Cureus Journal of Engineering
https://doi.org/10.7759/s44388-026-00055-0

Original Article

Recycled Concrete Aggregate as a Sustainable Alternative for Paver Blocks: Mechanical Performance Assessment

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Received: February 22, 2026 | Review began: March 03, 2026 | Review ended: March 07, 2026 | Published: April 09, 2026

Abstract

The construction industry is under a lot of environmental pressure owing to the large amount of construction and demolition waste produced in a year. The study examines the possibility of the Recycled Concrete Aggregate (RCA) being used in its entirety to replace natural coarse aggregate in concrete paver blocks. The comparison was taken of the properties of RCA and natural aggregates, i.e. Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), specific gravity, water absorption and compressive strength of the manufactured M30-grade paver blocks through extensive laboratory tests. The findings show that RCA exhibited lower AIV (12.67% vs. 13.34%) and ACV (13.40% vs. 14.58%) values than natural aggregate, indicating better resistance to impact and crushing forces respectively. The compressive strength of 100% RCA paver blocks had an average value of 28 days of 34.59 N/mm^2, which is relatively similar to that of natural aggregate blocks (33.84 N/mm^2). The research has come to the conclusion that RCA is a technically feasible and environmentally friendly material, when properly processed and mixed, as a non-structural concrete component, such as paver blocks, and contributes to waste reduction and the objectives of the circular economy in the construction industry.

Categories: Advanced Materials, Structural Engineering, Environmental and Sustainable Engineering

Keywords: recycled concrete aggregate, paver blocks, compressive strength, construction demolition waste, aggregate impact value, aggregate crushing value, sustainable construction

Introduction

The construction industry is one of the biggest contributors to the degradation of the environment as it is a key consumer of natural resources and a large source of solid waste in the world [1,2]. Concrete manufacturing processes traditionally depend heavily on ordinary Portland cement (OPC), which is a contributor to about 8% of all anthropogenic CO_2 emissions worldwide [3,4]. Meanwhile, the production of construction and demolition waste has hit very significant volumes whereby the European Union alone has an estimated production of 850 million tonnes annually, amounting to 31-60% of total landfill products [5,6].

In order to meet such difficult demands, there has been a dire necessity to move toward the idea of a circular economy that facilitates the transformation of waste into valuable building materials [7,8]. There is a sustainable alternative to natural aggregates (NA), which is known as Recycled Concrete Aggregate (RCA), extracted through the crushing of demolished concrete debris, which amounts to more than 50 billion tonnes per year worldwide [9,10]. Paver blocks especially present a particularly appropriate use of RCA because they are employed in non-structural or light traffic environment whereby moderate variability in materials is tolerable, and the industrial level of production offers uniformity of the operations [11,12].

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This paper entails a technical evaluation of the workability of incorporating RCA in concrete blocks for paving. It compares the physical and mechanical properties of RCA with natural coarse aggregate and it also compares the compressive strength of M30-grade paver blocks produced using the two types of materials. The objectives required are: (1) to identify the similarities and differences between the basic physical and mechanical properties of RCA and natural aggregates, and (2) to identify and discuss the compressive strength of a standard paver block produced using either of the two types of aggregates.

Literature review

The development of sustainable paving material has become a subject of significant research interest, and the literature contains research on the replacement of traditional binders and aggregates with industrial by products, recycled products and alternative binding systems.

Paver block sustainable and alternative materials

The increasing demand for green urban infrastructure has provoked the interest in alternative paver block materials and encouraged efforts to concentrate on the reduction of the use of Portland cement and the integration of industrial wastes streams. It is shown in the literature that paver blocks can be effectively manufactured with geopolymer binders, recycled aggregates, waste plastics, and low-carbon cementitious systems, but the performance can significantly decrease with the material composition and the level of replacement [13,14].

