

*This study focuses on paving block composites using fine aggregate from brick construction and demolition waste (CDW). The study addresses two issues that contribute to excessive resource extraction, environmental degradation, and rising material costs in urban construction: the steadily increasing production of brick CDW and the growing reliance on natural sand in the production of paving blocks. The accumulation of brick CDW in landfills and uncontrolled disposal further emphasizes the need for technically and economically feasible alternative material solutions. The results demonstrate that recycled brick CDW aggregates can be seamlessly incorporated into cement-based paving composites due to their complementary mineral compositions. Mechanical testing confirms that paving blocks made from recycled CDW have a noticeably higher compressive strength than natural sand. This performance improvement is caused by the rough surface and angular particle shape of brick CDW. These elements enhance the cement matrix's and aggregate's mechanical interlocking, creating a stronger composite structure. Furthermore, comparative analysis demonstrates that paving blocks manufactured with recycled brick CDW can achieve up to two times higher compressive strength while reducing production costs by about 50% when compared to conventional combinations. These findings suggest that recycled brick aggregates outperform natural sand in terms of cost and structural soundness. These findings suggest that recycled brick aggregates outperform natural sand in terms of cost and structural soundness. The study's findings can be used to support more resource-efficient and environmentally friendly building techniques, particularly in urban areas where brick demolition waste is easily accessible*

**Keywords:** brick waste, circular economics, paving block, substance aggregate, sustainable construction

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# IDENTIFICATION OF MECHANICAL AND TECHNO-ECONOMIC IMPACTS OF RECYCLED BRICK DEMOLITION WASTE IN PAVING BLOCK PRODUCTION

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## 1. Introduction

Building demolitions will be common in emerging nations and areas, which will cause the output of construction and demolition waste (CDW) to rise quickly. In addition to these issues, the demand for natural materials will keep increasing, leading to widespread material resource exploitation that will harm the current ecosystem and create nature imbalance. 80% of the carbon emissions come from the usage of cement in construction project, which motivates academics to investigate and solve environmental issues, global warming, fuel oil use, and human-caused toxicity to a life cycle assessment (LCA) construction material production using CDW reuse [1, 2].

According to earlier research on the use of recycled concrete aggregates (RCA) and plastic waste as a sand substitute, waste-derived aggregates can greatly enhance physical characteristics while also lowering material procurement costs when compared to natural sand, resulting in a circular material flow while preserving mechanical strength [3, 4]. Despite these remedies, there is still little research on the re-

purposing of demolition debris from building masonry walls, a common component of construction and demolition trash in Asia. The mechanical behavior, microstructural features, technical viability, and economic research as a substitute for traditional sand are questions that still need to be addressed on a global scale.

Despite the fact that fired clay bricks have qualities like high porosity, a rough surface texture, and a silica metal composition that make them a robust material for reuse, there has not been enough thorough research to draw global conclusions that directly compare them with natural sand materials in the production of paving blocks. The issue of the depletion of natural resources, including river sand, which is still being exploited, followed by more stringent laws mandating the management of construction and demolition waste (CDW), which will eventually be transformed into eco-friendly methods.

One of the current issues is the focus on circular economy concepts as a framework for recycling construction activities from CDW. One important area of research is the CDW valorization as a substitute for natural materials. This finding

lends credence to the idea that CDW is not just a disposal issue but also a potential resource stream that might close construction material loops. In addition to offering a workable solution for urban areas with extremely high demolition rates, research on the effects of repurposing demolition waste particularly brick walls as paving block construction materials can also help the construction industry become more resource-efficient and sustainable. Therefore, research on the development of so-and-so is relevant.

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## 2. Literature review and problem statement

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The [5] study show that CDW and recycle aggregate indicates have chemical composition and behaviors that cause environmental risk such as calcium, sulfates, alkalis, and trace metals under specific exposure condition. The study confirms that treatment and reuse processing can reduce the contaminant and keeping the environmental balance. But still have unsolved questions related to the scalability, economic feasibility, and applicability this treatment and reuse methods, especially in urban environments. The reasons for this can be objective difficulties connected to the variability of CDW composition is depend on the characterization of building as well as the principal impossibility of applying uniform treatment procedure to all waste, which makes the research outcome difficult to transfer into routine municipal waste management systems. An option to overcome the relevant difficulties can be the development of material assessment in physical and chemical for safety for reuse pathways. This study has detailed the CDW chemical hazard and environmental risk, but this study does not fully address how such analytical framework reuse and urban-scale waste management planning. All this allows to argue that it is appropriate to conduct a study devoted to linking physical and chemical behavior of brick CDW with practical reuse as substitute material for environmental safety.

