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Carbon Footprint Reduction in Road Construction

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ABSTRACT

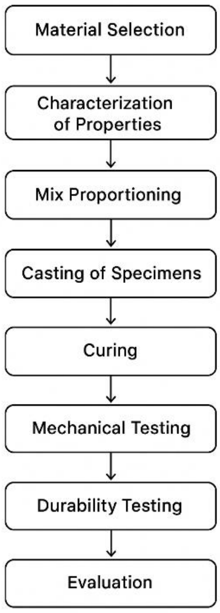
The present research focuses on the use of sustainable materials in rigid pavement construction, with a specific emphasis on incorporating natural fibers such as bamboo fiber, coconut fiber, and human hair fiber, along with supplementary cementitious materials including fly ash and ground granulated blast furnace slag (GGBFS). The study was carried out with the dual objectives of addressing pressing environmental concerns such as waste management, greenhouse gas emission reduction, and conservation of natural resources, while simultaneously enhancing the engineering performance and durability of rigid pavements. Through an extensive experimental program and analytical evaluation, the research demonstrated that these materials offer significant improvements in the mechanical, durability, and functional performance of pavement concrete when compared to conventional mixes. The findings establish that natural fibers serve as effective reinforcing agents, improving tensile strength, crack resistance, flexural performance, and post-cracking ductility, while industrial by-products such as fly ash and GGBFS improve workability, long-term strength gain, and resistance to environmental aggressiveness. The synergistic effects of fibers and supplementary cementitious materials resulted in optimized pavement mixes that displayed superior strength and resilience, along with extended service life and reduced maintenance requirements. Furthermore, the adoption of these materials contributes to the reduction of carbon footprint by minimizing dependence on cement and virgin aggregates, both of which are highly energy-intensive and environmentally harmful. The cost-effectiveness of these materials was also established, as the use of waste resources like human hair and coconut fiber, along with industrial by-products, resulted in lower raw material expenses, thereby reducing construction costs without compromising structural integrity. The broader implications of the research highlight the potential for large-scale adoption of such sustainable practices in civil engineering and infrastructure development.

By integrating these alternative materials, the construction industry can move towards more environmentally responsible methods that balance engineering performance with ecological sustainability. The results reinforce the idea that the incorporation of bamboo fiber, coconut fiber, human hair fiber, fly ash, and GGBFS in rigid pavement construction is not only technically feasible but also socially and environmentally necessary, aligning with global sustainability goals and paving the way for eco-friendly infrastructure systems.

