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Enhancing he Sustainability and Performance of Bituminous Concrete Using Ceramic Waste and Copper Slag Additives

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Abstract
This study investigates the use of ceramic dust and copper slag as partial replacements in bituminous concrete to enhance performance and sustainability. Marshall Stability tests were conducted on traditional bituminous concrete with VG-30 bitumen in varying proportions (4%, 5%, 6%, 7%, and 8%), identifying 6% as the optimal content. Further tests with ceramic dust (5%, 10%, 15%, 20%, 25%) and copper slag (10%, 20%, 30%, 40%) found 10% ceramic dust and 20% copper slag to perform best individually. The combination of 10% ceramic dust and 20% copper slag showed the highest stability, improved strength, and better moisture resistance. This approach not only enhances pavement performance but also promotes environmental sustainability by repurposing industrial waste.

Keywords: Bituminous Concrete, Ceramic Waste, Copper Slag, Sustainable Pavement, Marshall Stability Test, Industrial Waste Recycling, Performance Enhancement, Eco-Friendly Construction.

1. INTRODUCTION

Road construction relies heavily on natural aggregates and bitumen, leading to resource depletion and environmental degradation. Incorporating industrial by-products like ceramic waste and copper slag into bituminous concrete addresses these challenges by enhancing performance while promoting sustainability. Ceramic waste, originating from discarded tiles and sanitary ware, is characterized by high strength, low water absorption, and durability, making it a suitable partial replacement for traditional fillers. Similarly, copper slag, an industrial by-product from copper smelting, offers high density, angularity, and excellent moisture resistance, making it an effective substitute for fine aggregates.

To ensure a fair comparison, we first conducted a Marshall Stability test on traditional bituminous concrete prepared with VG-30 grade bitumen in varying proportions of 4%, 5%, 6%, 7%, and 8%. The results indicated that 6% bitumen yielded the highest stability and optimum performance. Hence, all subsequent tests involving ceramic dust, copper slag, and their combinations were conducted using 6% bitumen as the baseline binder content.

Previous studies have shown that incorporating waste materials can enhance bituminous concrete's mechanical properties, but finding the optimal combination is crucial. Through comprehensive laboratory testing, this study determined that 10% ceramic dust and 20% copper slag individually yielded optimal performance in terms of strength and durability. Furthermore, a combination of 10% ceramic dust and 20% copper slag demonstrated the highest Marshall Stability value, surpassing other mix ratios. This indicates a synergistic effect between the two additives, balancing strength, flexibility, and moisture resistance. By using these industrial wastes effectively, this study aims to provide a cost-efficient, eco-friendly alternative for sustainable road construction.

2. METHODOLOGY

2.1 Material Collection and Preparation

- **Bitumen:** Standard penetration grade bitumen (VG-30).
- **Ceramic Waste:** Crushed ceramic tiles and sanitary ware, finely ground.
- **Copper Slag:** By-product from copper smelting, angular and coarse.
- **Aggregates:** Fine aggregate and 6mm,12mm,20mm Coarse Aggregate.

2.2 Mix Design Development

- **Traditional bituminous concrete:** 4%, 5%, 6%, 7%, 8% (Bitumen)
- **Ceramic Dust:** 5%, 10%, 15%, 20%, 25% (by weight of fine aggregate).
- **Copper Slag:** 10%, 20%, 30%, 40%, 50% (by weight of fine aggregate).

2.3 Laboratory testing

2.3.1 Preliminary test

We conducted preliminary tests to assess the physical and mechanical properties of materials. For aggregates, we performed impact value tests, Los Angeles abrasion tests, flakiness and elongation index tests, specific gravity tests, and water absorption tests. The ceramic dust and copper slag underwent specific gravity tests to ensure they met the required standards for use as additives. Additionally, the bitumen was tested for its softening point and ductility to ensure it maintained the necessary performance characteristics when mixed with these additives.

