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Carbon Footprint Reduction in Road Construction: Experimental Evaluation of Sustainable Materials for Rigid Pavement Concrete

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Abstract: ***Road construction consumes large quantities of cement, aggregates, bituminous materials and fossil fuel energy. The production and transportation of these materials, together with on-site construction operations, contribute to greenhouse gas emissions. This paper examines the use of natural and waste-derived materials in rigid pavement concrete, based on the experimental programme reported in the supplied thesis. The materials considered are human hair, bamboo pieces/fibre, coconut (coir) fibre, ground granulated blast furnace slag (GGBS) and fly ash. The study compares compressive strength at different curing ages and material replacement or addition levels. The reported results indicate that human hair addition increased the 28-day M30 compressive strength from 33.60 MPa for the control mix to 37.25 MPa at 3% addition. Coconut fibre produced the highest reported 28-day strength of 40.50 MPa at 5% addition. For GGBS, the highest 28-day average strength was 34.22 MPa at 30% replacement, compared with 29.98 MPa for the control. In contrast, the bamboo series showed a progressive reduction in compressive strength as the reported replacement level increased, while fly ash replacement above 5% reduced 28-day strength in the reported series. These results demonstrate that sustainable materials must be proportioned individually rather than assumed to improve all concrete properties at every dosage. The thesis identifies potential environmental benefits through reduced use of conventional cement and aggregates and the productive use of waste resources. However, a project-specific life-cycle carbon inventory was not reported; therefore, this paper does not claim a quantified percentage reduction in CO_2 emissions. Further work should combine mechanical testing with a transparent life-cycle assessment and field validation.***
Keywords: Carbon footprint, rigid pavement, sustainable concrete, human hair fibre, bamboo, coconut fibre, GGBS, fly ash, compressive strength, life-cycle assessment.

I. INTRODUCTION

Road infrastructure is essential for economic and social development, but its construction requires energy-intensive materials and equipment. Cement production contributes substantially to global carbon dioxide emissions because of clinker production and the energy required for kiln operation. Asphalt production, aggregate quarrying, crushing, material haulage and diesel-powered construction machinery add further emissions. Road projects may also cause land-use change and disturbance to soil, vegetation and drainage systems [1]–[4].

Reducing the carbon footprint of roads therefore requires attention to the complete project life cycle: raw-material extraction, material processing, transportation, construction, maintenance and end-of-life management. Life-cycle assessment (LCA) provides a systematic framework for evaluating these stages and comparing alternative pavement materials and construction methods [5]–[7].

In rigid pavement construction, concrete mix design offers opportunities to reduce embodied impacts through partial replacement of cement with supplementary cementitious materials and through the use of recycled or renewable constituents. Fly ash and GGBS are industrial by-products that can reduce the demand for Portland cement. Natural fibres such as human hair and coconut coir may act as crack-bridging reinforcement. Bamboo, when suitably processed and proportioned, is another renewable construction resource. Their benefits depend on material quality, dosage, dispersion, curing and the required pavement performance.

The , titled “Carbon Footprint Reduction in Road Construction”, investigates human hair, bamboo, coconut fibre, GGBS and fly ash in concrete. The present paper condenses its experimental findings and interprets the reported compressive-strength results in the context of sustainable rigid pavement construction.

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II. OBJECTIVES OF THE STUDY

1) To examine the potential use of human hair, bamboo, coconut fibre, GGBS and fly ash in rigid pavement concrete.
2) To compare the compressive strength of modified concrete mixes with the corresponding control concrete at the curing ages reported in the thesis.
3) To identify the dosage ranges that produced the highest reported compressive strength within each individual material series.
4) To discuss the potential resource-efficiency and carbon-reduction benefits, while identifying the need for quantified life-cycle assessment.

III. REVIEW OF RELATED WORK

Earlier studies cited in the thesis address carbon accounting for highway materials, pavement life-cycle assessment, green highway technologies and the use of alternative concrete constituents. Sreedhar et al. [1] developed a carbon-footprint calculation approach for highway construction materials in India, considering design, material production, transportation and construction. Baek et al. [2] evaluated green highway technologies and reported that low-carbon pavement and industrial by-product technologies can provide measurable emission reductions. Nema [3] discussed strategies for reducing carbon emissions in Indian road construction, including life-cycle assessment and construction-process optimisation.