1. INTRODUCTION

The transportation industry is widely acknowledged as a major source of global greenhouse gas (GHG) emissions, with road infrastructure development serving as a key contributor within this sector. Roads form the backbone of modern transportation networks, facilitating the movement of goods, services, and people, and contributing directly to economic growth and social development. However, the process of constructing and maintaining roads is inherently carbon-intensive, leading to substantial environmental impacts. A large proportion of these emissions originates from the production of construction materials, such as cement, asphalt, steel, and aggregates, which are fundamental to road construction. Cement manufacturing is responsible for nearly 8% of worldwide CO_2 emissions, primarily resulting from the calcination process and the substantial energy demand involved in clinker production. In a similar manner, asphalt—commonly used in flexible pavements—is derived from petroleum-based bitumen, whose extraction and refining contribute considerably to carbon emissions. Aggregates, though considered low-carbon in comparison, require quarrying, crushing, and transportation, which involve diesel-powered machinery that further contributes to the overall carbon footprint. In addition to material production, the operational phase of construction activities is a major source of emissions. Construction machinery, including excavators, bulldozers, rollers, and pavers, typically relies on fossil fuels such as diesel, and their continuous operation during excavation, grading, compaction, and paving releases large quantities of CO_2 and other pollutants. The intensity of fuel consumption varies depending on the scale of the project, terrain, and machinery efficiency, but collectively, the energy requirements for constructing a kilometer of highway can be staggering. For instance, heavy machinery emissions are not only a direct consequence of fuel combustion but also contribute indirectly by necessitating additional material production due to inefficiencies and waste. The construction process often leads to the overuse of materials, spillage, and repeated work due to design or execution errors, all of which amplify the carbon footprint. The transportation of construction materials from quarries, factories, or stockpiles to the construction site contributes significantly to greenhouse gas (GHG) emissions. Factors such as the mode of transport, distance traveled, and type of vehicle greatly influence the total emissions, emphasizing the need for efficient logistics planning in low-carbon road construction. Another major source of emissions is land-use change. Road construction often involves clearing vegetation, altering topography, and modifying drainage systems, which can release stored carbon from soil and biomass into the atmosphere. Converting forests or wetlands into paved surfaces reduces the land's carbon sequestration capacity, increasing net GHG emissions. Rapid urban expansion and encroachment into peri-urban and rural areas further exacerbate these impacts. Beyond direct emissions, road construction can cause indirect environmental consequences, such as disturbances to soil structure, hydrological cycles, and local ecosystems, potentially triggering additional emissions like methane release from disturbed soils or increased energy demand due to microclimatic changes affecting maintenance and operations. With the growing severity of climate change, there is an urgent global need to minimize carbon emissions from infrastructure projects. Governments, international organizations, and industry stakeholders are increasingly recognizing that traditional road construction methods are unsustainable. Policies including carbon pricing, emission reduction targets, and green certification schemes are being introduced to promote sustainable practices. Road agencies are exploring innovative approaches, such as the use of low-carbon materials, energy-efficient machinery, and optimized pavement designs that extend service life and reduce maintenance requirements. For example, incorporating supplementary cementitious materials (SCMs) like fly ash, slag, or silica fume as partial replacements for ordinary Portland cement can significantly lower embodied CO_2 while maintaining the structural strength and durability required for pavement performance. The use of waste-derived materials, such as recycled asphalt pavement (RAP), crushed concrete, and plastic-modified bitumen, offers dual benefits: diverting waste from landfills and reducing the demand for virgin materials, thereby mitigating associated carbon emissions. Advances in construction techniques, including mechanized paving, modular prefabrication, and intelligent compaction methods, further reduce operational emissions by lowering fuel consumption and shortening construction time. In addition to technological innovations, strategic planning plays a crucial role in minimizing carbon emissions in road projects. Life-cycle assessment (LCA) is a valuable tool for evaluating environmental impacts across the entire lifespan of a road, encompassing material production, transportation, construction, maintenance, and end-of-life disposal. LCA helps engineers and decision-makers identify high-emission stages and assess the benefits of alternative construction strategies. By adopting an integrated approach—combining material substitution, efficient construction practices, and design optimization—road projects can achieve substantial reductions in carbon emissions while maintaining functional performance and economic viability. Additionally, climate-responsive planning, including route alignment, gradient optimization, and local sourcing of materials, can further reduce the carbon intensity of projects. Within the context of sustainable development, reducing the carbon footprint of road construction is both an environmental imperative and a contribution toward international commitments, including the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), particularly those focused on climate action and the development of sustainable cities and communities. Road construction is a complex, resource-intensive process that contributes substantially to global GHG emissions through multiple pathways, including material production, machinery operation, transportation, and land-use change. As climate change concerns escalate, reducing carbon emissions from road infrastructure has become a critical priority. The utilization of low-carbon construction materials, energy-efficient machinery, and optimized design and planning approaches offers a viable pathway for reducing the environmental impacts associated with road construction. When these measures are incorporated within a life-cycle assessment (LCA) framework, they enable a holistic evaluation of environmental performance and support evidence-based decision-making in sustainable infrastructure development. Consequently, addressing the carbon footprint of road construction extends beyond a technical concern; it represents a strategic priority for fostering climate-resilient and sustainable transportation systems at the global level. The increasing global emphasis on sustainable construction practices has intensified research into alternative materials that not only enhance the durability and performance of infrastructure but also reduce reliance on non-renewable resources and mitigate environmental impacts. In rigid pavement construction, there is a growing focus on the use of natural fibers and industrial by-products, which offer notable mechanical, environmental, and economic advantages. Among natural fibers, bamboo, coconut, and human hair fibers have gained attention due to their wide availability, high tensile strength, biodegradability, and ability to enhance concrete performance. Bamboo fiber, in particular, is valued for its high strength-to-weight ratio, flexibility, and sustainability. Its inclusion in concrete improves the tensile capacity and reduces crack formation and propagation, thereby enhancing the durability of the pavement. Studies have shown that bamboo-reinforced concrete exhibits improved resistance to bending and cracking, which are crucial factors for extending the service life of rigid pavements and ensuring long-term structural performance. Coconut fiber, on the other hand, is distinguished by its excellent toughness, fibrous structure, and inherent resistance to water absorption, properties that make it a highly effective reinforcement material in concrete applications exposed to environmental stresses such as moisture variation, freeze-thaw cycles, and heavy traffic loads. Human hair fiber, often treated as an industrial or domestic waste product, offers a novel approach to resource utilization by serving as a reinforcing agent in concrete matrices, enhancing bonding and providing additional tensile strength, thereby mitigating the brittle nature of conventional concrete. These natural fibers, when appropriately processed and incorporated, can significantly improve the crack resistance, ductility, and toughness of rigid pavement structures, contributing to longer lifespan and reduced maintenance requirements. Similarly, industrial by-products such as ground granulated blast furnace slag (GGBFS) and fly ash have been widely investigated as partial replacements for cement because of their pozzolanic properties, which enhance the mechanical strength, durability, and long-term performance of concrete. GGBFS, a by-product of the steel manufacturing process, has demonstrated the ability to improve compressive strength, increase resistance to sulfate attack, enhance durability in aggressive environments, and lower permeability, thereby strengthening the overall resilience of pavement structures. Similarly, fly ash, a fine particulate residue from coal-fired power plants, improves workability, reduces water demand, and contributes to long-term strength gain while simultaneously diverting waste from landfills, addressing significant environmental management concerns. By substituting conventional cement with these industrial by-products, the carbon footprint of concrete production can be substantially lowered, as cement manufacturing is highly energy-intensive and contributes significantly to global CO_2 emissions. Furthermore, the incorporation of fly ash and GGBFS promotes circular economy principles by valorizing waste materials that would otherwise pose disposal challenges, thereby aligning construction practices with sustainability goals and environmental stewardship. The combined utilization of natural fibers and industrial by-products in rigid pavement construction presents multiple synergistic benefits. The incorporation of fibers in concrete improves tensile strength, toughness, and crack resistance, while pozzolanic materials enhance durability, compressive strength, and resistance to chemical attack. From an environmental perspective, this approach reduces reliance on virgin raw materials, lowers greenhouse gas emissions, and supports responsible waste management. Economically, the resulting enhanced durability and extended service life lead to reduced maintenance requirements and life-cycle costs, making this strategy attractive for both public and private infrastructure projects.

