Sustainable Interlocking Concrete Paver Blocks from Recycled Road Demolition Waste: an Experimental Taguchi-Based Approach

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Abstract. This study investigates the use of recycled road demolition waste as a partial replacement for fine and coarse aggregates in the development of sustainable interlocking concrete paver blocks. A Taguchi-based experimental approach was used to analyze the effects of varying the recycled aggregate contents and water-cement ratio on compressive strength, water absorption, and abrasion resistance. The results indicate that incorporating recycled waste materials significantly impacts the overall performance of the paver blocks. Regression analyses were conducted to develop predictive models, which demonstrated strong predictive capabilities and enabled the optimization of the mix design. The researchers recommend an optimum mix design comprising 20% recycled fine aggregates, 25% recycled coarse aggregates, and a water-cement ratio of 0.4, as this combination can provide high compressive strength, low water absorption, and improved wear resistance, ensuring the long-term sustainability and durability of the pavement system. The study highlights the potential for using recycled road demolition waste as a sustainable alternative to traditional pavement materials, contributing to the reduction of the construction industry's environmental impact.

1 Introduction

1.1 Background of the Study

The rapid growth of the construction industry in the Philippines has raised pressing environmental concerns, as the energy-intensive production of cement and the extensive extraction of natural aggregates have emerged as significant contributors to the industry's substantial carbon footprint and unsustainable consumption of natural resources [1]. This has prompted a growing need to develop more sustainable construction materials that can effectively reduce the environmental impact of the building sector [2].

One potential solution to this challenge is the incorporation of recycled waste materials, such as those derived from road demolition projects, into the production of concrete paver blocks and other construction materials. Recycling demolition waste from roads and other infrastructure projects can provide a valuable source of alternative aggregate materials. Replacing a portion of the fine and coarse aggregates in concrete with these recycled materials can lead to a reduction in the environmental impact of concrete production, as it diminishes the demand for virgin aggregate extraction [3][4]. Furthermore, diverting demolition waste from landfills and finding productive uses for it can contribute to the overall sustainability of the construction industry, reducing the strain on natural resources and mitigating the environmental challenges associated with waste disposal [5][6].

In this study, the researchers aim to investigate the feasibility and performance of using recycled road demolition waste as a partial replacement for fine and coarse aggregates in the fabrication of sustainable interlocking paver blocks. The researchers will employ a Taguchi-based experimental approach to optimize the mix design and evaluate the mechanical properties of the resulting paver blocks, with the goal of developing a cost-effective and environmentally friendly construction solution that can be readily implemented in the Philippine context.

1.2 Objectives of the Study

The main objective of this study is to investigate the potential of using recycled road demolition waste as a partial replacement for fine and coarse aggregates in the production of sustainable interlocking paver blocks. The specific objectives of this research are:

1. To characterize the physical and chemical properties of the recycled road demolition waste and determine its suitability as a replacement for traditional aggregates in concrete paver block production.
2. To develop an optimized mix design for the sustainable interlocking paver blocks using a Taguchi-based experimental approach, considering the partial replacement of fine and coarse aggregates with recycled demolition waste.

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3. To evaluate the mechanical properties, including compressive strength, water absorption, and abrasion resistance, of the optimized sustainable interlocking paver blocks and compare them to the performance of conventional paver blocks.

2 Materials and Methods

2.1 Research Design

The research design for this study employs a multifaceted approach, combining rigorous quantitative experimentation with advanced statistical optimization techniques. This integrated methodology aims to thoroughly investigate the feasibility and performance of using recycled road demolition waste as a partial replacement for traditional fine and coarse aggregates in the production of sustainable interlocking paver blocks. Figure 1 shows the conceptual framework used in the study.