The research [6] shows that reuse brick aggregates (RBW) can effectively replace natural fine aggregate in concrete paving blocks, significantly improving strength and abrasive resistance while reducing structural cost. However, the insufficiently resolved questions relate to the wider application of this method outside of controlled laboratory settings, especially in terms of long-term durability, environmental safety, and performance variability when RBW comes from various industrial or demolition sources. The reasons for this can be the heterogeneity of brick CDW in physical and chemical characteristic as well as the principal impossibility of directly extrapolation the laboratory scale to large scale urban reuse systems. An option to overcome the relevant difficulties can be the combination of streamlined processing paths and application with material-specific characterization-oriented performance standards specific to the local waste stream. The approaches used in is detailed mechanical testing, microstructural analysis and cost evaluating to RBW reuse, but, the study does not address long-term exposure of recycled materials. All this allows to argue that in order to promote sustainable and context-adapted building techniques, it is appropriate to carry out a study focused on assessing recycled brick-based construction and demolition.

The study [7] shows that plastic waste, particularly polyethylene terephthalate (PET) can be combined with manufactured sand (M-sand) to produce paving blocks. This substitute material can improve the strength and material

accepted gradation and homogeneity with the optimum plastic-sand ratio is 1:4. But the long-term durability and large-scale applicability of this material is still a resolved question. The reason for this gap is like others research is the heterogeneity of CDW fragments makes the corresponding research outcomes less expedient for low-resource or decentralized construction contexts. An option to overcome the relevant difficulties can be the integration of plastic-based composites with simplified processing routes. Mechanical testing and microstructural analysis are employed to justify material feasibility; However, the study does not compare plastic-sand systems with alternative waste-derived aggregates from building and demolition debris, nor does it completely consider environmental risk pathways.

The [8] review shows that concrete paving blocks can effectively use a variety of waste materials and industrial by-products as partial substitutes for cement or natural aggregates, including recycled plastics, crumb rubber, steel slag, fly ash, eco-processed pozzolan, waste glass, marble waste, and volcanic ash. The review shows that several of these materials can exceed the compressive strength criteria for pedestrian and light-traffic applications while also lowering the use of natural resources and the disposal of solid waste when the right mix proportions and processing techniques are used. An option to overcome the relevant difficulties can be the targeted study of a widely available waste material utilizing a standardized experimental framework that concurrently assesses material properties, mechanical behavior, and practical applicability. The study does not offer experimental validation or comparative performance analysis for a single waste stream under controlled settings; instead, it is descriptive in nature.

The research [9] considers that closing material loops in CDW sector through selective demolition, resource mapping, and local market creation can significantly improve reuse rates, reduce CO<sub>2</sub> emissions, and create economically business plan. The study shows how localized circular economy methods and well-coordinated stakeholder networks can improve material recirculation in construction value chains. But the transferability and scalability of these circular practices beyond geographically constrained contexts still the insufficiently resolved questions. The reason of this gap is that in areas with weak economic incentives and regulatory support, the plan's expensive components such as selective demolition procedures, additional labor, documentation requirements, and market development for secondary materials may restrict adoption, making the corresponding research findings less practical for broad implementation. An option to overcome the relevant difficulties can be the integration of application-specific reuse paths, material-level characterization, and circular economy planning. Although market research and selective demolition are used to show viability, the study does not specifically evaluate the performance of recycled CDW materials in new building applications.

The paper [10] shows that recycling CDW provides an environmental advantage over landfilling in all significant effect areas, especially when it comes to the potential for global warming, primary energy use, and land occupation. The study shows that recycling one ton of CDW can prevent up to 6.41 kg CO<sub>2</sub>-eq emissions and save roughly 90 MJ of primary energy using a life cycle assessment (LCA) framework applied to various management scenarios in an Indian metropolitan context. The important questions, however, are how these system-level environmental benefits transfer into

material-level performance, application-specific appropriateness, and long-term sustainability of recovered C&D trash when reused in construction products. The costly part of the plan, such as the development of transfer stations, logistics networks, and recycling infrastructure may restrict practical implementation in many areas, making the associated research findings insufficient to inform choices on recycled material reuse paths. All this allows to argue that it is appropriate to conduct a study devoted to facilitating well-informed and implementation-focused decisions in sustainable construction practice by connecting the environmental advantages of recycling construction and demolition waste with the technical viability and material performance of recycled aggregates in construction applications.