2. PROPOSED METHODOLOGY



Flowchart 2.1: Proposed Methodology

The rigid pavement in this study is constructed using a carefully balanced combination of conventional and sustainable materials, designed to optimize structural performance while promoting environmental sustainability. Conventional materials such as cement, aggregates, and water from the fundamental structural base, providing strength, stability, and durability required for long-lasting pavement systems, while innovative sustainable alternatives are incorporated to improve material efficiency and reduce the ecological footprint of the construction process. Cement, traditionally the most carbon-intensive material in concrete, is partially replaced by supplementary cementitious materials such as fly ash, a by-product of thermal power plants, and ground granulated blast furnace slag (GGBS), a residue of the steel industry, both of which enhance durability and long-term strength while simultaneously reducing clinker demand and greenhouse gas emissions. To further enhance mechanical properties and extend service life, natural fibers such as bamboo, coconut, and human hair are introduced as micro-reinforcements, bridging cracks, improving tensile and flexural performance, and contributing to greater ductility and toughness under repeated traffic loading. Bamboo fiber, with its high tensile strength, imparts improved crack resistance and energy absorption capacity; coconut fiber, rich in lignin and cellulose, provides toughness, shrinkage control, and resistance to environmental degradation; while human hair fiber, an abundant waste material with excellent tensile properties, acts as a sustainable crack arrester and enhances bonding within the cementitious matrix. Together, these fibers reduce brittleness, improve post-cracking behavior, and provide enhanced resistance against fatigue, shrinkage, and impact stresses. Aggregates, both fine and coarse, ensure dimensional stability, volume integrity, and load-bearing capacity, while carefully graded mixes contribute to better compaction, reduced voids, and optimized cement usage. Potable water is used to ensure proper hydration, workability, and durability without introducing impurities that could compromise structural integrity. This comprehensive material strategy satisfies engineering requirements for strength and performance while supporting sustainability goals through the use of industrial by-products and natural waste-derived reinforcements. By reducing dependence on virgin resources, lowering carbon emissions, promoting circular economy practices, and addressing waste disposal challenges, the approach ensures that the resulting rigid pavement mix is both structurally robust—capable of withstanding heavy traffic and environmental stresses—and environmentally responsible, offering a sustainable solution for modern road construction.

