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(RESEARCH ARTICLE)

Assessment of crumb rubber as a partial substitute with quarry dust for the production interlocking paving stone

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Abstract

The generation of huge amounts of waste rubber from used tires poses serious environmental challenges due to its non-degradable nature. Meanwhile, the rising cost of construction materials has significantly increased overall construction expenses. This research investigates the use of crumb rubber (CR) as a partial replacement for quarry dust in the production of interlocking paving stones. Waste tires were shredded and processed into fine crumb rubber. Sieve analysis were conducted on both materials, revealing that quarry dust was well-graded, while CR was gap-graded, with 66.5% retained at 0.425 mm and 22.6% at 0.300 mm sieve sizes. Cement, quarry dust, and CR were batched by weight with a 1:6 cement-quarry dust ratio and a 0.45 water-cement ratio. Slump tests demonstrated that the addition of crumb rubber improved workability, with slump values increasing from 2 mm (0%) to 11 mm (40%). Paving stones were cast with 0-40% CR replacements and cured for 7-28 days. Compressive strength results showed a decline from 11.5 MPa (0%) to 4.24 MPa (40%) after 7 days, with similar trends observed at 14, 21, and 28 days. Splitting tensile strength also decreased, with 0% replacement yielding 3.27 MPa at 28 days, compared to 1.62 MPa for 40% replacement. Flexural strength followed the same pattern, dropping from 8.5 MPa (0%) to 5.33 MPa (40%) at 28 days. While crumb rubber enhanced workability, its inclusion reduced compressive, tensile, and flexural strengths, compromising structural integrity. This research promotes sustainable civil engineering practices by utilizing waste materials, offering insights into optimizing crumb rubber content to balance workability and strength in construction applications for both economic and environmental benefits.

Keywords: Crumb rubber (CR); Quarry dust; Slump tests; Flexural strength; Compressive strength; Workability

1. Introduction

In modern construction, aesthetics and functionality drive material innovation, shaping the way infrastructure is designed and built [1]. Among these advancements, interlocking concrete paving stones have become a popular choice due to their durability, ease of installation, and aesthetic appeal. These paving stones are traditionally made from cement, fine aggregates, coarse aggregates, and water, ensuring strength and longevity in outdoor applications. However, the rising cost of construction materials and the environmental burden of solid waste disposal necessitate alternative solutions [2]. One such approach is the integration of waste crumb rubber, derived from discarded tires, into paving stone production. Huge waste rubber and plastic bottles are being generated with little means of disposal due to their non-degradable nature, while the costs of construction materials are increasing at an alarming rate which led to increase in construction cost [3]. The optimum use of Crumb rubber as a partial replacement for fine aggregate can be made up to 5% and could be used to reduce the water absorption rate and improve the compressive strength of mortar, [4]. Waste tires present a significant environmental challenge due to their non-biodegradable nature and increasing accumulation worldwide. Global rubber waste production continues to rise, with millions of discarded tires contributing to pollution and landfill overflow [5]. Without proper recycling strategies, these materials pose serious ecological and health risks, including air and soil contamination from improper disposal methods (Ahmed, 2023). Crumb rubber,

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obtained through the mechanical grinding of waste tires, offers a sustainable alternative for partial replacement of conventional aggregates like quarry dust, which is becoming increasingly expensive in many regions, including Nigeria [6]. Utilizing crumb rubber in interlocking paving stones not only provides an eco-friendly solution to tire waste management but also helps reduce reliance on quarry dust, lowering production costs. Interlocking paving stones have been widely adopted in residential, commercial, and industrial settings due to their flexibility, strength, and ability to withstand varying loads [7]. The durability of concrete incorporating crumb rubber (CR) is adversely affected due to the incompatibility of the CR particles with other ingredients of conventional concrete [8]. By incorporating crumb rubber as a partial substitute for quarry dust, paving stones could achieve enhanced workability, improved resilience, and better impact resistance, although the potential effects on compressive strength require thorough investigation [9, 10 and 11]. In regions like south west of Nigeria, where improper waste disposal contributes to environmental degradation, repurposing waste tires into construction materials aligns with global sustainability efforts [12, 13 and 14]. This study explores the feasibility of using crumb rubber as a partial replacement for quarry dust in interlocking paving stone production, focusing on its impact on strength properties, workability, and overall performance. Through this approach, the research aims to promote cost-effective, sustainable construction while addressing the environmental concerns associated with waste tire disposal.

2. Methodology

This study explores the impact of crumb rubber as a partial replacement for quarry dust in the production of interlocking paving stones. It analyzes the variation in strength properties with increasing crumb rubber content and determines the optimal replacement percentage that achieves the best performance.