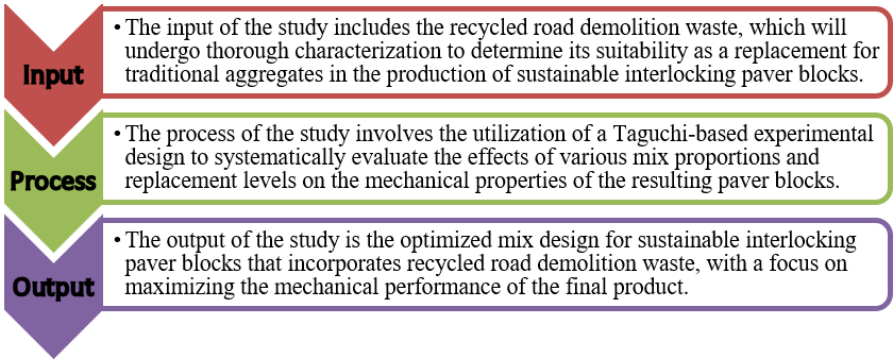

Fig. 1. Conceptual Framework of the Study

2.2 Characterization of Recycled Road Demolition Waste

The recycled road demolition waste used in this study was collected from a local infrastructure project in Davao City, Philippines. The physical and chemical properties of the recycled concrete road demolition waste, including particle size distribution, specific gravity, water absorption, and chemical composition, were thoroughly analyzed to assess its suitability as a replacement for fine and coarse aggregates in concrete paver block production. Tables 1 and 2 present the key findings of the characterization analysis.

Table 1. Physical Properties of Recycled Concrete Road Demolition Waste.

Property	Fine Aggregates	Coarse Aggregates
Particle Size Distribution (mm)	0.075 – 4.75	4.75 – 19
Specific Gravity	2.52	2.38
Water Absorption (%)	3.5	4.8
Bulk Density (kg/m^3)	1480	1320
Fineness Modulus	2.65	6.95

Table 2. Chemical Composition of Recycled Concrete Road Demolition Waste.

Component	Fine Aggregates
Silicon Dioxide (SiO_2)	58.9
Calcium Oxide (CaO)	25.7
Aluminum Oxide (Al_2O_3)	6.9
Iron Oxide (Fe_2O_3)	3.1
Magnesium Oxide (MgO)	2.0
Sulfur Trioxide (SO_3)	1.1
Loss on Ignition (LOI)	4.3

The results indicate that the recycled concrete road demolition waste exhibits physical and chemical properties that are generally suitable for its partial replacement of traditional fine and coarse aggregates in the production of concrete paver blocks.

2.3 Experimental Design using Taguchi Method

To optimize the mix design of the sustainable interlocking paver blocks, the researchers employed a Taguchi-based experimental methodology. The Taguchi approach is a robust statistical technique that enables the identification of the optimal combination of factors and their corresponding levels, while minimizing the number of experiments required [7][8][9]. Specifically, the researchers utilized the Taguchi design to investigate the effects of three key factors on the mechanical properties of the paver blocks: the replacement percentage of recycled fine aggregates, the replacement percentage of recycled coarse aggregates, and the water-cement ratio, as presented in Table 3.

Table 3. Selected Factors and their Levels.

Level	Recycled Fine Aggregates	Recycled Coarse Aggregates	Water-Cement Ratio
Level No. 1	10%	25%	0.4
Level No. 2	20%	50%	0.5
Level No. 3	30%	75%	0.6

2.4 Design Mix Preparation

Table 4 presents the detailed design mix proportions used in the Taguchi-based experimental investigation. The nine additional mixes incorporated varying replacement levels of recycled fine and coarse aggregates, ranging from 10% to 30% and 25% to 75%, respectively, as per the Taguchi L9 orthogonal array experimental design. This systematic approach allowed the researchers to explore the effects of different substitution levels of the recycled demolition waste on the properties of the sustainable interlocking concrete paver blocks, providing a comprehensive understanding of the optimal mix composition to be developed [10][11].

Table 4. Design Mix Proportions (in kg).

Design Mix	Cement	Natural Fine Aggregates	Natural Coarse Aggregates	Recycled Fine Aggregates	Recycled Coarse Aggregates	Water
M1	3.20	5.76	7.20	0.64	2.40	1.28
M2	3.20	5.76	4.80	0.64	4.80	1.60
M3	3.20	5.76	2.40	0.64	7.20	1.92
M4	3.20	5.12	7.20	1.28	2.40	1.60
M5	3.20	5.12	4.80	1.28	4.80	1.92
M6	3.20	5.12	2.40	1.28	7.20	1.28
M7	3.20	4.48	7.20	1.92	2.40	1.92
M8	3.20	4.48	4.80	1.92	4.80	1.28
M9	3.20	4.48	2.40	1.92	7.20	1.60

2.5 Taguchi L9 Orthogonal Array

The researchers performed a comprehensive set of laboratory experiments to thoroughly assess the properties, such as compressive strength, water absorption, and abrasion resistance, of the optimized sustainable interlocking concrete paver blocks. The detailed results of these tests examined the influence of varying the proportions of the recycled road demolition waste. This systematic investigation of the performance characteristics of the sustainable interlocking concrete paver blocks provided a solid foundation for further analysis and optimization. The Taguchi L9 orthogonal array used in the experimental design is shown in Table 5.

