minimizing environmental impact. Given that construction debris holds significant potential for reuse [7], implementing recycling efforts can significantly reduce construction waste while promoting sustainable development.

One method to repurpose this waste is by recycling building debris into aggregates, which may be used in concrete mixtures [8]. Zang et al. [9] conducted a study on recycled coarse aggregate from waste bricks in concrete mixtures. The recycled aggregate was used as 0%, 30%, 40%, and 50% by weight replacements of the natural aggregate. Their research found

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that recycled aggregates from waste bricks have high water absorption, which leads to a reduction in compressive strength. However, they also discovered that using up to 30% recycled coarse aggregate from waste bricks in concrete mixtures can still meet the required strength standards.

Conversely, Opara et al. [10] established that high-quality recycled coarse aggregate can substitute natural coarse aggregate in concrete production. A comparative analysis of experimental results of some properties of concrete produced with 100% recycled coarse aggregate and 100% natural coarse aggregate is presented in this paper. Recycled aggregate exhibited 7%–10% lower bulk density and 30%–40% lower compressive strength than natural aggregate. However, the 28-day recycled aggregate met the standards, making it suitable for non-structural applications such as pavements and lightly loaded structures.

The study conducted by Wang et al. [11] demonstrated that natural coarse aggregates can be replaced with recycled coarse aggregates for paving blocks. The recycled aggregate was used as 20%, 40%, 60%, 80%, and 100% by weight of the total coarse aggregate content. The results show that recycled aggregate for paving blocks can achieve up to 60% replacement, resulting in optimal compressive strength and water absorption that meet quality standards.

Various studies have demonstrated that recycled aggregates can be used in concrete production, often with different mixtures of recycled and natural aggregates. Although previous research has explored the use of recycled aggregates in concrete and paving blocks [9-11], there are still limitations in the research on how variations in recycled aggregate size affect the quality of paving blocks, including compressive strength, abrasion resistance, and water absorption. In addition, most previous research has primarily focused on the mechanical or technical aspects of paving blocks. However, evaluations of their environmental impact, such as construction waste reduction and CO_2 emissions through the Life Cycle Analysis (LCA) approach, remain limited. Therefore, this study aims to evaluate the mechanical performance of paving blocks that involve two variations of recycled aggregate sizes and assess their environmental impact based on waste reduction and the LCA approach.

2. Materials and Methods

This study focused on the use of recycled coarse aggregate obtained from rubble waste, manually crushed and sieved to the desired sizes. Determining the physical properties and size distribution of these materials is crucial for optimizing the mix design and ensuring the quality of the paving blocks produced. The information presented in this section forms the foundation for evaluating the mechanical performance and environmental impact of the paving blocks.

2.1. Material

The materials utilized in this experiment include PCC (Portland Composite Cement), recycled coarse aggregate, and fine aggregate. The recycled coarse aggregates were classified into two categories based on their particle size range: CA1 (12.5–4.75 mm) and CA2 (37.5–4.75 mm). All recycled coarse aggregates were derived from rubble waste collected from Jl. Gardu Dalam, Margajaya, West Bogor District, Bogor City, Indonesia. The rubble utilized for this investigation is depicted in Fig. 1. The recycled coarse aggregates were manually manufactured by hammer crushing and subsequently sieved to meet the specified size category. The physical parameters of these coarse aggregates are presented in Table 1, and their size distribution is shown in Fig. 2. The fine aggregate was sourced from Cimangkok, Sukabumi, Indonesia, with its physical parameters detailed in Table 2, and its size distribution is shown in Fig. 3.