The research was conducted through laboratory experiments at the Concrete and Materials Laboratory, Department of Civil Engineering, Ajayi Crowther University. This chapter details the experimental procedures, testing methods, and results obtained. A series of tests were carried out to assess the properties of crumb rubber (CR) and quarry dust at varying replacement levels in interlocking paving stones (concrete paver blocks).

2.1. Materials

The materials used in the production of crumb rubber (CR) interlocking paving stones include:

- Cement
- Quarry dust (stone dust)
- Crumb rubber (shredded waste tires)
- Portable water
- Engine oil (lubricant)
- Interlocking moulds

Cement was used as a binder in the production of interlocking paving stones, while quarry dust served as the primary fine aggregate. Crumb rubber replaced a portion of the quarry dust to assess its effect on the mechanical properties of the paving stones. Engine oil was applied as a mould release agent to facilitate the easy removal of the paving stones.

2.2. Material Sourcing and Sample Preparation

The materials used in this study were sourced from a location in Ibadan, Oyo State. The cement and lubricating oil were purchased from a local distributor. Quarry dust (stone dust) was obtained from a granite quarry in Lagos, while the potable water used for mixing was drawn from the borehole at the Engineering Workshop, Ajayi Crowther University. The crumb rubber, derived from discarded vehicle tires, was sourced from local vulcanizers and tire recycling centers in Gate, Ibadan, Oyo State. The collected rubber waste was then processed into fine particles through mechanical grinding and sieve as shown in figure 1

Figure 1 Processed powdered crumb rubber

2.3. Sample Preparation

The inner surface of the moulds was coated with engine oil to ensure easy removal of the interlocking paving stones after casting. Once lubricated, a mixture of cement, quarry dust, and crumb rubber was batched by weight in a 1:6 ratio (cement to quarry dust). A water-cement ratio of 0.45 was used to achieve the desired workability. The prepared mixture was poured into the moulds using a hand trowel, ensuring a smooth and even surface. Manual mixing was carried out using shovels, head pans, and buckets to ensure uniformity. For each mix, 15 specimens were produced, resulting in a total of 180 interlocking paving stones. Strength tests were conducted at different curing ages, with 45 specimens tested per curing period. The quarry dust was partially replaced with crumb rubber at varying levels of 10%, 20%, 30%, 40%, and 50% to assess its effect on the performance of the paving stones.

2.4. Sieve Analysis:

Sieve analysis was carried out on the quarry dust to determine the particle size distribution of quarry dust. This was done by sifting a weighed sample of quarry dust through a stack of wire mesh sieves on a mechanical sieve shaker. Separating it into discrete size range, a sieve shaker is used to vibrate the sieve stack for a period of time, after which each sieve with retained quarry dust was weighed and recorded. Sieve analysis was conducted on the quarry dust and Crumb rubber after oven dry for 24hours in accordance with BS 1377-1979.

2.5. Mixing Process

After obtaining the weight of cement, crumb rubber and stone dust required, mixing was done manually by adding water to the constituents and thoroughly mixed. Proportions of mix is cast and placed into the moulds with the aid of the hand trowel. The cast products are then left for 24 hours to set properly in Figure 2 before they were removed from the mould. The interlocks were cured by placing them in a curing tank for 7, 14, 21 and 28 days to attain adequate strength and the physical strength were carried out on the interlocks.

Figure 2 Interlocking paving stones

2.6. Slump test

The slump test was carried out on the fresh concrete to determine the workability of the concrete.

2.7. Compressive Strength Test

Compressive strength test on the cured paving stone specimens was carried out in accordance with BS EN 12390-3:2019 at 7, 14, 21 and 28 days. The specimen was loaded up on the compression testing machine until failure occurs. The maximum load capacity of. Compressive strength machine used for this research is 2000 kN. The strength of each specimens determined using equation 1 below.

$$\text{Compressive strength } (N/mm^2) = \frac{\text{Crushing}}{\text{Cross section area of paving stone}} \quad equation\ 1$$

2.8. Flexural Strength Test

Flexural strength test on the cured paving stone specimens was performed in accordance with BS EN 12390-3:2019 at 7, 14, 21 and 28 days. The specimen was loaded up in the universal testing machine until failure occurs. The maximum load capacity of the UTM machine used is 600kN. Flexural strength value of the specimen was determined using equation 2.

$$\text{Flexural strength} - \sigma\ (N/mm^2) = \frac{3\text{PL}}{2\text{BH}^2} \qquad equation\ 2$$

Where P is the breaking load, L is the span of the simple support, B is the width and H is the thickness of the specimen.