The study [11] through reuse, recycling, and selective deconstruction, it demonstrates how the implementation of the circular economy (CE) in the CDW sector has substantial potential to lessen reliance on landfills, save natural resources, and enhance environmental performance. However, the retractile addressed issues pertaining to a life-cycle oriented framework that methodically connects operational procedures, policy instruments, and life-cycle material substances. The reasons of it can be objective difficulties connected to addressing challenges related to the construction industry's fragmentation, the variety of CDW materials, regional regulations, and the lack of standardized quality standards and secondary building material market systems. Furthermore, extensive CE adoption is frequently unfeasible in real-world construction projects due to economic uncertainties, high initial costs of selective demolition, and logistical limitations in collection and transfer. An option to overcome the relevant difficulties can be the creation of a comprehensive and organized model that incorporates CE strategies at every stage of the lifecycle while specifically taking technical, financial, and regulatory connections into account. This is the approach used in this study is the selection of CE tactics at various CDW lifecycle stages, however the paradigm is still primarily conceptual and lacks quantitative evaluation of strategy interactions under real-world limitations as well as empirical validation. All this allows to argue that it is appropriate to carry out a study focused on developing and operationalizing integrated CE models for CDW management, with an emphasis on closing the gap between theoretical frameworks and their successful application in construction practice.

In addition to the depletion of natural resources, particularly river sand, and the lack of a thorough techno-economic assessment of the recycling of wall demolition waste into sand, increased development in a region will also increase the volume of construction and demolition waste (CDW), particularly brick walls, which will impact the ecological balance. Therefore, more research is required. By addressing these outstanding problems and obstacles, funding for research on brick wall demolition debris that can operate both mechanically and economically will be strengthened, enabling the practical and lucrative use of this alternative on a broad scale.

The lack of an integrated mechanical and techno-economic evaluation of recovered brick wall demolition waste when utilized as fine aggregate in paving block manufacture is still a glaring unresolved issue despite a great deal of study on the recycling of building and demolition waste. Without explicitly connecting material behavior, strength performance, and manufacturing cost feasibility in a cohesive

framework, current research either examines mechanical performance under controlled laboratory circumstances or concentrates on environmental consequences at the system level. The relevance of earlier findings to actual construction practice is particularly limited by the lack of comparative data between recycled brick aggregates and natural sand under identical mix proportions and realistic manufacturing settings. Thus, it is necessary to conduct a targeted study that concurrently assesses the mechanical performance and techno-economic viability of paving blocks made from recycled brick demolition waste.

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### 3. The aim and objectives of the study

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This study aims to assess the techno-economic possibilities of recycling brick-based construction and demolition waste (CDW) into inorganic composite materials for the manufacturing of paving blocks.

To achieve this aim, the following objectives were accomplished:

- to compare the mechanical performance of paving blocks made using recycled brick aggregate with those made with natural sand;
- to evaluate production costs, cost savings, and resource efficiency under realistic production conditions in order to determine the techno-economic viability of recycled brick waste utilization.

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### 4. Material and methods

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#### 4.1. The object and hypothesis of the study

The object from this study is construction and demolition waste (CDW) refers only to brick wall demolition waste from building restorations or demolished buildings, which is the most prevalent sort of waste in Asia's emerging nations. Brick CDW microstructure will be excellent by knowing how the waste is recycled as an inorganic substitute fine aggregate that interacts with cement. Therefore, this study has hypothesis that, in comparison to natural fine aggregate, fine aggregate made from recycled brick wall construction and demolition debris has physical and mineralogical properties that affect the mechanical performance and structure formation of paving block composites.

For this study, the following presumptions have been made:

1. The application of the utilized brick demolition waste in this study is representative of fired clay masonry waste generated from urban demolition activities in Malang, Indonesia.
2. The physical and mineral properties of the recycled brick aggregate will remain consistent after crashing and sifting.
3. The curing processes usually applied to small- to medium-scale paver block production are representative of those applied under standard conditions of laboratory curing.
4. For assessing structural properties of paving blocks under normal conditions of service, the compressive strength test is considered a reliable first indicator.
5. For estimating production cost, market prices are assumed to remain steady throughout the period under investigation.

Simplifications were made to ensure the viability and focus of the experiment:

1. Durability tests like abrasion resistance, freeze-thaw cycles, and long-term exposure to weather are not conducted; instead, compressive strength test results are primarily used to evaluate the material's performance.

2. Without direct microscopic observation like SEM, the interactions of recycled brick aggregates with cement are deduced based on the macroscopic observation of the shapes of the particles.

3. In the techno-economic evaluation, a complete life cycle assessment of environmental effects was not conducted; instead, direct production costs are considered.

4. Only one source was used for the experiment, and the difference in the percentage of demolition wastes coming from various sources was not investigated.

5. Long-term shrinkage and water absorption were not thoroughly investigated.

Experimental analysis of compressive strength and techno-economic performance is used to assess the validity of this theory.