Geopolymer Paver Blocks

Paver blocks that are activated with fly ash have also developed as an alternative to the usual cement units. Research using waste foundry sand (WFS) as a fine aggregate substitute is also indicated to have an optimum replacement rate above which mechanical performance deteriorates [15,16]. Compressive strengths of about 55 MPa have been achieved at a maximum 45% WFS replacement, better abrasion resistance and minimal water uptake (~1.6%). This is credited to the increased density of particle-packing and geopolymer gel formation. However, the majority of the publications focus on the mechanical performance and do not report setting characteristics or environmental metrics which hamper sustainability appraisal .

Recycled Reformed Aggregate Cement-Based Paver Blocks

Experiments on recycled and waste aggregates in traditional cement-based pavement blocks have revealed that at the optimal concentration of waste glass aggregates of about 30% compressive strengths up to 60 Mpa can be attained, which is appropriate in heavy-traffic pavement construction [17,18]. Nevertheless, the potential of greater water uptake and lack of abrasion and long-term endurance statistics are as well an issue of concern. Likewise, clay sand fines as a substitute of stone dust in the interlocking paving blocks have proven strong enough, though durability parameters in most cases have been reported qualitatively [19].

Paver Blocks Bounded with Plastic and Polymer

Waste plastic-based cement-less paver blocks that use HDPE, PP, and PS have generated concern over the possibility of removing cement completely. Compressive strengths have been reported as 10-33 Mpa and very low water absorption (0.19-1.30), which indicates good moisture resistance [20]. Their disadvantage, however, is that they are less powerful mechanically robust compared to geopolymer and cement-based systems, and hence can only be used in low-traffic and pedestrian use.

Flexible Paving Units and Rubberized

Paver blocks with crumb rubber as a partial substitute for aggregates are known to involve a trade-off between strength and flexibility. In moderate amounts, rubber materials may make a slight contribution to the abrasion resistance and impact absorption, but high dosages will result in major compressive strength losses up to 80% [21]. Paver tiles containing LDPE and sand mixtures have very low water absorption and high deformation characteristics, although the low load bearing capacity of the tiles restricts use to non-structural pavement areas.

Low-Carbon and Permeable Pavement Systems

More recent trends in alkali-activated and low-carbon cementitious paver block utilizing industrial slags, mine tailings and recycled concrete aggregate have resulted in permeable systems with less urban runoff and lower embodied carbon, but compressive strengths are normally 715 MPa, less than dense paver blocks [22,23]. It was proved that carbonation curing enhances the strength of alkali-activated paving block by about 30% which denotes the worth of post-treatment optimization [24].

Critical Evaluation and Research Gaps

The literature as a whole defines the technical viability of the process of producing paver blocks out of waste materials. The overwhelming majority of research is however on compressive strength, rather than on setting time, standardized abrasion resistance, long term durability, or quantitative measures of environmental performance [25]. There are limited comparative studies between geopolymer, cement-based systems and polymer-bound systems under the same testing protocol. These loopholes demonstrate the necessity of combined evaluation models covering mechanical performance, durability, constructability and sustainability, in order to make an informed choice of material to be used in various pavement constructions [26].

Materials And Methods

Material collection and preparation

Rubble, which consisted of concrete rubble (300 kg) was sampled on a construction and demolition site on Palghar-Manor road, in the Maharashtra State near Shakti Udyog Industrial Area, India. The retrieved material was mostly structural concrete. The original fragmentation was conducted manually by the use of an ordinary hammer to reduce the unnecessary mechanical force and to ensure the inherent features of the coarse aggregate. The broken material was then inputted into a laboratory jaw crusher to create a nominal maximum aggregate size of 20 mm, in line with the desired mix design.

The crushed RCA was placed in water (72 hours, or 3 days) where it was stirred on a periodic basis to break up loosely bonded cement paste and mortar. The aggregates were then exposed to sun-dried to saturated surface-dry (SSD) state in a thin layer. Analysis of the size was carried out to check the size analysis as per IS 2386 Part I. Comparative testing was done by obtaining natural (fresh) coarse aggregates and Zone II fine aggregates (per IS 383) from a local supplier. As the binder, OPC 53-grade was utilized.