2.9. Tensile Strength Test

Tensile strength test on the cured paving stone specimens was performed in accordance with BS EN 12390-3:2019 at 7, 14, 21 and 28 days. The specimen was loaded up in the universal testing machine until failure occurs. The maximum load capacity of the machine used is 600kN.

3. Results and discussion

3.1. Sieve Analysis of Quarry Dust and Crumb Rubber

The results of the sieve analysis for quarry dust are presented in Table 1. The analysis reveals a well-graded material, with the mass of quarry dust retained for various sieve sizes, along with the percentage mass retained and cumulative percentage retained. As the sieve size decreases, the percentage mass retained increases, indicating that larger particle sizes dominate the sample. The majority of particles fall within the range of 600 µm to 1.18 mm, with a significant portion passing through smaller sieves. This particle size distribution is critical for evaluating the suitability of quarry dust in construction applications, particularly in the production of interlocking paving stones. Similarly, Table 2 presents the sieve analysis results for crumb rubber, showing the mass retained for various sieve sizes and the percentage of crumb rubber passing through each sieve. As the sieve size decreases, the percentage mass retained increases, suggesting that larger particle sizes are more prevalent in the sample. The majority of crumb rubber particles are retained in the larger sieves, with significant percentages passing through smaller ones. This data provides insight into the particle size distribution of crumb rubber, which is essential for assessing its potential as a partial substitute for quarry dust in the production of interlocking paving stones. Understanding the physical characteristics of crumb rubber is crucial for determining its compatibility and effectiveness in this application.

These results highlight the importance of particle size distribution in evaluating the performance of quarry dust and crumb rubber in paving stone production. The findings provide a foundation for further investigation into the feasibility of using crumb rubber as a sustainable alternative in construction materials.

Table 1 Sieve analysis of Quarry dust [Weight of quarry dust 'W'= 1000g.]

Sieve size (mm)	**Mass of quarry dust retained (g)**	**Percentage mass of quarry dust retained (%)**	**Cumulative percentage mass of quarry dust retained (%)**	**Percentage of quarry dust passing (%)**
5	17	1.7	1.7	98.3
3.35	54	5.4	6.8	93.2
2	73	7.3	14.1	85.9
1.18	179	17.9	33.7	66.3
600 µ	286	28.6	62.6	37.4
425µ	272	27.2	89.6	10.4
212µ	90	9.0	98.6	1.4
150µ	0	0	98.6	0
63µ	0	0	98.6	0
Base	0	0	98.6	0

Table 2 Sieve analysis of Crumb Rubber (CR) Weight of milled plastic bottle = 1000g

Sieve Diameter (mm)	**Mass of Sieve (g)**	**Mass of Sieve & CR (g)**	**Mass Retained (g)**	**Mass Retained (%)**	**CR Passing (%)**
4.750	340.0	350.0	0.00	0.0	100.0
2.000	330.0	342.0	2.00	0.1	99.9
1.180	300.0	306.0	6.00	0.5	99.1
0.600	336.0	348.0	12.00	1.0	98.0
0.425	322.0	986.0	664.00	66.5	31.8
0.300	304.0	531.0	227.00	22.6	8.7
0.212	330.0	376.0	42.00	4.3	4.5
0.150	273.0	296.0	22.00	2.3	2.3
0.075	270.0	294.0	22.00	2.1	0.2
0.063	332.0	334.0	2.00	0.3	0.1

Pan	232.0	232.0	0.00	0.0	0.1
		TOTAL:	**999.00**	**99.9**	

3.2. Slump Test

Table 3 demonstrates the correlation between the percentage of crumb rubber (used as a partial substitute for quarry dust) and the corresponding slump values, measured in millimeters, which reflect the workability of the concrete mixture. As the proportion of crumb rubber increases from 0% to 40%, the slump values rise progressively from 2 mm to 11 mm. This trend indicates that the inclusion of crumb rubber improves the workability and flow ability of the concrete. The results suggest that higher percentages of crumb rubber lead to increased slump values, signifying enhanced workability—a critical factor in the production of interlocking paving stones and other construction applications.

Table 3 Percentage of crumb rubber and the corresponding slump values

Percentage Replacement With CR	Slump (mm)
0%	2
10%	5
20%	7
30%	10
40%	11

3.3. Compressive Strength Analysis

The Table 4 below presents the compressive strength results of concrete samples at various curing periods (7, 14, 21, and 28 days) with different percentages of crumb rubber as a partial replacement for quarry dust. The results indicate that the compressive strength of the interlocking paving stones decreases as the percentage of crumb rubber replacement increases, ranging from 10% to 40%. The data, detailed in table 4, reveals that while the strength of the concrete improves with curing age (e.g., 14-day strength is higher than 7-day, and 28-day strength is higher than 21-day), the overall compressive strength declines with higher crumb rubber content.