Fig. 1 Unprocessed rubble waste

Table 1 Physical characteristics of recycled coarse aggregates

No	Parameter	CA1	CA2	Standard	
				Code	Value
1	Size range (mm)	12.5–4.75	37.5–4.75	-	-
2	Fineness modulus	6.05	5.01	SII.0052-80	6.0–7.1
3	Water content (%)	6.67	5.58	-	-
4	Mud content (%)	0.23	0.80	SII.0052-80	≤ 1
5	Apparent specific gravity	2.47	2.27	-	-
6	Water Absorption (%)	19.51	14.97	-	-

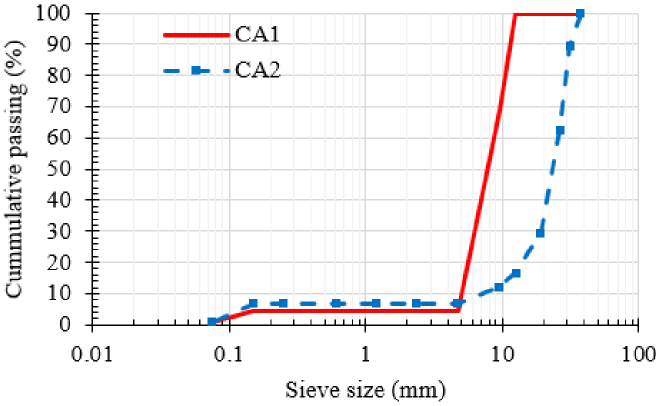

Fig. 2 Size distribution of recycled coarse aggregates

Table 2 Physical characteristics of fine aggregate

No	Parameter	Value	Standard	
			Code	Value
1	Size range (mm)	4.75–0.075	-	-
2	Fineness modulus	2.69	SII.0052-80	1.5–3.8
3	Water content (%)	11.13	-	-
4	Mud content (%)	7.12	SII.0052-80	≤ 5
5	Organic content (organic plate number)	2	SNI 2814:2014	≤ 3
6	Specific gravity	2.30	-	-
7	Water Absorption (%)	3.52	-	-

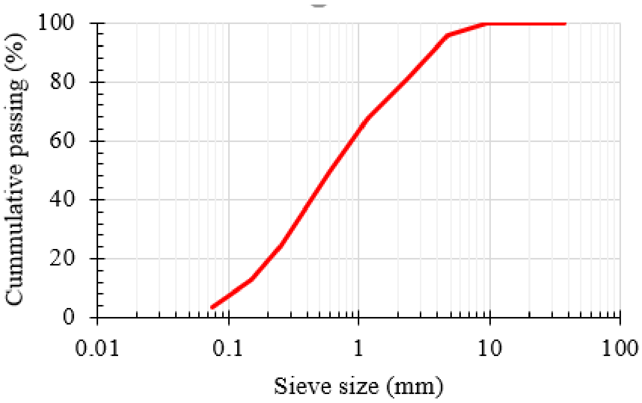

Fig. 3 Size distribution of fine aggregate

2.2. *Proportion of mixture*

The mix proportions in this experiment were obtained through trial and error, with the option of making adjustments based on observed results. The mix proportion was designed to assign recycled coarse aggregates as a complete replacement for natural virgin aggregates. The ideal combination of cement, fine aggregates, recycled coarse aggregates, and water was discovered through trial and error to be 1.1:2.2:0.6:0.2 by weight. The water content was decided to be roughly 20% of the cement weight. This ratio was intended for a single paving block measuring 20 cm × 10 cm × 8 cm and weighing around 4 kg. As a result, one unit of paving block requires 1.1 kg of cement, 2.2 kg of fine aggregates, 0.6 kg of recycled coarse aggregates, and 0.2 kg of water. This amount also ensures ideal workability when mixing and improves the aesthetic quality after mold removal. The iterative technique enables fine-tuning to meet both practical and performance objectives, making the blend appropriate for its intended application.

2.3. *Preparation of samples*

The fabrication of paving block test specimens adheres to Indonesian national standards, with dimensions of 20 cm, 10 cm, and 8 cm for each specimen. A total of 24 test specimens were produced, categorized into three segments for the evaluation of compressive strength, wear resistance, and water absorption. The process of employing concrete waste as coarse aggregates for paver block production commences with the collection of intact building concrete debris.