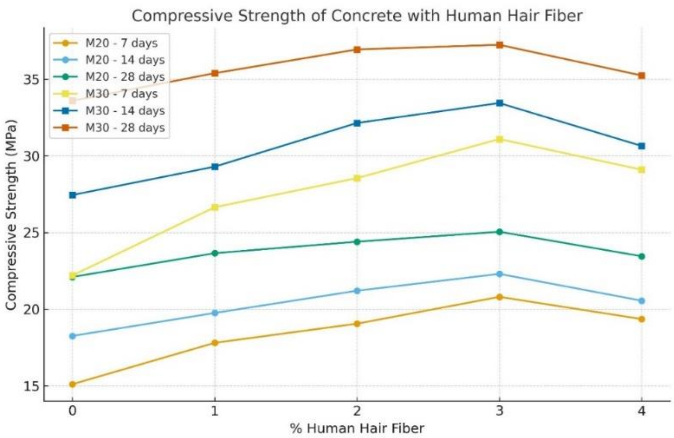
3. RESULTS AND DISCUSSION

3.1 Human Hair Fiber

In batching plant laboratories, the compressive strength of concrete is determined for every batch to ensure the desired quality during casting. This strength is essential for calculating the load-bearing capacity of structural members. Concrete specimens are cast and tested under compressive loads to evaluate their strength. In simple terms, compressive strength is calculated by dividing the failure load by the area over which the load is applied, typically after 28 days of curing. The strength of concrete is controlled by the proportioning of cement, fine and coarse aggregates, water, and any admixtures. The water-to-cement ratio is a critical factor: lower ratios result in higher compressive strength. For quality control, the average 28-day compressive strength of at least three 150 mm concrete cubes prepared with the intended mixing water should not be less than 90% of the average strength of three similar cubes prepared with distilled water. In mass concreting, compressive strength testing via cube tests is performed at regular intervals to ensure consistent quality. As per Indian Standards, concrete cubes of size 150 × 150 × 150 mm were cast and cured for 7, 14, and 28 days. The compressive strength tests were conducted using a compression testing machine. Human hair fibers were incorporated at percentages of 0%, 1%, 2%, 3%, and 4% by weight of cement. For each fiber content, three cubes were cast to ensure reliability and reproducibility of results. After curing, the cubes were tested, and the compressive strength values obtained are presented in the following tabular form.

Table 3.1: Compressive Strength of Concrete with Human Hair Fiber

SN	Curing Age	% Human Hair Fiber	M20 Strength (MPa)	M30 Strength (MPa)
1	7 days	0%	15.10	22.20
2	14 days	0%	18.25	27.45
3	28 days	0%	22.10	33.60
4	7 days	1%	17.80	26.65
5	14 days	1%	19.75	29.30
6	28 days	1%	23.65	35.40
7	7 days	2%	19.05	28.55
8	14 days	2%	21.20	32.15
9	28 days	2%	24.40	36.95
10	7 days	3%	20.80	31.10
11	14 days	3%	22.30	33.45
12	28 days	3%	25.05	37.25
13	7 days	4%	19.35	29.10
14	14 days	4%	20.55	30.65
15	28 days	4%	23.45	35.25



Graph 3.1: Compressive strength of M30 grade concrete at various % of human hair

Observations from the Graph:

1. **Baseline (0% Human Hair Fiber):**
- At 0% hair content, the compressive strength values for both M20 and M30 mixes reflect the natural hydration and strength-gaining capacity of plain concrete.
- For M20, compressive strengths are recorded as approximately 15.10 MPa at 7 days, 18.25 MPa at 14 days, and 22.10 MPa at 28 days, while for M30, the values are higher, around 22.20 MPa, 27.45 MPa, and 33.60 MPa at the respective curing ages.
- This establishes a control benchmark against which the performance of hair fiber reinforced mixes can be compared.