In addition to fine aggregate, a crucial component of sustainable paving manufacturing is the binder, specifically cement. Higher performance and cost efficiency can be attained by minimizing discrepancies and optimizing the mixture. Portland composite cement (PCC), as shown in Fig. 1, *a*. As the binder, PCC that complied with SNI 7064:2014 was utilized. While recycled fine aggregate was made from brick wall construction and demolition waste (CDW), natural river sand served as the reference fine aggregate. The brick CDW came from masonry buildings that had been demolished in Malang City, Indonesia. After manually sorting the collected garbage to eliminate contaminants, it was crushed and sieved to produce fine aggregate fractions that passed through a 4.75 mm sieve.



Fig. 1. Paving block materials: *a* – binder; *b* – waste aggregate; *c* – natural aggregate

Fine aggregate produced by grinding brick wall CDW, as seen in Fig. 1, *b*, can be used in laboratory based as an inorganic substitute for natural sand as a paving block composite material. However, because of this alternative material's high absorption and porosity, the mixing proportions need to be precisely calculated.

As seen in Fig. 1, *c*, natural sand (ordinary fine aggregate) from alluvial deposits is frequently utilized as fine material for traditional paving blocks. This sand has a medium to fine grain texture, a water absorption of 1.5–3.0%, a fineness modulus of 1.8–2.4, and a specific gravity of 2.55–2.65. Because river sand is made up of pieces of clayey sedimentary rocks that have been eroded by rivers, its mineral makeup is quartz and feldspar with trace amounts of iron oxide and clay. To prevent mud from affecting the performance of the

cement-sand paving blocks, the 3–7% clay content of this sand must be removed during the mixing process.

**4. 2. Experimental equipment and test methods**

The recycled brick wall waste aggregate utilized in this study has an outer particle size and is retained on sieves ranging from 20 to 100. To ascertain whether the aggregate has physical properties comparable to those of natural materials, it will also be evaluated for specific gravity. This test is based on the SNI use, as shown in Fig. 2. Brick wall CDW aggregate has a porous microstructure that lets the material absorb between 10% and 20% of its water, according to scanning electron microscopy (SEM). Because the physical characteristics will differ from those of natural aggregates, researchers and practitioners must double-check the water content in their mix design because the pore number will impact the absorption of aggregates when mixing aggregates with binders or cement.



Fig. 2. Waste material's specific gravity testing

In addition to being porous, brick demolition waste also contains fine silt, which has an impact on the water content needs. The presence of Si-Al-Ca verifies compatibility with the cement system. Waste that has a lot of calcium will make the composite matrix more reactive, even though it can alter the pH of the soil if it is disposed of untreated. Fig. 3 illustrates the mixing procedure for reuse of brick CDW into paving blocks. The process takes five minutes to fully hydrate the cement and bind every aggregate particle.



Fig. 3. Waste reuse procedure: *a* – collect raw waste; *b* – recycling fine aggregate; *c* – binder material; *d* – paving block mixing; *e* – paving block; *f* – universal testing machine

The new composite material is swiftly put into paving block molds after five minutes of mixing. Large-scale machinery or traditional techniques can be used for paving block molding. To reduce big voids and enable the paving block mold until reach the ideal density, all techniques use synchronous mechanical vibration. The blocks must be carefully taken out of the mold and let to cure at room temperature after the paving block mixture has solidified.

A calibrated compression testing machine with a maximum capacity of 2000 kN was used to conduct compressive strength tests in accordance with applicable paving block testing criteria. The load was applied gradually until the specimen failed. With an accuracy of ±0.01 g, the specimens' mass was measured using a digital balance. Sieve analysis was performed using a conventional mechanical sieve shaker and certified sieves with sizes ranging from 4.75 mm to 0.075 mm. The compressive strength equipment as seen as Fig. 4 is using universal testing machine (UTM) for the loading test and data logger for reading the UTM result.



Fig. 4. Compressive strength testing equipment: a – universal testing machine; b – data logger

Fig. 4 illustrates the universal testing machine (UTM) utilized in this investigation, which was utilized to guarantee accurate and consistent compressive strength data. The apparatus was used in a controlled laboratory setting, and an inbuilt data logger continually recorded the applied force during testing, allowing for digital load application monitoring. To reduce measurement uncertainty before testing, the UTM was calibrated in accordance with the manufacturer's instructions. Operator-dependent error was decreased and failure loads were accurately determined with the installation of a digital load display and data logging system. This experimental design guaranteed uniformity across all specimens and offered a reliable foundation for evaluating the mechanical performance of paving blocks made from natural sand aggregates and recycled brick demolition waste.

**4. 3. Experimental procedure and error estimation**

Portland cement composite (PCC) and sand are the two primary components of this material; in this study, the sand was contrasted with traditional paving block sand. To maintain a steady cement concentration, this study employed four different types of proportions for the sand-cement mix design, ranging from high to low binder compositions that are frequently utilized in building practice. Paving block

specimens were produced using four cement-to-aggregate ratios (1:1, 1:2, 1:3, and 1:4). Dry materials were mixed first, followed by the gradual addition of water until a zero-slump consistency was achieved. The mixtures were placed into steel molds and compacted using a vibration-compression method. After demolding, specimens were cured under laboratory conditions prior to mechanical testing. The specimen codes and associated criteria are listed in Table 1.