Fig. 4 Paving block samples

This study utilized two varieties of concrete waste aggregate, designated as CA1 and CA2, based on the treatment applied. Concrete waste for CA1 is crushed to a maximum size of less than one-fifth of the shortest dimension of the mold, with aggregate sizes ranging from 12.5 to 4.75 mm. Concrete waste for CA2 is crushed to a maximum size of less than half the shortest dimension of the mold, with aggregate sizes ranging from 37.5 to 4.75 mm. The subsequent labor process adheres to a mixed design produced using several molding techniques. Given the disparity in aggregate size, in CA1, the aggregate is promptly included in the blend of other components, subsequently placed into a mold, and compacted incrementally. In CA2, the aggregate is not combined with other mixtures; instead, it is incrementally introduced, initially occupying all voids in the mold, followed by gradual compaction until it is filled. The produced samples are depicted in Fig. 4.

2.4. Testing procedure

Paving blocks undergo a curing period of 28 days following the standards outlined in SNI 03-0691-1996. The curing process involves fully submerging the paving slabs in water. Upon completion of the curing period, to ascertain quality, tests for compressive strength, water absorption, and wear resistance are conducted on the paving blocks following the standard reference SNI 03-0691-1996 pertaining to concrete bricks (paving blocks). The quality of paving stones, depending on their physical attributes, is presented following SNI 03-0691-1996 in Table 3.

Table 3 Paving block grading standard [12]

Grade	Compressive strength (Mpa)		Weir resistance (mm/min)		Maximum water absorption (%)	Usage
	Average	Min.	Average	Min.		
A	40	35	0.09	0.103	3	Road
B	20	17	0.13	0.149	6	Parking place
C	15	12.5	0.16	0.184	8	Pedestrian pavement
D	10	8.5	0.219	0.251	10	Garden or park path

Compressive strength testing necessitates a test specimen measuring 8 cm × 8 cm × 8 cm in cubic form, according to the dimensions of the test sample. The compressive strength of the paver stone can be determined by:

$$\text{Compressive Strength} = \frac{P}{A} \tag{1}$$

where P is the maximum compressive load (N), and A is the cross-sectional area (mm^2).

Wear resistance testing necessitates a test specimen of 5 cm × 5 cm × 2 cm in a square configuration. The examination was performed under SNI 03-1974-1990, which cites SNI 03-0028-1987 for cement tile methodologies [12-13]. The wear resistance value of the paver block can be determined by:

$$\text{Wear Resistance} = \frac{\Delta g \times 10}{D \times A \times t} \tag{2}$$

where Δg is the mass loss (g), D is the density of the specimen, A is the wear cross-sectional area, and t is the wear time.

The water absorption test necessitates a fully immersed test specimen that has been saturated in water for roughly 24 hours. Subsequently, it is desiccated in the oven for approximately 24 hours. The water absorption value of the paver block can be determined by:

$$\text{Water Absorption} = \frac{(M - D)}{D} \times 100\% \tag{3}$$

where M is the saturated mass of the paving block, and D is the dry mass of the paving block.

Each test was conducted for both recycled coarse aggregate types, CA1 and CA2. Every kind of recycled coarse aggregate was provided with three samples for each test. The final results for all tests were then averaged from those three samples according to their type. The average value of each recycled coarse aggregate from all tests was then compared to one another and used to determine the grade of the paving block based on SNI 03-0691-1996. All of these test data are presented in Tables 4, 5, and 6.

Table 4 Compressive strength test data

No	Parameter	Value					
		CA1			CA2		
		1	2	3	1	2	3
1	Length (mm)	89.81	84.05	81.79	82.76	82.81	83.72
2	Width (mm)	87.07	81.24	81.62	81.67	81.01	81.17
3	Surface area (mm^2)	7819.76	6828.22	6674.06	6841.77	6708.44	6795.55
4	Maximum load (N)	107584.00	96955.02	30743.92	48518.16	160983.60	110072.00
5	Compressive strength (MPa)	13.71	14.15	4.59	7.07	23.91	16.14
Average compressive strength (MPa)		10.81			15.70		
Standard deviation		±5.40			±8.43		