Table 1 Aggregate Tests

	Impact value	Abrasion Value	Specific Gravity	Water Absorption Value
Aggregate	17%	30%	2.8	0.32%

Table 2 Bitumen Tests

	Softening point	Ductility Value
Bitumen	47 °C (VG-30)	53

Specific Gravity of Ceramic Dust: 2.79
Specific gravity of copper slag: 3.71

2.3.2 Traditional Bituminous Concrete

Traditional bituminous concrete is widely used in road construction due to its durability, flexibility, and ability to withstand traffic loads and weathering. It consists of a mixture of aggregates (coarse and fine) bound together by bitumen, which acts as a binder. This type of pavement is designed to provide a balance between strength, stability, and flexibility — essential for long-term performance under varying traffic and environmental conditions. However, traditional mixes heavily rely on natural aggregates and bitumen, contributing to resource depletion and environmental concerns. For comparison, we prepared traditional bituminous concrete mixes with VG-30 bitumen in varying proportions of 4%, 5%, 6%, 7%, and 8%. Each mix underwent a comprehensive Marshall Stability test to evaluate stability, flow, bulk density, air voids, and voids filled with bitumen (VFB). The results indicated that 6% bitumen provided the highest stability, balanced flow, and optimal voids content, making it the ideal bitumen content for further experimentation. This proportion ensured the mix achieved durability, load resistance, and workability — essential parameters for high-performance bituminous concrete.

Table 3 Marshal Stability test on Traditional Bituminous Concrete

Percentage of Bitumen	Stability Value (KN)	Flow (mm)	Unit Weight (g/cc)	Va(%)	Vb(%)	VMA(%)	VFB(%)
4%	14.23	6.8	2.42	8.68	9	17.68	50.90
5%	15.52	8.12	2.45	6.13	11.28	17.41	64.79
6%	16.28	8.86	2.49	3.48	13.63	17.11	79.66
7%	12.45	9.24	2.42	4.7	15.31	20.01	76.51
8%	11.09	9.95	2.36	5.6	16.90	22.5	75.11