Table 1

Mix design composition for paving block

Mix ID	Cement: sand	Description
M-1	1part:1part	High-cement mix; reference for maximum strength evaluation for medium-high traffic load paving road
M-2	1part:2parts	Medium binder content; balanced mechanical performance for medium traffic load paving road
M-3	1part:3parts	Economical mix; reduced cement usage with acceptable strength range for low traffic load paving road like bicycle
M-4	1part:4parts	Low binder content: for human live load like garden and used to evaluate minimum feasible cement proportion

To attain quality and consistency, the conventional paving block mixing procedure is employed. In this work, a water-to-cement ratio of 0.6 was employed, with water introduced gradually and without degradation. As is typical in traditional pavement production, this mixture will be stiff, giving the paving blocks high density and dimensional stability. For every mix percentage, three specimens were evaluated for compressive strength, and the average result was provided. Measurement uncertainty was calculated using the equipment's accuracy and repeatability. To reduce experimental errors, all specimens were maintained at the identical loading rates and curing conditions.

**4. 4. Techno-economic assessment method**

The techno-economic analysis method for the process of reusing brick wall demolition waste into paving blocks begins by calculating all costs, from waste collection to paving block molding.

The following is a description of the techno-economic analysis process in this study:

- a) the price of cement is determined by the current market rates per kilogram;
- b) the price of natural sand is an example of the conventional cost of fine aggregate;
- c) the cost of recycling from brick demolition, including material preparation, screening, and crushing;
- d) labor expenses for the processes of mixing, molding, and curing;
- e) energy expenditure related to the operation of machines during compaction and crushing;
- f) the cost of transportation, which takes into consideration the transportation of raw materials from their source locations to the production site;
- g) the combination of these components represents the total cost of producing paving blocks using recycled and natural aggregates.

The following is a comparative analysis of the technical and economic uses of the two materials:

- a) cost per unit, measured in square meters of finished paving blocks (IDR/block);
- b) cost savings (%), which is the percentage reduction in production costs when recycled brick waste is used instead of natural sand;
- c) resource efficiency, which represents the financial and environmental benefits of using recycled aggregates, is calculated as the percentage reduction in natural sand use.

The economic feasibility of this study is based on a direct comparison of performance with consistent live applications. This value is based on:

- a) energy, cement, and natural sand were used based on local market prices in the area;
- b) production capacity is expected to be consistent with small-scale paving block manufacturing conditions, where molding, drying, and mixing are performed by hand or with light mechanical equipment;
- c) to avoid performance bias between recycled aggregate and natural sand combinations, technical limitations and assumptions include fixed mix proportions for all cost comparisons, comparable drying conditions, and equivalent specimen sizes;
- d) these boundary conditions define the economic environment of the analysis and ensure that the comparison accurately reflects typical production conditions in Asia.

**5. Results from a study on recycled brick demolition waste aggregates for techno-economic paving blocks**

**5.1. Mechanical performance of paving block composites made from recycled brick demolition waste**

The inorganic substitution material test from the recycled brick wall demolition and construction waste initially revealed the results of the physical test of the material, namely the specific gravity. The particle density of the recycled aggregate will be exposed by the graffiti, which will affect the mechanical performance of the paving block. The physical properties of the aggregate affect the amount of the mixture that determines the quality of the paving block. Burned clay brick pieces often have lower specific gravity aggregates, which show increased porosity and decreased particle strength.

The specific gravity test results for aggregates made from recycled brick wall CDW are displayed in Table 2. The data shows that the specific gravity values vary from 2.55 to 2.79, suggesting that the specific gravity of waste aggregates is like that of natural sand, which ranges from 2.6 to 2.7. These findings also show that the specific gravity of the substitute aggregate provides a lower average value, even though it is not significantly different from the properties of natural sand. This is because the bricks are made of fired clay, which produces internal pores in the microstructure area. Additionally, the ceramic mortar residue on the brick wall also has an impact on lowering the specific gravity of the substitute material. Nevertheless, paving blocks can still be made using the alternative aggregate as a composite.

Compression testing, a crucial measure of the mechanical performance and durability of paving blocks, can be used to directly assess the quality of the interaction between aggregate and binder or cement in the composite matrix. Brick wall CDW fragments have a porous microstructure and a superior mineral composition than traditional natural sand, can give

influence of hydration behavior, density, and internal bonding. Important data regarding the viability and possible performance of alternative aggregates that outperform natural aggregates will be obtained from the compression strength test. Table 3 lists the findings of compression tests conducted on conventional and recycled brick wall CDW paving blocks.