Table 5 Wear resistance test data

No	Parameter	Value					
		CA1			CA2		
		1	2	3	1	2	3
1	Mass (g)	10.288	10.243	10.251	10.277	10.313	10.576
2	Volume (ml)	4.4	4.4	4.6	4.3	4.5	4.6
3	Density (g/ml)	2.34	2.33	2.23	2.39	2.29	2.3
4	Length (cm)	4.998	5.372	5.232	5.344	5.303	5.17
5	Width (cm)	4.911	5.042	5.066	5.265	5.143	5.163
6	Surface area (cm^2)	24.545	27.086	26.505	28.136	27.273	26.693
7	Mass before test (g)	93.07	101.36	90.33	95.38	93.2	88.54
8	Mass after test (g)	89.96	99.2	89.51	93.35	92.55	88.12
9	Mass loss (g)	3.11	2.16	0.82	2.03	0.65	0.42
10	Wear time (minutes)	5	5	5	5	5	5
11	Wear resistance (mm/minute)	0.1084	0.0685	0.0278	0.0604	0.0208	0.0137
Average wear resistance (mm/minute)		0.0682			0.0316		
Standard deviation		±0.0403			±0.0252		

Table 6 Water absorption test data

No	Parameter	Value					
		CA1			CA2		
		1	2	3	1	2	3
1	Saturated mass (g)	3550.50	3401.50	3226.50	3375.00	3325.00	3398.00
2	Dry mass (g)	3158.50	2951.50	2710.00	3017.50	2821.00	2963.00
3	Water absorption (%)	12.41	15.25	19.06	11.85	17.87	14.68
Average water absorption (%)		15.57			14.80		
Standard deviation		±3.34			±3.01		

3. Finding and Analysis

This section presents the results of an experiment evaluating the mechanical performance and ecological prospects of paving blocks made from recycled construction waste aggregates in two different particle size ranges. The analysis encompasses compressive strength, wear resistance, water absorption, and sustainability performance, with particular emphasis on the percentage reduction of construction waste and an estimation of Carbon Dioxide (CO_2) emissions using Life Cycle Assessment (LCA) to assess environmental impacts.

3.1. Compressive strength

According to Fig. 5, in the CA1 sample, the maximum compressive strength attained was 14.15 MPa, the minimum was 4.59 MPa, and the average compressive strength over the three samples was 10.81±5.40 MPa. In the CA2 sample, the maximum compressive strength recorded was 23.91 MPa, the minimum was 7.07 MPa, and the mean compressive strength of the three samples was 15.70±8.43 MPa. According to SNI 03-0691-1996 [12], the average compressive strength of the CA1 sample categorizes it as a Class D paving block, whereas the CA2 sample is classified as a Class C paving block.

A notable disparity exists between the two samples, possibly attributable to the human fabrication of the test specimens without the aid of a press machine, leading to inconsistencies in density and aggregate dispersion [14]. The aggregate size has a significant influence on compressive strength [15]. Concrete using larger aggregates features more substantial and organized pores, which diminishes structural weaknesses and hence enhances the overall compressive strength of the material [16]. The findings of Liu et al. [17] and Wang et al. [18] align with the compressive strength of paving stones derived from the CA2 sample. When the ratio of recycled coarse aggregates in the recycled aggregates is significantly elevated, the cement mortar produced in the concrete is inadequate to encapsulate the interstices between the aggregate surfaces and the particles that occupy those voids [19]. Consequently, the compressive strength of the paving block can be enhanced by integrating the proportion of recycled aggregates with virgin aggregates [18].