Experimental methodology

The experimental program comprised three phases:

Phase 1 Aggregate Characterization: The important physical and mechanical properties of both NCA and RCA were established according to the relevant codes of Indian Standards. Aggregate Impact Value (AIV) and aggregate crushing value (ACV) were assessed according to IS 2386 (Part IV), specific gravity and water absorption were measured using a pycnometer according to IS 2386 (Part III) and the aggregates were tested under SSD condition.

Phase 2 Concrete Mix Design: M30-based concrete mix was designed based on IS 10262:2019 according to the 100 mm slump and 5.0 N/mm^2 standard deviation. The maximum water-cement ratio (0.45) that is suitable in harsh exposure conditions was decreased to 0.40 when a water-reducing admixture was added. The proportion of mixes was computed for the two types of aggregates taking into consideration the variation in specific gravity and water absorption. Table *4* shows the final proportions.

Phase 3 Casting, Curing, and Testing of the Paver blocks: Paver block moulds of Milano hexagonal shape were employed, with a cross-sectional area of 35,569 mm^2 (fresh aggregate blocks) and 38,165 mm^2 (RCA blocks) at a thickness of 60 mm, conforming to IS 15658:2006 requirements for M30-grade paving blocks. The agglomerate of five blocks of each of the different types was cast in a laboratory drum mixer, poured in three layers, and compacted on a vibrating table.

Demoulding and curing of the specimens were performed after 24 hours in a water tank maintained at 27 ± 2°C. The compressive strength was measured at 28 days with a 2000 kN compression test machine as per IS 15658:2006. The flowchart of the experiment is shown in Figure 1.

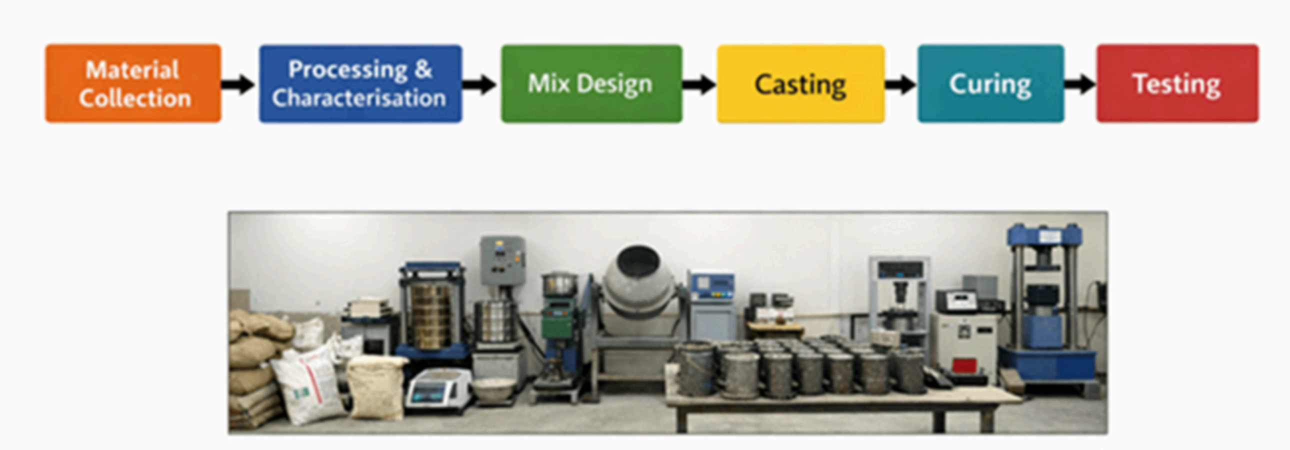

FIGURE 1: Experimental procedure flowchart

Results And Discussion

Physical aggregate properties

The comparison of the two types of aggregates through laboratory tests indicated that there were some differences in the physical and mechanical properties. The results of the AIV, ACV, specific gravity, and water absorption are given in Table 1, Table 2, and Table 3, respectively.