2. **Effect of 1% Human Hair Fiber Addition:**
- A noticeable increase in compressive strength is observed when 1% human hair fiber is added, especially at early curing ages.
- For M20, the 7-day strength rises to 17.80 MPa (an increase of ~17.9%), while M30 improves to 26.65 MPa (around 20% higher than control).
- At 28 days, M20 shows 23.65 MPa, while M30 reaches 35.40 MPa, both higher than their corresponding control mixes.
- This indicates that at 1% hair fiber, the reinforcement effect is significant, improving the load-bearing ability of concrete.

3. **Effect of 2% Human Hair Fiber Addition:**
- The compressive strength continues to rise with the addition of 2% human hair fiber, showing one of the strongest improvements in the trend.
- For M20 concrete, the 28-day strength reaches 24.40 MPa, whereas M30 peaks at 36.95 MPa, demonstrating a marked improvement over both control and 1% mixes.
- The increase in strength highlights that fibers enhance the concrete matrix by restricting crack propagation and improving post-cracking behavior.
- This suggests that around 2% fiber content is close to an optimum level where strength enhancement is most effective.

4. **Effect of 3% Human Hair Fiber Addition:**
- Further increase to 3% hair fiber shows a continued strength improvement, though the margin of gain compared to 2% is less pronounced.
- For M20, the compressive strength reaches 25.05 MPa at 28 days, while M30 achieves 37.25 MPa.
- This indicates a plateauing effect, where the benefits of additional fibers start to diminish, although the values remain higher than the control and 1% mixes.
- It reflects the saturation point of fiber reinforcement where fiber dispersion is effective but not drastically increasing strength.

5. **Effect of 4% Human Hair Fiber Addition:**
- At 4% fiber content, a slight decline in compressive strength is observed compared to 2% and 3%.
- For M20, the 28-day strength drops to 23.45 MPa, and for M30, it decreases to 35.25 MPa, though both values are still higher than the control mix.
- This reduction can be attributed to the difficulties in achieving uniform fiber dispersion at higher dosages, leading to fiber balling, reduced workability, and void formation in the concrete matrix.
- It indicates that excess fibers may start to compromise the homogeneity of the mix rather than contribute to strength.

6. **Comparative Performance of M20 vs. M30 Concrete:**
- Across all curing ages and fiber contents, M30 consistently achieves higher compressive strength than M20 due to its lower water-cement ratio and denser matrix.
- The effect of hair fiber addition is visible in both grades, but the percentage gain in M20 appears more significant, highlighting that lower-grade concretes benefit more prominently from fiber reinforcement.
- M30, though stronger, shows relatively smaller percentage increments, suggesting that high-strength concrete is less dependent on fibers for strength gains but still benefits in terms of crack control and durability.

7. **Curing Age Effect (Strength Gain Over Time):**
- Both M20 and M30 concretes exhibit a systematic increase in compressive strength with curing age across all fiber contents.
- The transition from 7 days to 14 days shows a sharper rise compared to 14 to 28 days, which aligns with the typical hydration process of cement where

the majority of strength development occurs in the first two weeks.

- The consistent upward trend confirms that human hair fiber reinforcement does not hinder cement hydration or long-term strength development.

8. **Overall Trend (Optimum Fiber Content):**

- The overall trend from the graph suggests that the optimum dosage of human hair fiber lies between 2% and 3%, as this range provides the highest compressive strengths without causing a drop due to workability issues.
- Beyond 3%, particularly at 4%, strength begins to decline, signifying that over-reinforcement with fibers is counterproductive.
- Thus, moderate inclusion of fibers ensures maximum efficiency, balancing strength improvement and workability.

9. **Practical Implications:**

- The results highlight that incorporating human hair fiber into concrete mixes can enhance compressive strength, especially in lower-grade concretes and in early curing stages.
- This makes human hair fiber a promising sustainable material for rigid pavement construction, offering improved crack resistance, reduced brittleness, and better load distribution.
- Since human hair is a widely available waste material, its use in construction also contributes to sustainable waste management practices.