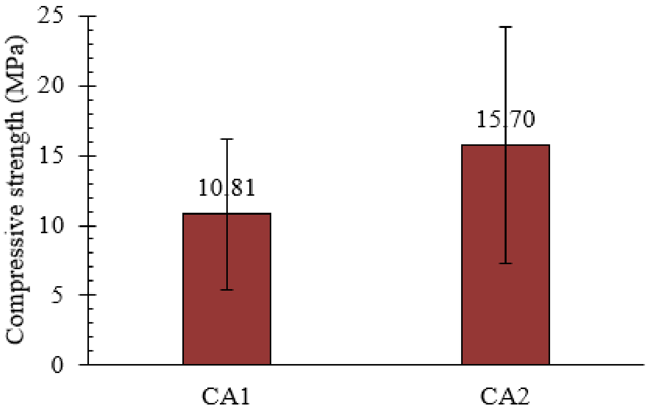

Fig. 5 Results of the compressive test

3.2. Wear resistance

Wear resistance is contingent upon the surface layer of the test specimen, with its level of wear resistance being ascertained by the magnitude of the wear mark on the specimen’s surface resulting from friction. Consequently, the deeper the wear mark on the specimen, the greater the volume of material extracted from the surface. As illustrated in Fig. 6, the CA1 sample exhibited the highest wear resistance value of 0.0682±0.0403 mm/min, whereas the CA2 sample demonstrated a wear resistance value of 0.0316±0.0252 mm/min. Gökalp and Uz [20] assert that a broader variation of aggregate particle sizes often diminishes fragmentation resistance. Moreover, wear resistance is affected by aggregate gradation. As demonstrated in Fig. 2, the aggregate gradation for CA1 exhibits a continuous gradation, while the aggregate gradation for CA2 displays a gap gradient. The diminished abrasion resistance of the CA2 sample is due to its adequate compaction between the paste and aggregates, yielding a surface with minimum voids and dense packing, hence enhancing its resistance to friction-induced wear.

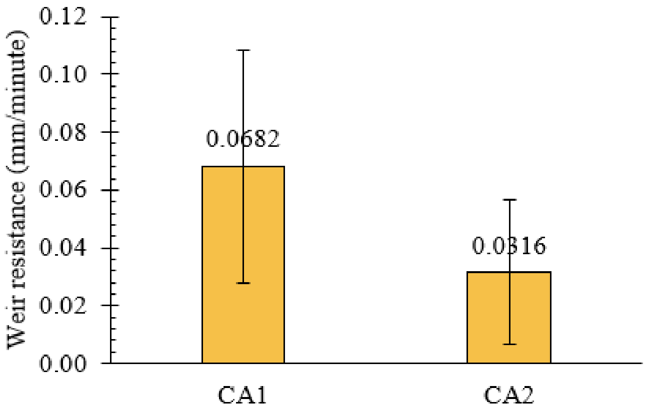

Fig. 6 Results of the wear resistance test

3.3. *Water absorption*

Water absorption is a metric that evaluates a paving block's capacity to absorb water, influencing its strength, wear resistance, and longevity. The testing findings indicate that the water absorption value for the CA2 sample was 14.80±3.01%, and the CA1 sample exhibited a value of 15.57±3.34%, as illustrated in Fig. 7. The absorption of water in concrete is associated with the pore structure within the cured concrete. Furthermore, this study utilized recycled concrete waste material as the aggregate, which markedly affects the water absorption capacity of the paving block. Increased porosity of the paving block correlates with reduced density and elevated water absorption [21]. The values obtained for water absorption in paving blocks do not conform to the SNI 03-0691-1996 standard range of 3–10% [12]. In order to reduce the porosity of the paving block, fine aggregates can be added to the mixture. Moreover, applying methods such as accelerated carbonation and nano-silica (mineral slurry) coating can further reduce the porosity of the paving block [22]. Owing to their elevated water absorption rates, these paving blocks are advised for application in garden areas that remain unsaturated.