Table 5. Taguchi L9 Orthogonal Array.

Recycled Fine Aggregates	Recycled Coarse Aggregates	Water-Cement Ratio	Compressive Strength (MPa)	Water Absorption (%)	Abrasion Resistance (mm)
10%	25%	0.4	32.1	4.9	2.12
10%	50%	0.5	28.3	6.5	2.70
10%	75%	0.6	26.8	7.8	3.24
20%	25%	0.5	30.5	5.4	2.38
20%	50%	0.6	26.6	7.4	3.15
20%	75%	0.4	30.1	7.6	3.21
30%	25%	0.6	25.9	6.1	2.58
30%	50%	0.4	28.8	6.9	2.89
30%	75%	0.5	25.3	7.9	3.43

3 Results and Findings

3.1 Taguchi Analysis

The Taguchi analysis provided valuable insights into the performance of the paver block mixes. The researchers were able to identify the optimal combination of factors - recycled fine aggregate replacement, recycled coarse aggregate replacement, and water-cement ratio - that would maximize the desirable mechanical and durability properties of the sustainable interlocking paver blocks. As depicted in Figure 2, the analysis revealed the average trends and variability in the measured responses, such as compressive strength, water absorption, and abrasion resistance [12].

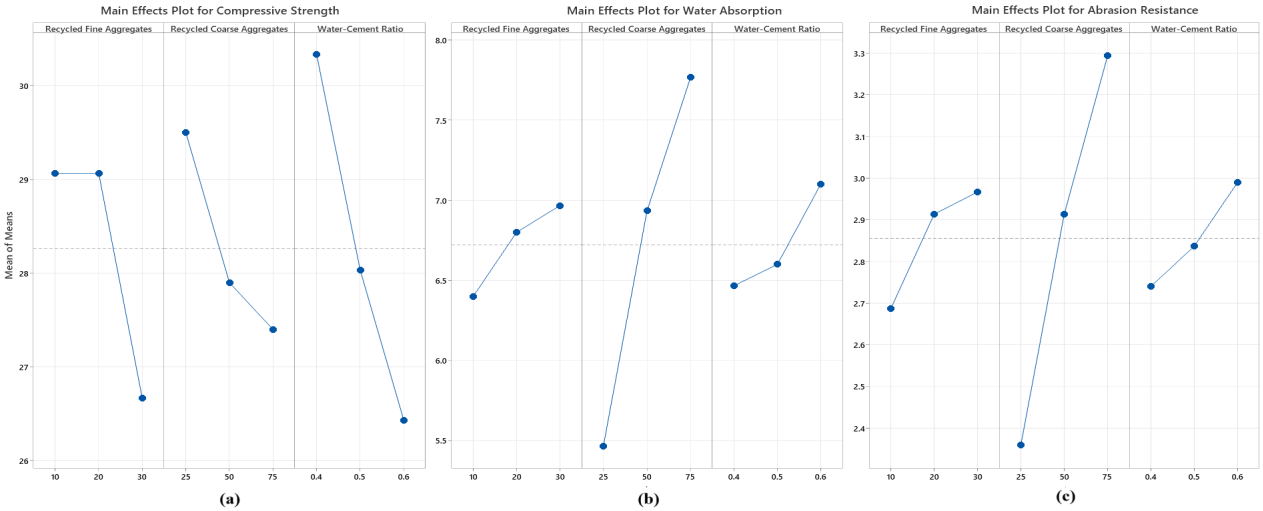

Fig. 2. Main Effects Plots for Means of (a) Compressive Strength, (b) Water Absorption, and (c) Abrasion Resistance of Interlocking Concrete Paving Blocks.