Table 2

Pycnometer measurements for determining substitute aggregate specific gravity

Trial	W1 (g)	Temperature (°C)	W2 (g)	Gs
1	366.7	97	345.1	2.55
2	368.9	80	347.0	2.59
3	370.5	70	348.2	2.69
4	371.9	60	349.3	2.74
5	373.2	55	350.4	2.79
6	374.3	50	351.6	2.77
7	375.4	49	352.9	2.71

Note: Each trial has 3 replications and averaging it: W1 – weight of pycnometer + water + soil (g); W2 – weight of pycnometer + water (g); Gs = Ws / (Ws – (W1 – W2)).

Table 3

Comparative analysis of compressive strength

Description	Conventional paving	Paving from demolition waste
Compressive strength	Mix proportion	Mix proportion
	M-1 = 13.41 MPa	M1 = 30.73 MPa
	M-2 = 14.45 MPa	M2 = 23.29 MPa
	M-3 = 10.98 MPa	M3 = 19.38 MPa
	M-4 = 9.728 MPa	1:4 = 13.41 MPa

The mechanical performance of paving blocks employing inorganic substitute aggregate made from recycled brick wall demolition waste consistently have stronger performance than conventional paving blocks, based on paving block compression tests. The resulting compressive strength reached 30.7 MPa at the maximum cement proportion (M1), which is twice as strong as the compressive strength of traditional paving blocks (12.5 MPa). This enhancement results from the substitute aggregate’s coarser and more angular physical properties, which fortify the cement matrix’s mechanical binding and locking. Brick CDW’s angular particle form and surface roughness increase mechanical interlocking at the macroscopic level, which raises compressive strength. More research utilizing sophisticated analytical methods is necessary to understand microstructural mechanisms. Fig. 5 shows that waste paving had a compressive strength of 13.4 MPa at the lowest cement proportion (M4), which was higher than conventional paving’s compressive strength of only roughly 9.7 MPa. As a result, recycled brick wall waste aggregate can greatly increase the mechanical strength of pavement composites in addition to serving as a natural aggregate substitute.

At four mixed proportions, the compressive strength performance of paving block composites manufactured using substitute sand was significantly contrasted with that of natural sand. Due to the decreased amount of cement connection and decreased matrix cohesiveness, both aggregate usages exhibited the same trend, which was directly correlated with the mechanical strength of the paving blocks.

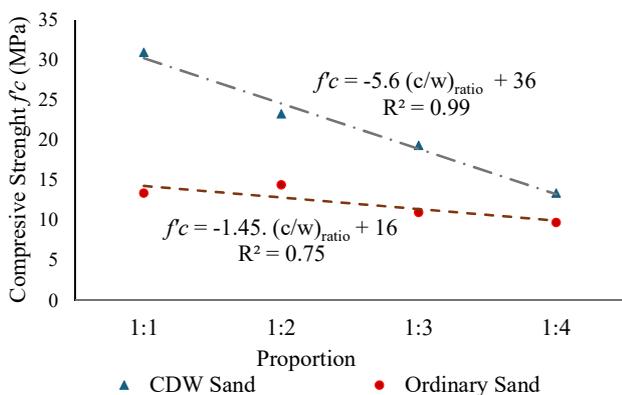


Fig. 5. Compressive strength of paving blocks – waste reuse aggregate vs natural sand

Overall, substitute fine aggregate has a substantially higher mechanical strength than natural sand, according to the compressive strength graph for paving blocks. Because of this, the composite material made from substitute sand is feasible, practical, and eco-friendly.

**5. 2. Results from a techno-economic analysis of paving block manufacturing using substitute material in place of natural sand**

A cost study was used to determine the operational expenses of the paving production process, including natural aggregate with a volume equal to 1 m<sup>3</sup> and fine aggregate from recycling brick wall CDW. The technical and economic aspects of labor, recycling procedures, and equipment functionality are all included in this examination. Based on an annual schedule of 48 weeks, five days a week, and eight times a day, the machine can be used four times a day, including the mobilization and demobilization of personnel and materials. The first calculation was performed on workers with an effective working time of eight hours. The machine operates for two hours in one production of 1 m<sup>3</sup> substitute sand. Due to inefficient equipment, the effective operation time is 960 times annually.