As the percentage of crumb rubber increases from 0% to 40%, a consistent reduction in compressive strength is observed across all curing periods. This suggests that while crumb rubber may improve certain properties like workability, its inclusion adversely affects the structural integrity and long-term durability of the concrete. These findings highlight the need for careful consideration when incorporating crumb rubber into concrete mix designs, particularly for applications requiring high strength and durability, such as interlocking paving stones.

Table 4 Compressive Strength Analysis Results

Percentage Replacement	7 days	14 days	21 days	28 days
0	11.5	12.33	12.37	12.69
10	10.45	12.15	12.25	12.22
20	6.47	10.03	10.44	10.44
30	5.73	8.51	8.95	9.57
40	4.24	4.92	7.94	8.02

3.4. Splitting Tensile Test on Hardened Concrete with Crumb Rubber Replacement

The results of the splitting tensile test, indicating that the replacement of quarry dust with crumb rubber reduces the tensile strength of the produced interlocking paving stones. The data detailed in Table 5 below, shows that at 7 days, the 0% replacement sample exhibits the highest strength, followed by the 10% replacement, with strength decreasing as the percentage of crumb rubber increases. However, as the curing age of the paving stones increases, their tensile strength also improves. For instance, the 28-day strength is greater than the 21-day strength, and the 21-day strength is higher than the 14-day strength.

From these results, it is evident that replacing quarry dust with crumb rubber negatively impacts the tensile strength of the paving stones. The splitting tensile strength results demonstrate the performance of concrete samples with varying percentages of crumb rubber at different curing periods (7, 14, 21, and 28 days). A clear trend is observed: as the percentage of crumb rubber increases, the splitting tensile strength decreases consistently across all curing periods. This indicates that higher proportions of crumb rubber reduce the concrete's ability to resist tensile stresses as also stated by (Kaushik et al., 2022).

Table 5 Splitting Tensile Test Results

Percentage Replacement	7 days	14 days	21 days	28 days
0	2.2	2.65	2.9	3.27
10	1.89	2.27	2.66	2.90
20	1.65	1.83	1.99	2.32
30	1.16	1.4	1.70	1.98
40	1.2	1.49	1.54	1.62

3.5. Flexural Strength on Hardened Concrete with Crumb Rubber Replacement

The flexural strength results illustrated below in Table 6 shows the performance of concrete samples with varying percentages of crumb rubber as a partial replacement for quarry dust at different curing periods (7, 14, 21, and 28 days). A clear trend is observed: as the proportion of crumb rubber increases, there is a consistent reduction in flexural strength across all curing periods. This indicates that higher concentrations of crumb rubber diminish the concrete's resistance to bending stresses.

The findings suggest that incorporating crumb rubber as a substitute for quarry dust adversely affects the concrete's ability to withstand bending forces, potentially compromising its structural integrity and load-bearing capacity. These results highlight the importance of carefully considering the trade-offs when using crumb rubber in concrete mix designs, particularly for applications requiring high flexural strength and durability, such as interlocking paving stones.

Table 6 Flexural Strength Results

Percentage Replacement	7 days	14 days	21 days	28 days
0	6.65	6.95	7.8	8.5
10	6.07	6.72	7.1	7.40
20	5.09	6.23	6.4	6.70
30	4.34	5.16	5.25	5.55
40	3.4	3.9	4.4	5.33

4. Conclusions

While crumb rubber enhances workability, its inclusion as a partial replacement for quarry dust reduces compressive, tensile, and flexural strengths, compromising structural integrity; thus, its use should be carefully optimized to balance workability and strength in interlocking paving stone production.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors, Olaniyi Oluwole A *, Oyelami Afeez K and Adeyemi Festus O., thereby disclosed that is no conflict of interest during the research work. All names of product mentioned in the research work were original and real.

Author contributions

Conceptualization: Olaniyi O.A. Methodology: Oyelami A.K and Adeyemi F.O. formal Analysis: Olaniyi O.A. and Oyelami A.K. investigation: Adeyemi F.O. and Olaniyi O.A. writing original draft preparation: Olaniyi O.A and Oyelami A.K. and editing: Olaniyi O.A. and Adeyemi F.O. The final manuscripts was read and approved by ALL the authors.

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