Research on natural and recycled materials also supports the need to assess both mechanical performance and environmental value. Parikh et al. [4] discussed bamboo as a sustainable construction material. Naveen Kumar et al. [8] investigated human-hair-fibre-reinforced concrete and reported improvements in mechanical properties at suitable fibre contents. Pillay et al. [9] examined paper-mill waste ash as a partial cement replacement, while Aliu et al. [10] studied coconut fibre in cementitious members. The thesis further identifies a continuing need for consistent fibre treatment, dosage optimisation, long-term durability data, field trials and integrated LCA.

The research gap addressed by the thesis is the limited integrated evidence for combining natural fibres and industrial by-products in rigid pavement concrete in the Indian context. In particular, mechanical performance, durability, economic feasibility and full life-cycle emissions need to be assessed together. The present paper reports the mechanical results available in the thesis and treats carbon reduction as a potential benefit requiring separate quantification.

IV. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. *Materials*

The experimental programme used conventional concrete constituents—cement, fine aggregate, coarse aggregate and water—together with selected sustainable materials. The thesis identifies Portland-Pozzolana Cement (PPC), conforming to IS 1489:1991 Part I, in its material description. Human hair was collected from salons, cleaned, washed, dried and sorted. The reported hair dimensions were approximately 100–120 μm in diameter and 60 mm in length, with a stated tensile strength of 380 MPa. Coconut fibres were washed, coated with coconut oil and sun-dried. Bamboo pieces were reported with lengths of 2–4 cm, breadths of 1–2 cm and thickness of approximately 1 cm; the thesis describes these as a partial replacement for coarse aggregate. GGBS and fly ash were used as partial cement replacements.

B. *Mix variations and specimen preparation*

The thesis reports different dosage series for each material rather than one combined factorial mix. Human hair was incorporated at 0%, 1%, 2%, 3% and 4% by weight of cement. Bamboo pieces were used at 0%, 2%, 4% and 5% replacement levels. Coconut fibre was used at 4%, 5% and 6% by weight of cement. GGBS replacement levels were 0%, 5%, 10%, 20%, 30%, 40% and 50%; fly ash replacement levels were 0%, 5%, 10%, 15%, 20% and 25%.

Concrete cubes of 150 mm × 150 mm × 150 mm were cast, demoulded after approximately 24 hours and water-cured. The thesis reports testing at 7, 14 and 28 days for human hair, GGBS and fly ash; bamboo results are reported at 7, 28 and 56 days; and coconut-fibre results are reported at 7 and 28 days. Three specimens were reported for each dosage in the tabulated GGBS, bamboo and coconut results. The human-hair table provides one strength value per grade, dosage and curing age.

C. *Testing and Analysis*

Compressive strength was determined using a compression testing machine and is expressed in MPa (equivalent to N/mm²). For the three-replicate datasets, the mean strength was calculated as the arithmetic average of the three reported specimen values. Percentage change relative to the control was calculated as [(modified mix mean − control mean) / control mean] × 100.

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V. RESULTS AND DISCUSSION

A. Human hair fibre

For M30 concrete, the reported 28-day compressive strength increased from 33.60 MPa in the control mix to 35.40 MPa at 1%, 36.95 MPa at 2% and 37.25 MPa at 3% human hair. At 4%, the strength reduced to 35.25 MPa. The highest reported value was therefore obtained at 3% addition, representing an increase of approximately 10.86% over the control. The thesis interprets the improvement as a result of crack bridging and improved post-cracking behaviour, while excessive fibre content may create dispersion and workability problems.

Human hair (%)	M30 28-day strength (MPa)	Change vs. control (%)
0%	33.60	0.00
1%	35.40	5.36
2%	36.95	9.97
3%	37.25	10.86
4%	35.25	4.91

The human-hair results indicate that moderate addition can improve compressive strength in the reported mix. The paper does not treat the 3% result as a universal optimum because fibre characteristics, cement content, mixing procedure and pavement design requirements may vary.