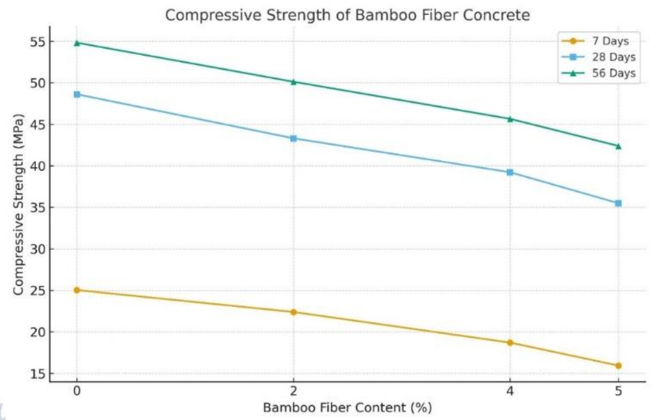
3.2 Bamboo

Pieces of bamboo:

Bamboo fibres with size of varying length from 2 to 4 cm, breadth from 1 to 2 cm, and thickness of 1 cm is also used as a partial replacement of coarse aggregate at the replacement levels of 0%, 2%, 4% and 5%. The physical properties of all these materials were tested as per IS 383-1970.

Table 3.2: Compressive Strength (N/mm²) for Bamboo Fiber Concrete

Bamboo %	Sample	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
0%	1	25.05	48.61	54.83
	2	24.85	48.35	54.60
	3	25.20	48.90	55.05
2%	1	22.43	43.33	50.12
	2	22.10	43.05	49.85
	3	22.65	43.55	50.40
4%	1	18.72	39.23	45.67
	2	18.50	38.95	45.40
	3	18.90	39.50	45.90
5%	1	15.97	35.53	42.43
	2	15.75	35.20	42.10
	3	16.10	35.75	42.65



Graph 3.2: Compressive strength of M30 grade concrete at various % of Bamboo

Observations from the Graph:

1. **Control Mix (0% Bamboo Fiber):**
   - The compressive strength of concrete without bamboo fiber (0%) shows the highest performance across all curing ages, with values averaging around 25.0 MPa at 7 days, 48.6 MPa at 28 days, and 54.8 MPa at 56 days.
   - This indicates that the plain mix develops strong compressive strength over time due to unhindered cement hydration and a dense matrix.

2.Effect of 2% Bamboo Fiber Addition:

- At 2% bamboo fiber content, the compressive strength decreases compared to the control but remains at a fairly high level.
- The average strength values are approximately 22.4 MPa at 7 days, 43.3 MPa at 28 days, and 50.1 MPa at 56 days.
- Although lower than the control mix, this dosage shows that bamboo fibers can still maintain significant strength while potentially offering better crack resistance and ductility.

3.Effect of 4% Bamboo Fiber Addition:

- Increasing the bamboo fiber content to 4% leads to a further reduction in compressive strength.

- Average values drop to around 18.7 MPa at 7 days, 39.2 MPa at 28 days, and 45.7 MPa at 56 days.
- The reduction suggests that higher fiber content affects the workability and compaction of concrete, introducing voids and weak points in the matrix.

4.Effect of 5% Bamboo Fiber Addition:

- At 5% fiber content, the strength reduction is even more pronounced, with average values of about 16.0 MPa at 7 days, 35.5 MPa at 28 days, and 42.4 MPa at 56 days.
- This clearly shows that excessive fiber addition negatively impacts the strength of concrete due to poor dispersion, fiber clustering, and reduced bonding between the cement paste and aggregates.

5.Curing Age Effect:

- Across all fiber percentages, compressive strength increases consistently with curing age, as expected due to continued hydration of cement.
- However, the relative difference between control and fiber-reinforced mixes becomes more evident at later curing ages, highlighting the adverse effect of higher bamboo fiber percentages on long-term strength.

6.Overall Trend:

- The graph indicates that compressive strength decreases progressively with increasing bamboo fiber content.
- The optimum performance in terms of strength is observed at 0% (control), while moderate retention of strength is seen at 2% bamboo fiber.
- At higher contents (4% and 5%), the negative effects outweigh the potential benefits.

7.Practical Implications:

- While bamboo fibers may enhance toughness, crack resistance, and energy absorption in concrete, their excessive inclusion compromises compressive strength.
- For practical applications in rigid pavement or structural concrete, limiting bamboo fiber content to around 2% or less is advisable to balance strength and durability.
- This also highlights the need for proper fiber treatment, uniform dispersion, and optimized mix design when using bamboo fibers in concrete.