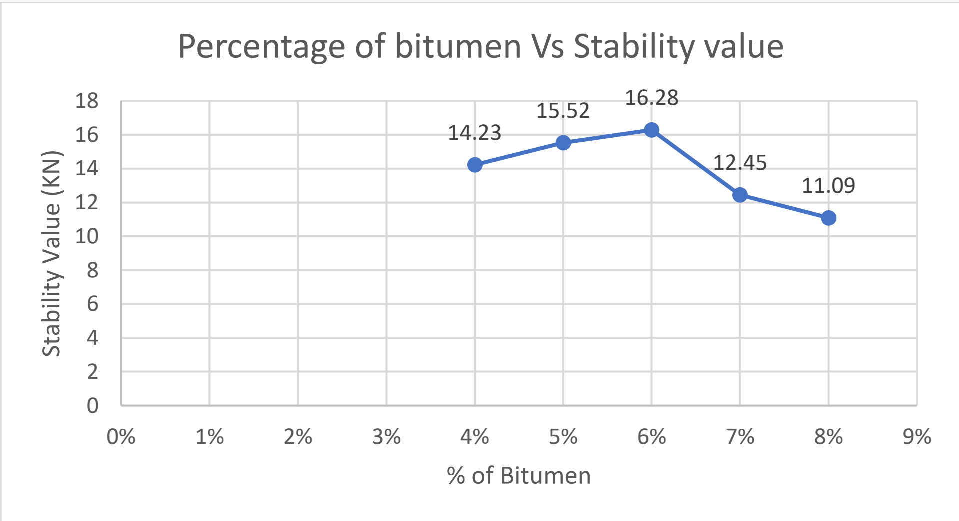

CHART 1 Percentage of bitumen Vs Stability value

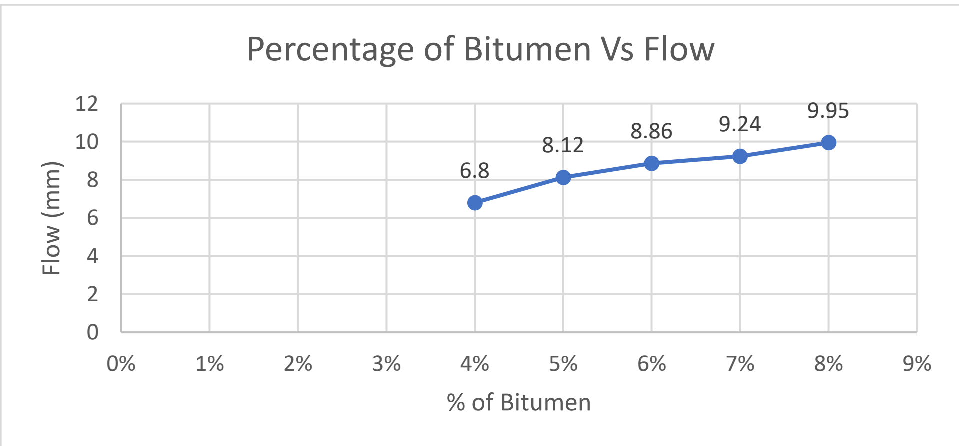

CHART 2 Percentage of bitumen Vs Flow

2.3.3 Ceramic Tile Waste as partial replacement

Ceramic tile waste, primarily derived from discarded tiles and sanitary ware, is an excellent alternative material for sustainable construction. It possesses high strength, low water absorption, and good durability, making it suitable for use as a partial replacement in bituminous concrete. The chemical composition of ceramic waste, rich in silica and alumina, contributes to enhanced bonding with bitumen, improving the mixture's stability and strength. Additionally, utilizing ceramic waste helps reduce the environmental burden of landfilling, cuts down the demand for natural aggregates, and supports eco-friendly infrastructure development. Ceramic tile waste was used as a partial replacement for the fine aggregates in bituminous concrete. We used bituminous concrete with a fixed bitumen content of 6% and introduced ceramic tile waste in different proportions — 5%, 10%, 15%, 20%, and 25%. Among these variations, the mix containing 15% ceramic waste exhibited better performance than traditional bituminous concrete in terms of stability, strength, and durability. The substitution of fine aggregates with ceramic tile waste helps reduce reliance on natural resources while offering a sustainable alternative that enhances mechanical properties. This method not only supports eco-friendly construction but also diverts industrial waste from landfills, contributing to a circular economy approach in road infrastructure.

Table 4 Marshal Stability test on Bituminous Concrete with Ceramic Tile Waste as partial replacement

Percentage of Ceramic Waste	Stability Value (KN)	Flow (mm)	Unit Weight (g/cc)	Va(%)	Vb(%)	VMA(%)	VFB(%)
5%	15.35	8.2	2.44	5.23	13.35	18.58	71.85
10%	16.05	7.4	2.48	3.65	13.57	17.22	78.80
15%	17.82	6.5	2.51	2.44	13.74	16.18	84.91
20%	15.13	5.6	2.49	3.22	13.63	16.85	80.89
25%	13.87	4.4	2.42	5.83	13.24	19.07	69.43