B. Bamboo

The thesis describes bamboo pieces of 2–4 cm length as a partial replacement for coarse aggregate, although the chapter title and narrative also use the term bamboo fibre. The three-specimen averages are shown below. The control mix achieved 48.62 MPa at 28 days, while the 2%, 4% and 5% mixes achieved 43.31, 39.23 and 35.49 MPa, respectively. The data therefore show a progressive reduction in compressive strength with increasing bamboo content. The 2% mix retained more strength than the higher replacement levels, but it remained below the control.

Bamboo level (%)	7-day mean (MPa)	28-day mean (MPa)	56-day mean (MPa)
0%	25.03	48.62	54.83
2%	22.39	43.31	50.12
4%	18.71	39.23	45.66
5%	15.94	35.49	42.39

This result is important because it qualifies the sustainability argument: renewable content does not automatically improve compressive strength. Bamboo treatment, geometry, replacement basis, compaction and mix redesign should be optimised before pavement use. The thesis suggests limiting the bamboo level to around 2% or less where a balance of strength and potential crack-control benefits is sought; field validation remains necessary.

C. Coconut fibre

Coconut fibre was added at 4%, 5% and 6% by weight of cement. The reported 28-day mean strengths were 38.02, 40.50 and 39.02 MPa, respectively. The 5% mix produced the highest mean strength. The corresponding slump values in the source table ranged from 104 to 111 mm, with superplasticiser dosage increasing from 0.3% at 4% coir to 0.8% at 6% coir. This suggests that the fibre dosage influences fresh-concrete handling and admixture demand as well as hardened strength.

Coconut fibre (%)	7-day mean (MPa)	28-day mean (MPa)	Slump range (mm)
4%	22.52	38.02	109–111
5%	24.80	40.50	104–106
6%	23.60	39.02	104–106

The 5% coconut-fibre mix achieved a 28-day mean strength approximately 6.53% above the 4% mix. The thesis attributes the improvement to fibre-matrix interaction and crack bridging, while the slight reduction at 6% may be associated with fibre clustering or void formation. This dosage should be treated as the best-performing level within the tested series, not as a universal design recommendation.

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D. Ground granulated blast furnace slag (GGBS)

The GGBS series demonstrates a clear rise in compressive strength up to 30% replacement, followed by a substantial reduction at 40% and 50%. The control mix had a 28-day mean strength of 29.98 MPa. The 30% GGBS mix reached 34.22 MPa, an increase of approximately 14.15%. At 40% and 50%, the 28-day means fell to 23.12 and 20.47 MPa, respectively.

GGBS replacement (%)	7-day mean (MPa)	14-day mean (MPa)	28-day mean (MPa)	28-day change (%)
0%	20.78	25.60	29.98	-0.11
5%	21.47	25.60	30.97	3.18
10%	21.73	26.40	32.08	6.86
20%	22.14	29.26	32.55	8.43
30%	22.80	30.00	34.22	14.01
40%	17.07	20.63	23.12	-22.97
50%	14.65	17.07	20.47	-31.79

The result indicates that moderate GGBS replacement can improve the reported 28-day compressive strength while reducing the proportion of conventional cement. The thesis identifies 20–30% as the favourable range in this test series. Higher replacement levels may reduce the quantity of clinker available for early hydration and lower strength. A separate binder-performance and durability programme is required before selecting a field mix.

E. Fly ash

The fly-ash results show that the 5% replacement mix had a 28-day mean strength of 29.87 MPa, slightly below the control mean of 31.24 MPa. At 10%, 15%, 20% and 25%, the 28-day means decreased further to 24.35, 23.83, 22.92 and 22.38 MPa. Thus, within the reported dataset, the control mix had the highest 28-day strength and higher fly-ash replacement levels reduced compressive strength.

Fly ash replacement (%)	7-day mean (MPa)	14-day mean (MPa)	28-day mean (MPa)	28-day change (%)
0%	13.84	26.14	31.24	0.00
5%	14.93	28.94	29.87	-4.39
10%	9.32	24.17	24.35	-22.06
15%	9.58	18.65	23.83	-23.73
20%	10.11	17.07	22.92	-26.62
25%	7.45	14.20	22.38	-28.36

The thesis describes 5% as the most favourable fly-ash level among the replacement mixes, particularly for early strength; however, its 28-day average remains below the control. It would therefore be inaccurate to state that fly ash increased the 28-day compressive strength in this series. A mix-design adjustment and longer curing assessment may be needed to establish a suitable replacement level.