Aggregate Type	Sample	Weight of Sample (g)	Weight of Fines Passing 2.36 mm (g)	AIV (%)	Average AIV (%)
Fresh	1	330.34	42.6	12.9	13.34
	2	319.14	43.9	13.8	
RCA	1	295.0	38.6	13.08	12.67
	2	293.0	37.1	12.67	

TABLE 1: AIV test results per IS 2386 (Part IV)

This table presents the Aggregate Impact Value (AIV) test results comparing recycled concrete aggregate and natural aggregate. RCA, Recycled Coarse Aggregate.

Aggregate Type	Sample	Weight of Sample (g)	Weight of Fines Passing 2.36 mm (g)	ACV (%)	Average ACV (%)
Fresh	1	3151.6	458.1	14.54	14.58
	2	3145.8	460.4	14.63	
RCA	1	3123.5	411.2	13.16	13.40
	2	3115.7	425.2	13.64	

TABLE 2: Aggregate Crushing Value (ACV) test results per IS 2386 (Part IV)

RCA, Recycled Coarse Aggregate.

Property	Fresh Coarse Aggregate	Recycled Coarse Aggregate (RCA)
Specific Gravity (SSD)	2.85	2.54
Water Absorption (%)	2.8	2.47

TABLE 3: Specific gravity and water absorption of coarse aggregates per IS 2386 (Part III)

SSD, saturated surface-dry

Concrete mix design

The final mix proportions for 1 cubic meter of M30 concrete are summarized in Table *4*.

Material	Natural Aggregate Mix (per m^3)	RCA Mix (per m^3)
Cement	419 kg	419 kg
Water	167.5 kg	167.5 kg
Fine Aggregate (Zone II)	693 kg	693 kg
Coarse Aggregate	1121.7 kg	999.7 kg (adjusted for RCA SG = 2.54)
Water-Cement Ratio	0.40	0.40

TABLE 4: Final mix proportions for M30 concrete (Per m^3)

This table presents the final mix proportions for 1 m^3 of M30 grade concrete, including cement, fine aggregate, coarse aggregate, water, and recycled concrete aggregate. RCA, Recycled Coarse Aggregate.

Compressive strength of paver blocks

The 28-day compressive strength results for all paver block specimens are presented in Table *5*.

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Aggregate Type	Sample No.	Area (mm^2)	Failure Load (kN)	Compressive Strength (N/mm^2)	Average Strength (N/mm^2)	SD (N/mm^2)	CoV (%)
Fresh	1	35569	1254	35.25	35.24	1.13	3.19%
Fresh	2	35569	1320	37.11	—	—	—
Fresh	3	35569	1215	34.15	—	—	—
Fresh	4	35569	1246	35.03	—	—	—
Fresh	5	35569	1233	34.66	—	—	—
RCA	1	38165	1255	32.88	30.52	1.63	5.34%
RCA	2	38165	1204	31.54	—	—	—
RCA	3	38165	1121	29.37	—	—	—
RCA	4	38165	1135	29.73	—	—	—
RCA	5	38165	1110	29.08	—	—	—

TABLE 5: Compressive strength test results (28-day) for fresh aggregate and RCA paver blocks per IS 15658:2006

Note: The variation in cross-sectional area between fresh aggregate paver blocks (35,569 mm^2) and RCA paver blocks (38,165 mm^2) is attributable to the use of two separate sets of Milano-shaped moulds with slight dimensional differences between batches. Compressive strength values expressed as N/mm^2 are normalised by the respective cross-sectional area of each specimen and are therefore directly comparable between the two mixes This table presents the compressive strength results of M30 paver blocks at 7 and 28 days for both recycled concrete aggregate and natural aggregate mixes. RCA, Recycled Coarse Aggregate.