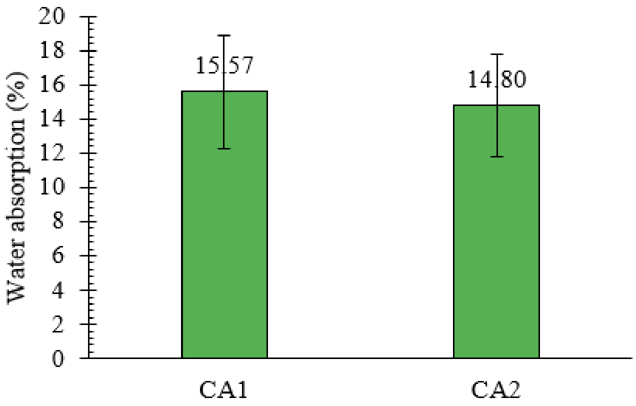

Fig. 7 Results of the water absorption test

3.4. *Ecological outlook*

This study gathered 16.777 kg of construction demolition waste, which was physically crushed for size modification. The cumulative weight of recycled aggregates utilized for 14 samples sieved to meet size specifications (12.5–4.75 mm for CA1 and 37.5–4.75 mm for CA2) was 8.064 kg. Consequently, this study successfully recycled approximately 48.1% of the gathered construction and demolition waste. Globally, approximately 0.509 Gt of concrete and mortar trash is processed in demolition management, while 0.499 Gt is disposed of as buried demolition waste [23]. This data reveals that merely 0.01 Gt, or around 2%, of concrete and mortar debris is being salvaged from construction waste disposal. Based on this research conclusion, it can be inferred that approximately 0.245 Gt of concrete and mortar waste may be recovered from the construction waste disposal site.

This study also considers the estimation of Carbon Dioxide (CO_2) emissions associated with the use of CA1, CA2, and virgin aggregates (VA) in the manufacturing of paving blocks through a life cycle analysis methodology. The functional unit employed in the life cycle study is 1 m^2 of pavement utilizing 0.21, 0.10, and 0.08 m paving blocks with a 2 mm interstice between the blocks. This functional unit necessitates around 45 blocks, which demand 25.92 kg of aggregates. The evaluated phase is from cradle to site. Table 7 illustrates the life cycle of each aggregate type.

Table 7 Life cycle of each aggregate type

No	Stage of life		
	CA1	CA2	VA
1	Construction demolition In the local area	Construction demolition In the local area	Quarry
2	Transportation to aggregates size processing site	Transportation to aggregates size processing site	Transportation to processing plant
3	Aggregates size processing	Aggregates size processing	Processing plant (size adjustment process)
4	Transportation to the paving block production site	Transportation to the paving block production site	Transportation to paving the block production site
5	Production of paving blocks (manual)	Production of paving blocks (manual)	Production of paving blocks (manual)

This study is based on numerous assumptions to provide clarity and boundaries. The assumptions are as follows:

(1) The paving block manufacturing facility is situated at IPB University in Bogor Regency, West Java, Indonesia.

(2) The demolition site is located 20 kilometers from the production facility, and demolition is conducted using a semi-mechanical method with light machinery, specifically a jackhammer (input power: 1500 W) in reference to Indonesian Minister of Public Works and Housing Regulation Number 28/PRT/M/2016 [24].

(3) The source of virgin aggregates is situated in Rumpin, Bogor Regency, West Java, Indonesia, approximately 20 kilometers from the production location.

(4) The recycled aggregates processing site and the aggregates plant processing site are presumed to be situated equidistantly between the aggregates source and the production site, referring to the LCA study of Rahman et al. [25].

(5) The processing of virgin aggregate size is performed using conventional methods or technology [26], whereas the processing of recycled aggregate size is conducted using a jaw crusher (input power: 5500 W; output size: 10–40 mm; capacity: 1–5 metric tons per hour).

(6) The vehicle utilized for aggregate transportation is a standard dump truck with a load capacity of 10 m^3 and a diesel fuel consumption rate of 6 km/L.

(7) Only the influence of aggregates is considered in this research. It is thought that other components, like cement, sand, and water, exert a uniform influence across all aggregate types and can therefore be disregarded.

(8) The computation of manual force for all aggregate types and electricity consumption for CA1 and CA2 adheres to SNI 7269:2009 [27] and Indonesian Minister of Public Works and Housing Regulation Number 28/PRT/M/2016 [24], whereas the electricity consumption calculation for VA relies on data published by Gursel and Ostertag [26].