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F. Comparative Interpretation

Material series	Best reported level within tested series	Reported 28-day mean (MPa)	Interpretation
Human hair	3%	37.25	Highest M30 value in this dosage series; about 10.86% above control.
Bamboo pieces	0% control; 2% best among modified mixes	48.62 control; 43.31 at 2%	Strength reduced as bamboo replacement increased.
Coconut fibre	5%	40.50	Highest among the three tested coir dosages.
GGBS	30%	34.22	About 14.15% above the control mean.
Fly ash	0% control; 5% best replacement	31.24 control; 29.87 at 5%	All reported replacement levels were below control at 28 days.

VI. ENVIRONMENTAL SIGNIFICANCE AND CARBON ACCOUNTING

The environmental rationale for the investigated materials is based on three mechanisms: (i) reducing demand for Portland cement through partial replacement by industrial by-products such as GGBS and fly ash; (ii) diverting waste materials such as human hair and coconut coir into useful applications; and (iii) using renewable or locally available materials such as bamboo to reduce reliance on virgin resources. If these materials also improve durability and service life, the frequency of repairs and associated material and fuel consumption may be reduced.

The thesis discusses LCA as a framework for assessing emissions from material production, transportation, construction, maintenance and end-of-life stages. However, the experimental tables do not provide a project-specific bill of quantities, emission factors, transport distances, fuel consumption, maintenance scenario or functional-unit-based carbon inventory. No numerical CO_2-equivalent saving can therefore be calculated from the reported compressive-strength results alone. A defensible carbon comparison should use a defined functional unit (for example, 1 m^2 of pavement of specified thickness over a stated design life), consistent system boundaries and verified emission factors, following ISO 14040 and ISO 14044 [6], [7].

VII. CONCLUSIONS

The reported experiments show that the influence of sustainable constituents depends strongly on material type and dosage; no single percentage is suitable for all materials.

Human hair addition improved the reported M30 28-day compressive strength up to 3%, reaching 37.25 MPa compared with 33.60 MPa for the control. Strength reduced at 4%.

Coconut fibre produced its highest reported 28-day mean strength at 5% addition (40.50 MPa). The 6% mix showed a small reduction, indicating the need to control fibre dispersion and workability.

The GGBS series achieved its highest 28-day mean strength at 30% replacement (34.22 MPa), about 14.15% above the control. Strength declined sharply at 40% and 50%.

The bamboo series showed lower compressive strength as the replacement level increased. The 2% mix performed better than the 4% and 5% mixes but remained below the control.

In the fly-ash series, 5% was the best-performing replacement level, but its 28-day strength was still slightly below the control. Higher replacement levels resulted in lower reported strengths.

The use of waste-derived and industrial by-product materials has potential environmental value through resource conservation and waste utilisation. Nevertheless, the thesis does not report a quantified LCA result; carbon savings must be established through a separate life-cycle inventory and assessment.

Before field adoption, the proposed mixes require confirmation through repeat testing, durability evaluation, pavement-specific flexural performance assessment, cost analysis and field trials under actual traffic and climatic conditions.

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VIII. LIMITATIONS AND FUTURE SCOPE

The present paper is limited to the data and explanations contained in the supplied thesis. The reported test series use different grades, dosage bases and curing ages, and some sections do not provide complete raw datasets. The bamboo material is described in the thesis both as fibre and as pieces replacing coarse aggregate; this terminology should be clarified in future experimental documentation. Numerical results for several durability and tensile/flexural tests are not available in the reported tables. In addition, the study does not provide a quantified project-level carbon footprint or a complete cost comparison.

Conduct a complete LCA for a clearly defined pavement functional unit, including material production, transport, site fuel, maintenance and end-of-life stages.

Report full mix proportions, water-binder ratios, fibre dimensions, treatment methods, replicate-level results and statistical variability.

Evaluate flexural strength, split tensile strength, fatigue, abrasion, shrinkage, water absorption, sorptivity and resistance to chemical and weathering exposure.