The study found that increasing recycled fine aggregate content and water-cement ratio decreases compressive strength, while a 25% replacement of coarse aggregates with recycled materials provides optimal performance. Recycled fine aggregates significantly increase water absorption, while recycled coarse aggregates and water-cement ratio also contribute to higher permeability. Abrasion resistance decreases with increasing recycled coarse aggregate content, but recycled fine aggregates and water-cement ratio have a moderate impact. The three factors significantly influence the compressive strength and durability, with recycled coarse aggregates being the dominant factor for abrasion resistance. The optimal mix design is 20% recycled fine aggregates, 25% recycled coarse aggregates, and a water-cement ratio of 0.4, providing high strength, low water absorption, and improved wear resistance.

3.2 Regression Analyses

To further elucidate the relationships between the key factors and the measured responses, the researchers conducted regression analyses to develop predictive models for compressive strength, water absorption, and abrasion resistance of the sustainable interlocking paver blocks [13][14]. The regression models, presented in Equations 1-3, demonstrate the significant influence of the recycled fine aggregate (RFA) and recycled coarse aggregate (RCA) contents and the water-cement ratio (WCR) on the performance characteristics of the concrete paver blocks.

$$Compressive\ Strength = 42.520 - 0.120*RFA - 0.042*RCA - 19.500*WCR \quad (1)$$

$$Water\ Absorption = 2.272 + 0.028*RFA + 0.046*RCA + 3.167*WCR \quad (2)$$

$$Abrasion\ Resistance = 1.017 + 0.014*RFA + 0.019*RCA + 1.250*WCR \quad (3)$$

The analysis of variance (ANOVA) revealed that the linear regression models developed for compressive strength, water absorption, and abrasion resistance were statistically significant. All model terms were found to be significant, indicating the importance of the individual factors. Recycled coarse aggregate was identified as the most influential parameter determining water absorption and abrasion resistance, while the water-cement ratio exhibited the most significant impact on compressive strength, as shown in Table 6.

Table 6. ANOVA Result.

Response	Source	df	SS	F-value	p-value	Significance
Compressive Strength	Model	3	38.070	13.82	0.007	Yes
	RFA	1	8.640	9.41	0.028	Yes
	RCA	1	6.615	7.21	0.044	Yes
	WCR	1	22.815	24.85	0.004	Yes
	Error	5	4.590			
	Total	8	42.660			
Water Absorption	Model	3	9.018	50.57	<0.001	Yes
	RFA	1	0.482	8.10	0.036	Yes
	RCA	1	7.935	133.49	<0.001	Yes
	WCR	1	0.602	10.12	0.024	Yes
	Error	5	0.297			
	Total	8	9.316			
Abrasion Resistance	Model	3	1.518	62.31	<0.001	Yes
	RFA	1	0.118	14.48	0.013	Yes
	RCA	1	1.307	160.90	<0.001	Yes
	WCR	1	0.094	11.54	0.019	Yes
	Error	5	0.041			
	Total	8	1.559			

The regression models developed in this study demonstrated strong predictive capabilities, as indicated by the high coefficients of determination shown in Table 7. These models effectively captured the relationships between the key design parameters - recycled fine and coarse aggregate replacement ratios, and water-cement ratio - and the critical performance attributes, including compressive strength, water absorption, and abrasion resistance. The high R-squared values suggest that the regression equations can reliably estimate the expected mechanical and durability performance of the paver blocks, enabling the optimization of the mix design to achieve the desired properties for specific applications [15][16].

Table 7. Validation of Models

Model Validation Parameter	Compressive Strength	Water Absorption	Abrasion Resistance
Standard Deviation of Residuals	0.958123	0.243812	0.090117
Coefficient of Determination (R^2)	89.24%	96.81%	97.39%
Adjusted R^2	82.78%	94.90%	95.83%
Predicted R^2	71.45%	91.21%	91.86%

3.3 Diagnostic Plots of Response Models

The researchers validated the reliability and accuracy of the regression models by generating diagnostic plots. As shown in Figure 3, the scatter plots demonstrate the predictive capability of the models, with strong linear correlations observed across the three measured responses - compressive strength, water absorption, and abrasion resistance. Water absorption exhibits the highest alignment with the prediction line, followed by abrasion resistance and compressive strength. These findings indicate that the regression models are highly reliable, effectively capturing the experimental

data trends with minimal error, and can be used to optimize the mix design of sustainable interlocking concrete paver blocks.