(9) The computation of CO_2 emissions relies on electricity and fuel usage, utilizing a CO_2 emission factor of 890 g/kWh for electricity and 2.61 kg/L for diesel [28-29].

Table 8 Life cycle analysis result of each aggregate type

Item	Value per functional unit			Optimal choice
	CA1	CA2	VA	
Life phase	5	5	5	CA1, CA2, VA
Manual force (kcal/hour)	1528	1528	1051	VA
Electricity (kWh)	0.318	0.318	0.933	CA1 and CA2
Fuel (L)	0.005	0.005	0.003	VA
CO_2 emission (g CO_2)	296.144	295.944	838.891	CA2

Table 8 indicates that, overall, CA2 and VA exhibit the most optimal performance, each being identified as the superior choice three times. Although CA2 and VA (along with CA1) are the optimal choices regarding the life phase, CA2 surpassed VA in electricity consumption and CO_2 emissions, while VA exceeded CA2 in manual force and fuel consumption. CA2 and CA1 exhibit identical electricity consumption values and display minimal variation in CO_2 emissions. Significant value discrepancies exist between CA2 and VA, indicating that one surpassed the other in specific ways. In terms of manual force, VA surpassed CA1 and CA2 by decreasing manual force requirements by 40.9%. In terms of electricity consumption, CA2, together with CA1, surpassed VA by decreasing electricity demand by 66.0%. The disparity in fuel usage between CA1 and CA2 with VA is 36.8% due to the low density of CA1 and CA2, which requires a greater volume to comply with the required aggregate weight. In terms of CO_2 emissions, CA2 surpassed VA, achieving a 64.7% reduction in emissions. These findings indicate that CA2 far surpassed VA in terms of environmental impact by decreasing electricity use and CO_2 emissions.

4. Conclusions

This study has successfully utilized construction waste in the form of rubble waste as a substitute for coarse aggregate in paving blocks called eco-pave. Two types of recycled aggregates, CA1 (12.5–4.75 mm) and CA2 (37.5–4.75 mm), were used. Performance was evaluated through compressive strength, wear resistance, and water absorption tests, referring to SNI 03-0691-1996. The environmental impacts were assessed by estimating construction waste and applying Life Cycle Assessment (LCA) for the cradle-to-site phase, which covers manual labor, electricity, fuel, and Carbon Dioxide (CO_2) emissions. The following conclusions can be drawn from the presented study:

(1) The average compressive strength was 10.81±5.40 MPa for CA1 and 15.70±8.43 for CA2. Based on SNI 03-0691-1996, CA1 falls under Class D, while CA2 qualifies as Class C paving blocks.

(2) The CA2 sample showed better wear resistance than CA1, with a lower wear rate of 0.0316±0.0252 mm/min versus 0.0682±0.0403 mm/min. Both samples met the required standard.

(3) Both samples showed high water absorption, with CA2 at 14.80±3.01% and CA1 at 15.57±3.34%, exceeding standard limits.

(4) Based on the waste reduction, incorporating recycled aggregate as a coarse aggregate substitute in paving block production can recycle roughly 48.1% of the gathered construction and demolition waste.

(5) Based on the LCA approach, paving blocks made from recycled concrete waste, especially CA2, are estimated to reduce CO_2 emissions by up to 64.7% compared to VA, while also consuming less electricity, making them more environmentally friendly options.

Paving blocks made with recycled aggregates from CA2 demonstrated better performance compared to those made with recycled aggregates from CA1. CA1 met the standard for garden paths, while CA2 met the standard for pedestrian pavement, except in areas prone to prolonged water submersion. In addition, recycling rubble waste has been proven to reduce the amount of construction waste and provide an efficient alternative to non-structural materials, such as paving blocks, contributing to waste management and minimizing environmental impacts. Future improvement may include blending virgin and recycled aggregates, adding fine aggregates, or applying methods such as accelerated carbonation and nano-silica (mineral slurry) coating to enhance mechanical performance.

Conflicts of Interest

The authors declare no conflict of interest.

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