Study hybrid combinations of fibres with GGBS or fly ash only after individual mix behaviour has been established.

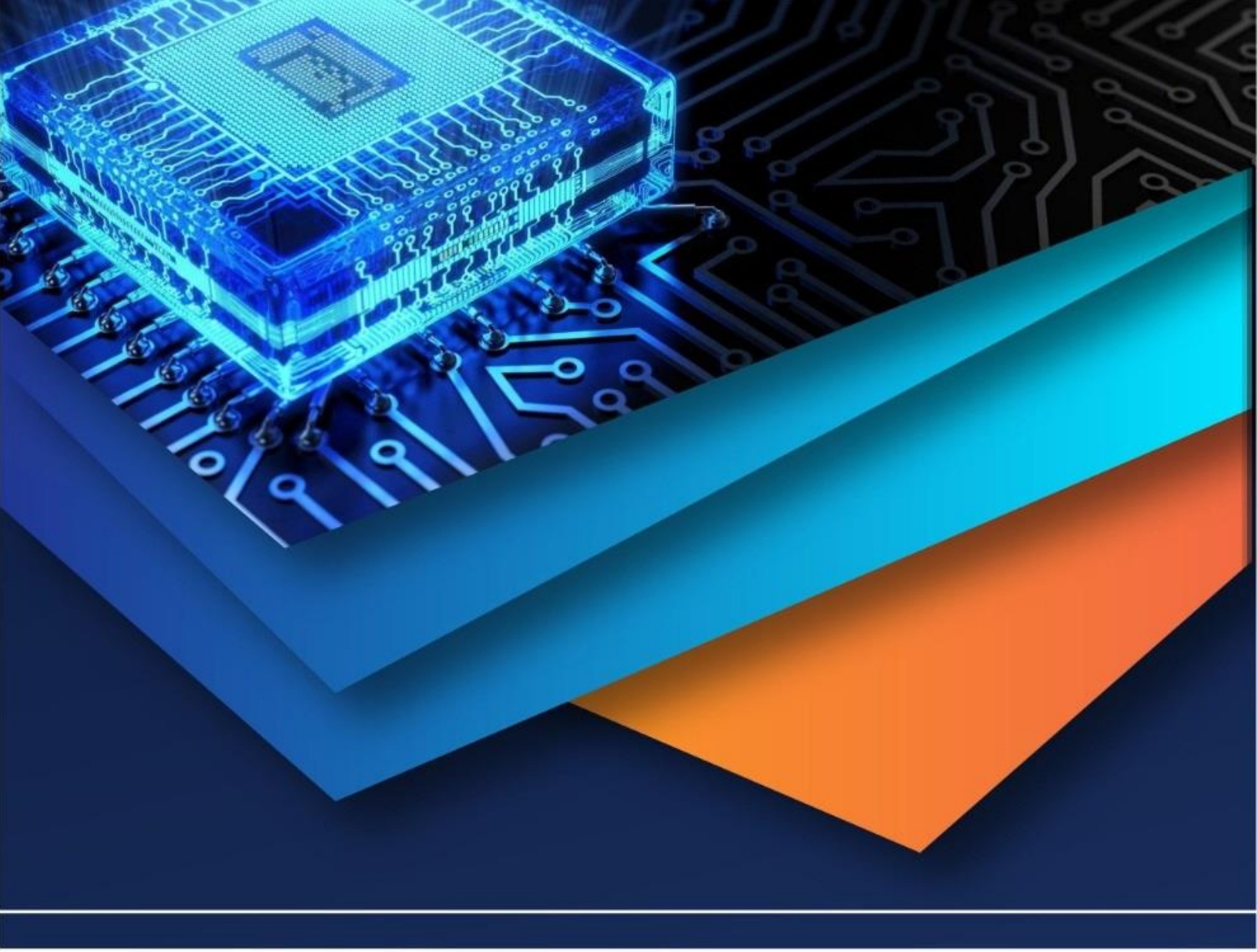
Carry out field trials and monitor cracking, riding quality, distress development and maintenance requirements over time.

Prepare a life-cycle cost analysis to compare initial material costs with potential maintenance savings and environmental benefits.

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