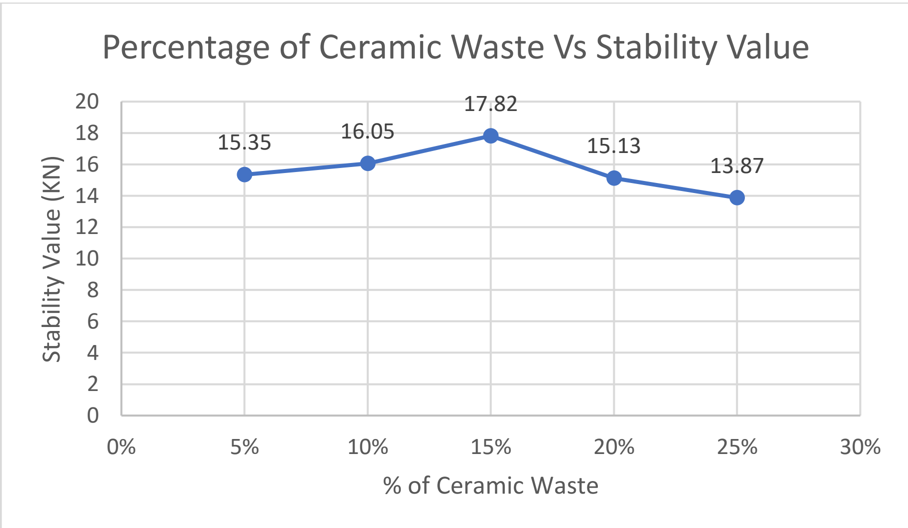

CHART 3 Percentage of Ceramic Waste Vs Stability Value

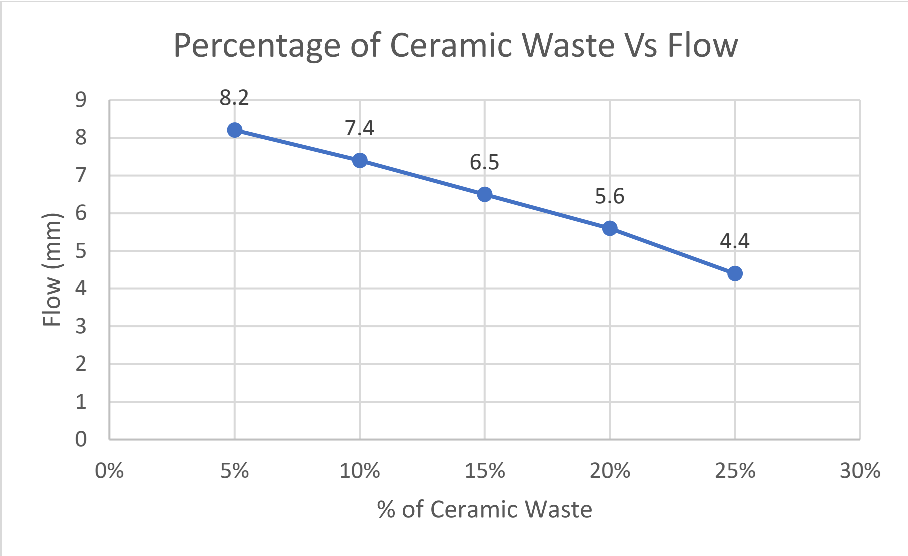

CHART 4 Percentage of Ceramic Waste Vs Flow

2.3.4 Copper Slag as partial replacement

We conducted a separate set of experiments using only copper slag in bituminous concrete with 6% bitumen. Copper slag was added in varying proportions of 10%, 20%, 30%, 40% and 50%. The results indicated that the mix with 20% copper slag achieved the highest stability among all the proportions tested, making it the most effective ratio for performance improvement.

Table 5 Marshal Stability test on Bituminous Concrete with Copper Slag as partial replacement

Percentage of Copper Slag	Stability Value (KN)	Flow (mm)	Unit Weight (g/cc)	Va(%)	Vb(%)	VMA(%)	VFB(%)
10%	16.32	10.2	2.47	4.59	13.52	18.11	74.65
20%	18.84	7.9	2.50	3.92	13.68	17.6	77.72
30%	17.55	7.6	2.56	2.14	13.90	16.04	86.66
40%	17.12	6.1	2.51	4.52	13.74	18.26	75.34
50%	15.96	4.9	2.45	7.3	13.41	20.71	64.75