The annual cost of the recycling machine is IDR10,000,000. So, the operational cost in m<sup>3</sup> is calculated as IDR10,000,000 / 960 times, or IDR10,416.66/m<sup>3</sup>, where the machine can process 1 m<sup>3</sup> in 1 process (2 hours). Two employees, each paid IDR 100,000/day, contributed to labor costs totaling IDR200,000. Furthermore, the daily mobilization cost of trucks is IDR150,000, resulting in daily labor and vehicle costs of IDR350,000. The total processing cost is IDR350,000/4 = IDR87,500. So, it all costs approximately IDR 98,000/m<sup>3</sup>. Therefore, processing demolition waste sand is estimated to cost IDR98,000/m<sup>3</sup> (Table 4).

Managing construction waste and supplying substitute materials, including paving blocks, are two advantages of utilizing CDW. By lowering the quantity of CDW, this supports sustainable development. Due to its appropriateness, scalability, and accessibility, this technology which emphasizes the idea of a circular economy is a workable solution for real-world applications in urban centers in quickly developing nations.

**6. Discussion of techno-economic paving block using recycling brick construction and demolition waste**

The study’s findings show that recycled aggregates from brick wall-based construction and demolition waste (CDW) can be used as an efficient substitute material, particularly in the manufacturing of paving blocks, providing cost savings and mechanical benefits over natural fine aggregates as it is possible to see at Table 3 and Fig. 5. The porous of brick waste fragments does not prevent them from being integrated with cement. It has been demonstrated that the angular surfaces and aluminosilicate composition of the particles strengthen the bond with the cement matrix, and specific gravity values based on Table 2 shows value between 2.55 and 2.79 indicate appropriate density. Studies using recycling brick wall CDW also indicated similar outcomes, with an increase in the strength of the replacement material due to microstructure compaction [6, 7]. These findings also show that improved cement-aggregate interactions are inherently strengthened by the mineral properties of brick demolition waste. The future work will be continued for the large-scale paving block manufacturing.

The primary finding of this study is that paving blocks made using recycled aggregates from brick wall CDW have a far higher compressive strength than those made with natural aggregate. From Fig. 5 also it is possible to see that sample M1, which has the maximum cement concentration, is reported to have a compressive strength value of 30.4 MPa, but paving blocks made with natural sand differ by 13.4 MPa. These findings support earlier review [8] and the research hypothesis that recycled aggregates have a rougher surface and that the mineral content of the substitute aggregate facilitates interaction with the cement matrix to greatly boost the paving block’s compressive strength. Additionally, the results demonstrate that the alternative paving block outperforms the ordinary paving block in M4, the specimen with the lowest cement concentration. This supports the idea that the smooth aggregate surface produces stronger mechanical inter-locking. Several researchers have also observed similar phenomena in sand-plastic composite items, where improved mechanical performance and durability are attributed to the contact performance of materials obtained from waste [3, 4].

The potential of brick-based construction and demolition waste (CDW) as an aggregate substitute for paving

blocks is further supported by a techno-economic analysis. According to the investigation on Table 4, the procurement of natural sand cost is IDR 180,000/m<sup>3</sup>, whereas substitute fine aggregate cost only IDR 90,000/m<sup>3</sup>. Results from previous CDW recycling experiments, which concentrated on processing brick CDW to lower sand procurement costs and offer more lucid fi-

Cost and sustainability metrics for both natural sand and substitute material from building and demolition waste reuse

Description	Natural sand material	Material from demolition waste
Production cost	IDR 180,000/m <sup>3</sup>	IDR 90,000/m <sup>3</sup>
Environmental aspect	Increases in exploitation of new sand mining sites	Reduces demolition waste in urban areas
Social aspect	Higher costs: increases demolition waste generation during renovation and demolition works	More cost-effective; minimizes demolition waste; employs suitable technology for community benefit; makes use of waste materials; and encourages environmentally friendly and sustainable practices

nancial incentives for its adoption, corroborate this efficiency [10]. The circular economy (CE) framework's environmental goals, especially the emphasis on local material cycles and less exploitation of river ecosystems, are strengthened by reducing reliance on natural sand [11]. The use of inorganic substitute aggregates made from construction and demolition waste (CDW) in the manufacturing of paving blocks supports international initiatives to turn waste into useful building materials from a wider sustainability standpoint. The study's findings show that brick CDW can satisfy mechanical performance without going through costly or energy-intensive processing procedures. This is especially important in growing nations, where economical and workable recycling paths are desperately needed while CDW sorting and selective demolition are still relatively new procedures [5, 9].

Brick CDW can be one of the most readily available waste resources for quick deployment in these areas because it is readily available in big quantities and frequently requires little processing. The results pertaining to mechanical and economic characteristics show that brick demolition debris is not only a feasible alternative to natural sand, but frequently a better choice. Therefore, there are many advantages to its widespread use in addition to reducing the detrimental effects on ecosystem balance brought about by brick CDW and the exploitation of natural sand at the river. As a result, brick demolition waste can significantly contribute to sustainable urban development.