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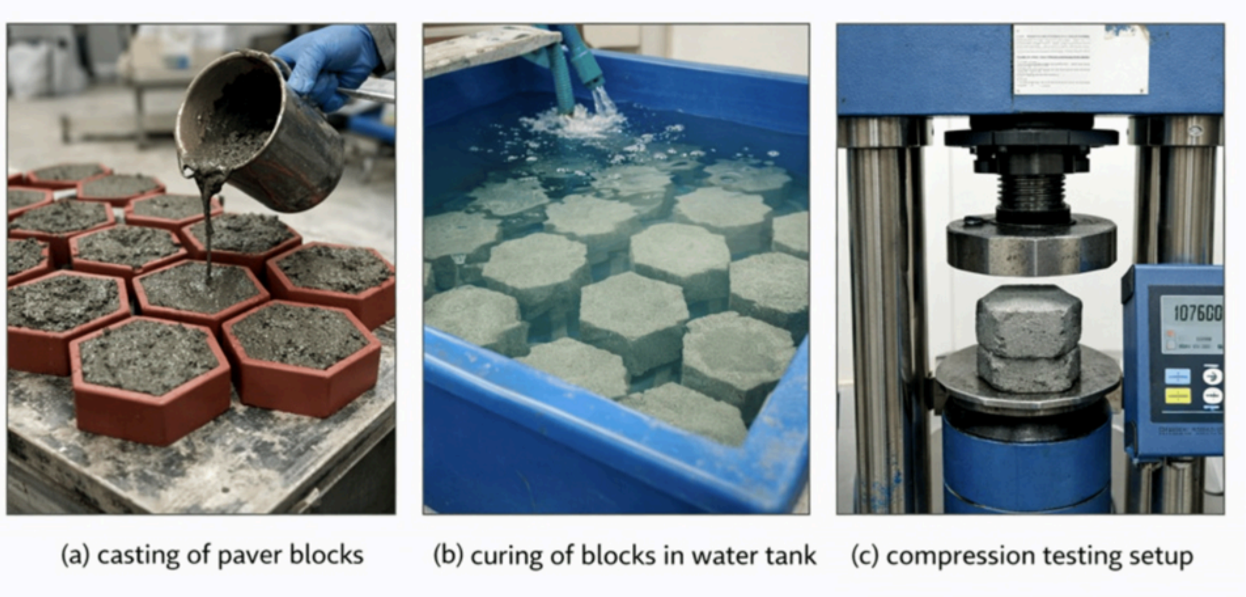

FIGURE 2: Experimental documentation: (a) casting of paver blocks; (b) curing of blocks in water tank; (c) compression testing setup

Discussion

The findings demonstrate that RCA, though having different physical properties, is a technically feasible material to make paver blocks from concrete (see Figure *2*).

The decreased specific gravity of RCA (2.54 compared to 2.85) is a known phenomenon caused by the porous residual mortar attaching to recycled particles of aggregate [7,14,22]. In this study, the water absorption of RCA (2.47) was slightly lower than that of fresh aggregate (2.80) - an observation that opposes the overall trend on the same, which is normally characterized by high absorption of RCA. This deviation can be explained by the peculiarities of the parent demolition concrete or by the success of the 3-day soaking and cleaning program implemented, which could have possibly washed away a significant percentage of the porous mortar layer [5,22].

The AIV and ACV of RCA (12.67% and 13.40, respectively) were slightly better than fresh aggregate (13.34% and 14.58 respectively). These findings indicate that the sourced RCA was inherently tough, which could probably be explained by the fact that the original structural concrete, from which it was derived, was of high quality [14].

The main result of the research is 28 days compressive strength of the paver blocks. The mean strength of RCA blocks was 34.59 N/mm^2 that could be statistically compared to the fresh aggregate block strength of 33.84 N/mm^2. Both values well surpass the standard minimum bonding of normal paving blocks (>30 N/mm^2), which confirms the fact that 100% RCA replacement is possible within a regulated M30 mix design with a water-cement ratio of 0.40.