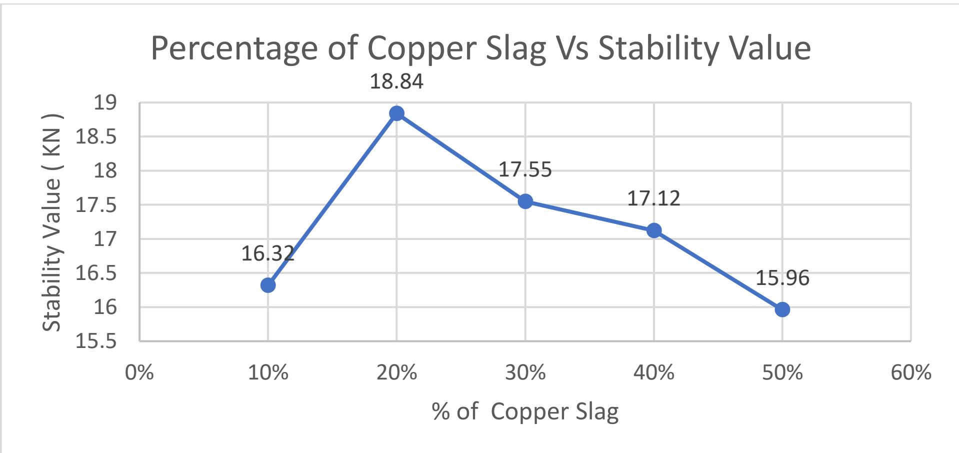

CHART 5 Percentage of Copper Slag Vs Stability Value

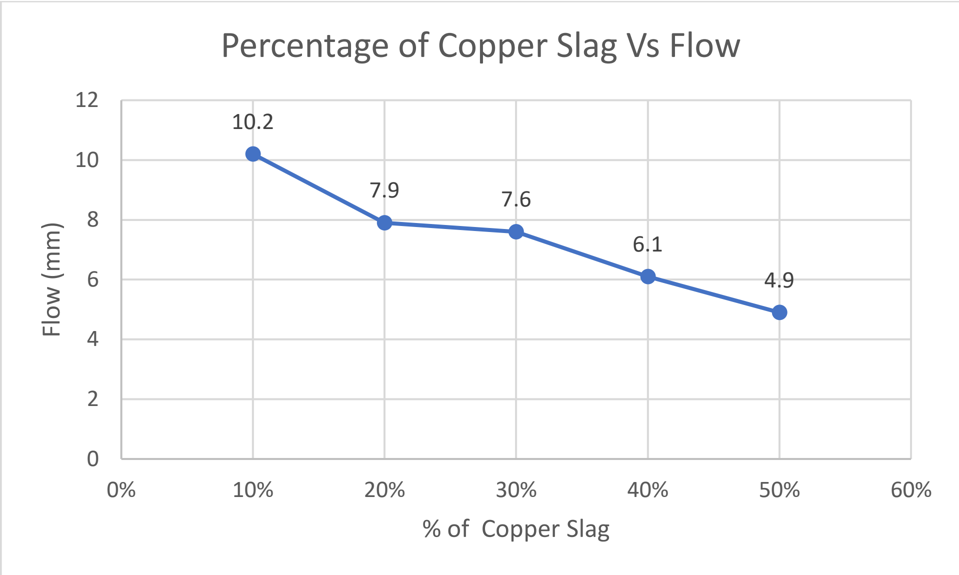

CHART 6 Percentage of Copper Slag Vs Flow

2.3.5 Ceramic Dust and Copper Slag as Partial Replacement

Copper slag is an industrial by-product generated during the smelting and refining of copper. It is characterized by its high density, angular particles, and excellent durability, making it an effective substitute for fine aggregates in bituminous concrete. The synergistic behavior of ceramic dust and copper slag likely arises from the contrasting physical properties of both materials — ceramic dust's fine, cohesive nature complements copper slag's angular, coarse particles. This combination balanced flexibility and rigidity, ensuring the mix maintained durability without becoming brittle. We conducted experiments on bituminous concrete with 6% bitumen, combining ceramic tile waste and copper slag in various proportions: 15% and 15%, 10% and 20%, 20% and 10%, 7.5% and 22.5%, and 22.5% and 7.5%. We replaced about 30 % of fine aggregate. Among these combinations, the mix containing 10% ceramic tile waste and 20% copper slag demonstrated the highest stability, outperforming all other variations.

Table 4 Marshal Stability test on Bituminous Concrete with a combination of Ceramic Tile Waste and copper slag as partial replacement

Combination of Ceramic Waste and Copper Slag in ratio	Stability Value (KN)	Flow (mm)	Unit Weight (g/cc)	Va(%)	Vb(%)	VMA(%)	VFB(%)
1:1	18.91	8.3	2.55	1.66	13.96	15.62	89.97
1:2	19.67	8.4	2.57	1.15	14.07	15.22	92.44
2:1	16.99	8.7	2.52	2.51	13.79	16.3	84.60
1:3	18.83	8.5	2.54	2.45	13.90	16.35	85.01
3:1	16.21	8	2.49	3.52	13.63	17.15	79.47