This study has several limitations even though it produced some encouraging findings that might help improve construction methods. Durability tests like abrasion, freeze-thaw behavior, and prolonged exposure to water were not included. These tests are essential for evaluating both the strength at the time of manufacturing and its future behavior. In this work, sophisticated methods like scanning electron microscopy were not used to directly analyze microstructural behavior. Consequently, conclusions about material interaction are predicated on indirect markers obtained from mechanical performance outcomes and macroscopic particle shape. The angular particle form and surface roughness of brick CDW, which enhances mechanical interlocking, are responsible for the increased compressive strength shown in paving blocks using recycled brick aggregates. Future studies must employ high-resolution analytical tools to further investigate the intricate microstructural dynamics at the cement–aggregate interface. Finally, no full life cycle analysis (LCA) evaluation was performed. While not necessary, using aggregates made from construction and demolition waste (CDW) would have allowed for a more complete understanding of the carbon savings, resource efficiency, and broader environmental effects. Further research in these fields would advance scientific understanding and promote the wider application of paving materials made from CDW.

This work's practical value comes from the demonstrated feasibility of using recovered brick demolition waste as fine aggregate under normal paver block production conditions. Small and medium-sized paving block manufacturers can use the recommended method because it doesn't require complex processing or specialized equipment. The technology's suitability for urban environments, where natural sand resources are becoming limited and brick demolition waste is readily available, is demonstrated by the improved mechanical performance and reduced manufacturing costs.

Under the same experimental conditions, this study is unique because it combines the mechanical and economic evaluation of using recycled brick wall construction and dem-

olition debris as an alternative fine aggregate in making paving blocks. Unlike previous research that looks at environmental benefits or material reuse separately, this study links production cost efficiency with compressive strength performance. The results provide evidence that recycled brick CDW can enhance mechanical performance while significantly reducing production costs. This offers a practical option for industrial use in environmentally friendly buildings.

Even with the positive mechanical and financial results, several limitations need to be addressed before implementing these findings. The study primarily focused on compressive strength testing; however, it did not evaluate long-term durability factors like shrinkage, abrasion resistance, and freeze-thaw behavior. Further research is required to establish whether the proposed paving blocks are appropriate for adverse environments or high-traffic applications. The proposed bonding mechanisms are based on the shape of the particles and the indirect mechanical properties, as the microstructural interactions between the recycled brick aggregates and the cement matrix have not been investigated using advanced techniques such as SEM or XRD.

Further research is required to include microstructural investigations to confirm these hypotheses. In addition, the recycled brick waste was obtained from a particular geographic region, and the techno-economic analysis was carried out in the context of the local market. The results may differ in other regions due to differences in material properties and economic conditions. Therefore, prior to widespread adoption, further validation and life cycle assessment are required.

Further research should be carried out to investigate durability parameters such as water absorption, freeze-thaw resistance, and abrasion resistance since paving blocks are subjected to cyclic environmental and mechanical loading. In addition, advanced microstructural analysis methods such as SEM or XRD analysis are required to verify the bonding processes between the cement paste and recycled brick aggregates, which are presently based on mechanical analysis results.

It is also proposed to conduct a comprehensive life cycle assessment to better assess resource efficiency and environmental gains. The effectiveness and economic viability of recycled brick CDW paving blocks should be verified through pilot-scale production and testing, which will also determine the limits of practical applications.

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## 7. Conclusions

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1. Paving blocks manufactured from brick-based construction and demolition waste (CDW) have a substantially higher and more reliable compressive strength than traditional paving blocks, according to mechanical laboratory tests. The interlocking strength with the cement matrix is improved by the replacement material grains' angular and coarse roughness. The substitute material's cohesiveness with the new cement matrix is enhanced by its residual cement content. According to test results, the replacement material has a mechanical strength advantage over the original material of up to 200%.

2. According to a techno-economic study, using replacement materials made from recycled brick wall demolition waste has the benefit of decreasing production costs by up to 50% when compared to natural materials. The practicality of using CDW-based paving blocks is strengthened by this

cost-effectiveness as well as the decreased amount of building demolition waste (CDW) dumped in landfills and the decreased requirement for new natural sand. These results show that this strategy provides a solution and alternative for sustainable urban construction from an economic and environmental standpoint.

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#### Conflict of interest

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The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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The study was performed without financial support.

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#### Data availability

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Manuscript has no associated data.

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#### Use of artificial intelligence

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The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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#### Authors' contributions

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**Ketut Sugiharto:** Conceptualization, Methodology, Writing – original draft, Funding acquisition; **Marjono Marjono:** Formal analysis, Investigation, Supervision; **Gatot Ciptadi:** Writing – review & editing, visualization, Project administration; **Wisnumurti Wisnumurti:** Validation, Data Curation, Resources.

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