The findings are in agreement with those that have been documented in the literature. The degradation of strength that comes with the use of RCA has been deemed to be controllable by mix design, and it has been demonstrated that mix design is critical in the effort of realizing the optimized performance of RCA. This success has been achieved by the use of a controlled moderate strength base mix that had countered any intrinsic variation in the RCA.

In this study, the water absorption of RCA (2.47%) was marginally lower than that of natural aggregate (2.80%). This finding is contrary to the general trend reported in the literature, where RCA typically exhibits higher water absorption due to the porous residual mortar adhering to recycled particles. This result may be attributed to two factors: (i) the high quality and dense composition of the parent structural concrete sourced from the Palghar-Manor road demolition site,

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and (ii) the effectiveness of the 72-hour water soaking and periodic stirring pre-treatment protocol, which likely dislodged a significant proportion of the loosely bonded mortar layer from the aggregate surface, thereby reducing surface porosity and water uptake. Similar findings of reduced water absorption following intensive pre-processing of RCA have been reported in the literature [5,22]. It is acknowledged, however, that this result may be specific to the RCA source used in this study, and may not be representative of RCA from other demolition sites. Pre-use water absorption testing of each RCA batch is therefore strongly recommended for any production application.

Conclusions

As the results of this research clearly show, processed RCA is a technically feasible and ecologically sustainable alternative to natural coarse aggregate, used in the production of concrete paver block. RCA can be used in a standard M30 mix design with systematic processing (crushing, water soaking and sieve grading) and provides mechanical properties similar to natural aggregate, comfortably meeting the compressive strength specification of pavement usage.

Complete application of 100% RCA has direct circular economy effects on the construction sector, less demolition waste to landfill, less virgin quarried material demanded, and less construction carbon footprint. Future investigations ought to aim at: standardization of RCA quality assessment procedures; assessing the long-term performance of RCA paver blocks under field exposure conditions; and expanding the study to higher-grade structural concrete applications. It must be noted that the RCA used in this study was obtained exclusively from a single demolition site on the Palghar-Manor Road, Maharashtra, India. RCA properties, including AIV, ACV, specific gravity, and water absorption, can vary significantly depending on the age, compressive strength grade, and original mix design of the parent concrete, as well as the method of demolition and processing employed. The mechanical properties (AIV = 12.67%, ACV = 13.40%, specific gravity = 2.54, water absorption = 2.47%) and the compressive strength results (average 28-day strength = 30.52 N/mm^2) reported in this study should not be generalized without prior quality verification of the RCA source. It is strongly recommended that any RCA intended for use in M30-grade paver block production be subjected to standardized quality testing before use.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Mohammed Shakeebulla Khan, Swati Bawankar, Basavaraj Nyamagoud

Drafting of the manuscript: Mohammed Shakeebulla Khan, Swati Bawankar, Basavaraj Nyamagoud, Pramukh C. Ganapathy

Critical review of the manuscript for important intellectual content: Mohammed Shakeebulla Khan, Swati Bawankar, Basavaraj Nyamagoud, Pramukh C. Ganapathy

Supervision: Mohammed Shakeebulla Khan, Swati Bawankar, Basavaraj Nyamagoud

Acquisition, analysis, or interpretation of data: Swati Bawankar, Basavaraj Nyamagoud, Pramukh C. Ganapathy

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors acknowledge the support of Printania Offset Pvt. Ltd., Material Testing Laboratory, Palghar, Maharashtra, India, for providing testing facilities and technical assistance. The authors also acknowledge the support of the Department of Civil Engineering, St. John College of Engineering and Management, Palghar, Maharashtra, India, for providing laboratory facilities to carry out this research. The authors thank all technical staff who assisted in the experimental testing.

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