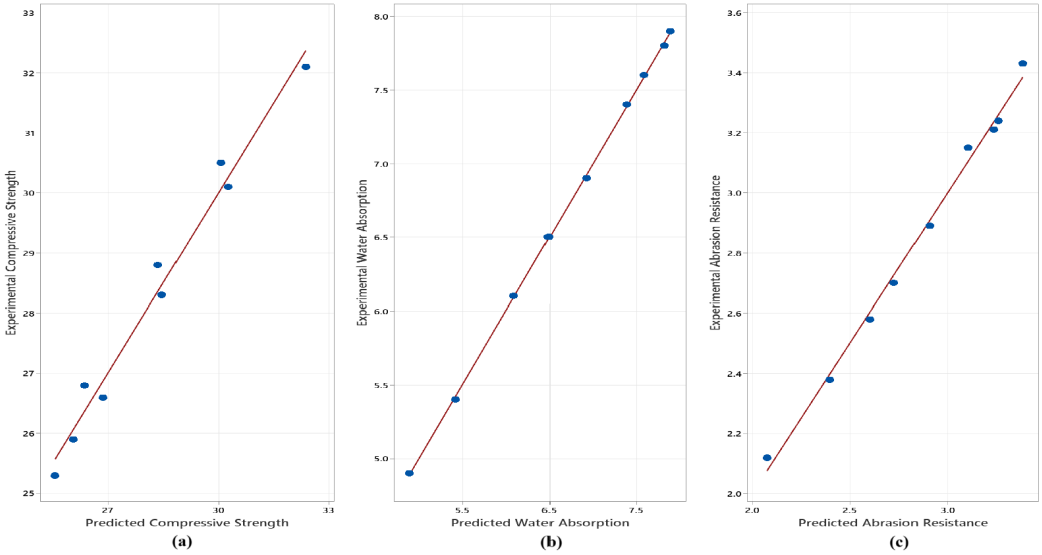

Fig. 3. Experimental vs. Predicted Plots of (a) Compressive Strength, (b) Water Absorption, and (c) Abrasion Resistance of Interlocking Concrete Paving Blocks.

4 Conclusions and Recommendations

This study investigated the innovative use of recycled road demolition waste as a partial replacement for natural aggregates in the development of sustainable interlocking concrete paver blocks. The researchers used a rigorous Taguchi-based experimental approach to analyze the effects of varying the recycled fine and coarse aggregate contents, as well as the water-cement ratio, on the performance characteristics of the paver blocks, including compressive strength, water absorption, and abrasion resistance. The results showed that incorporating these recycled waste materials significantly impacted the overall performance and properties of the concrete paver blocks [16][17].

To further understand the relationships between the key design parameters and the measured responses, the researchers conducted regression analyses to develop predictive models. These models effectively quantified the influence of recycled fine aggregate content, recycled coarse aggregate content, and water-cement ratio on the compressive strength, water absorption, and abrasion resistance of the sustainable interlocking paver blocks. The high coefficients of determination obtained for these regression equations indicate their strong predictive capabilities, enabling the optimization of the mix design to achieve the desired performance attributes [18]. Based on the findings, the researchers recommend an optimum mix design comprising 20% recycled fine aggregates, 25% recycled coarse aggregates, and a water-cement ratio of 0.4. This combination can provide high compressive strength, low water absorption, and improved wear resistance, ensuring the long-term sustainability and durability of the pavement system.

The researchers recommend further optimizing the mix design using the developed regression models to determine the ideal combination of recycled fine aggregate, recycled coarse aggregate, and water-cement ratio to maximize compressive strength, minimize water absorption, and enhance abrasion resistance of the sustainable interlocking paver blocks. They also suggest conducting pilot-scale production and field trials to evaluate the real-world performance and suitability of the optimized paver blocks for large-scale deployment. Additionally, a comprehensive life-cycle assessment should be carried out to quantify the environmental benefits and sustainability of the proposed solution, which could support the widespread adoption of sustainable interlocking paver blocks as a viable alternative to traditional pavement systems.

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