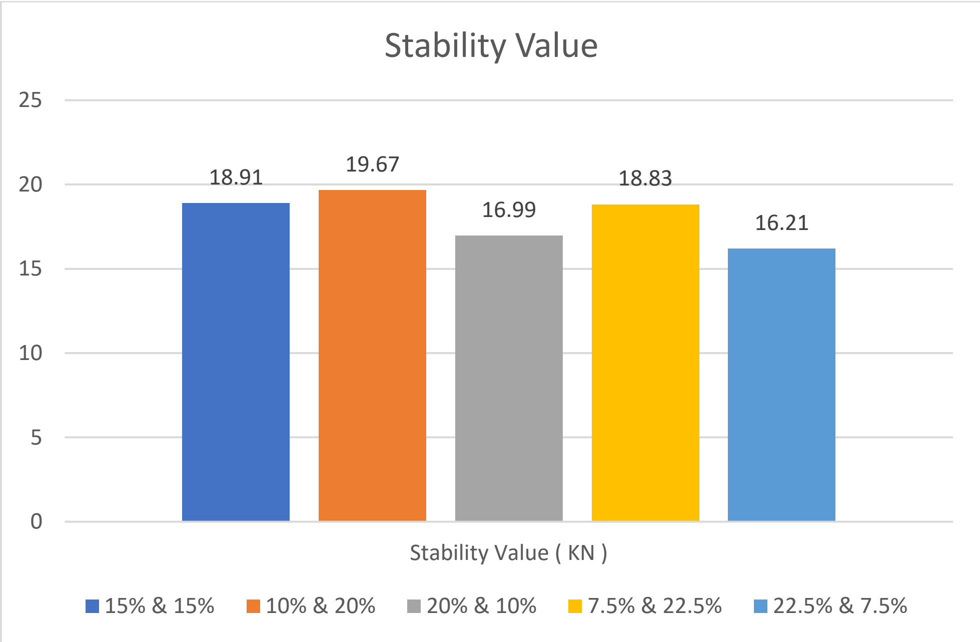

CHART 7 Percentage of ceramic tile waste, Copper Slag Vs Stability value

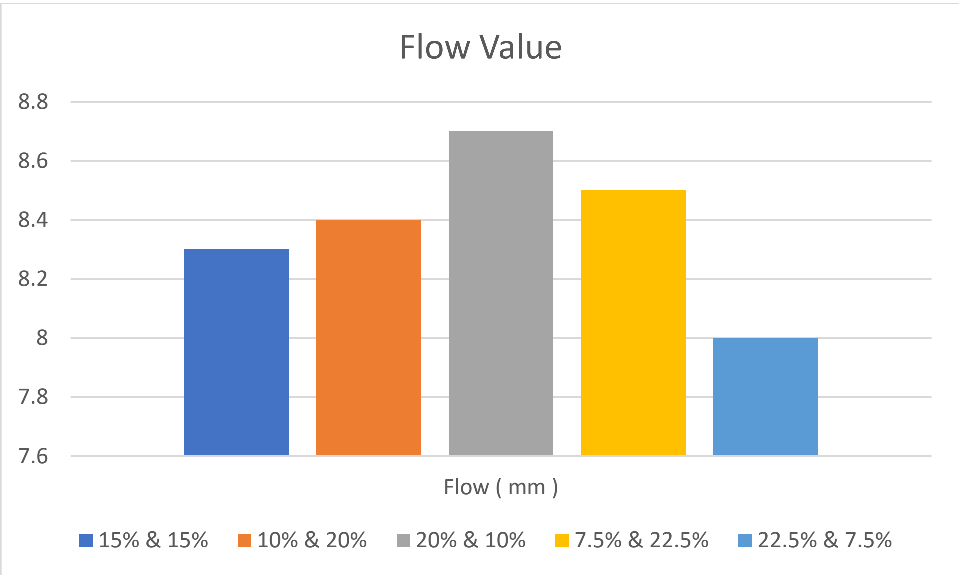

CHART 8 Percentage of ceramic tile waste, Copper Slag Vs Flow

3. CONCLUSION

The study demonstrates that incorporating ceramic dust and copper slag as partial replacements in bituminous concrete significantly enhances its performance and sustainability. Among the various proportions tested, the combination of 10% ceramic tile waste and 20% copper slag yielded the highest Marshall Stability, surpassing both traditional bituminous concrete and other experimental mixes. This optimal combination exhibited improved strength, moisture resistance, and durability, making it a promising alternative for pavement construction. Individually, 10% ceramic tile waste and 20% copper slag were identified as the most effective proportions, offering enhanced stability compared to the control mix. The combination of both materials, however, produced a synergistic effect, further improving the overall performance. The results suggest that ceramic dust enhances the mix's cohesive properties, while copper slag improves the load-bearing capacity and moisture resistance, creating a balanced, high-performance blend. Moreover, the use of industrial waste materials supports environmental sustainability by reducing the reliance on natural aggregates, minimizing landfill waste, and promoting a circular economy in road construction. This study encourages further research on optimizing waste material combinations and assessing long-term field performance to ensure practical implementation in large-scale infrastructure projects.

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