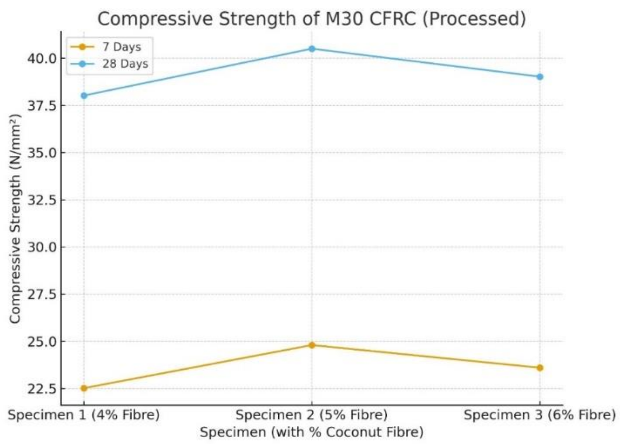
3.3 Coconut Fiber

This study aimed at analyzing the variation in strength of coconut fiber (oil coated raw and oil coated processed fibres) reinforced concrete at varying fibre contents and to compare it with that of conventional concrete. The various strength aspects analyzed are the compressive strength of the coconut fiber reinforced concrete at varying percentages (4%,5%,6% by the weight of cement) of fibre. The influence of shape of fibre on strength is also studied by testing on coconut fibre mesh of predetermined dimensions. The optimal percentage of both the processed fibre strands and raw fibre meshes were found out by trial and error and the optimum percentage of superplasticizer needed for the required workability was also determined. The calculated amount of cement and fine aggregate are mixed till a uniform mix is obtained. In this study, coir fibre was used at dosages of 4%, 5%, and 6% by weight of cement. The coir strands were cut to a length of 5 cm, thoroughly washed, coated with coconut oil, and then dried in sunlight for 24 hours. The treated fibres were gradually added to the concrete mix until a uniform distribution and color was achieved. Subsequently, coarse aggregates were incorporated and mixed, followed by the gradual addition of water. Care was taken to add water in stages to prevent bleeding, which could negatively affect strength development and hydration efficiency. Any admixture was introduced during the final stage of water addition, allowing sufficient mixing time before the concrete began to set. The concrete was then placed in molds, compacted, and finished, preparing uniform cubes for curing. The compressive strength of the cubes was determined after 7 and 28 days, providing an assessment of the impact of coir fibre incorporation on concrete performance.

Compressive Strength of CFRC (Processed): Coconut fibre reinforced concrete was added to concrete at varying proportions (4%, 5%, 6% of that of weight of cement) at a water cement ratio of 0.5 The desired slump value and compressive strength was obtained for conventional concrete at this ratio. However, when fibre is added to the mix low workability was observed. Hence superplasticizer was added at different proportions of cement to get a concrete mix of suitable workability.

Table 3.3: Compressive Strength of M30 CFRC (Processed)

Specimen	Sample	W/C Ratio	% Coconut Fibre	% Superplasticizer	Slump (mm)	7-Day Strength (N/mm²)	28-Day Strength (N/mm²)
1	1	0.38	4%	0.3%	110	22.50	38.00
	2	0.38	4%	0.3%	111	22.65	38.20
	3	0.38	4%	0.3%	109	22.40	37.85
2	1	0.36	5%	0.4%	105	24.80	40.50
	2	0.36	5%	0.4%	106	24.95	40.70
	3	0.36	5%	0.4%	104	24.65	40.30
3	1	0.35	6%	0.8%	105	23.60	39.00
	2	0.35	6%	0.8%	106	23.75	39.20
	3	0.35	6%	0.8%	104	23.45	38.85



Graph 3.3: Compressive strength of M30 grade concrete at various % of Coconut

Observations from Graph:

1. **Baseline Observation (Specimen 1 – 4% Coconut Fibre):**
   - The first specimen with 4% coconut fiber shows an average 7-day strength of approximately 22.5 N/mm² and 28-day strength around 38 N/mm².
   - Slight variations among samples indicate good repeatability and consistent concrete performance.
   - The concrete achieves almost 70% of its 28-day strength by the 7th day, reflecting typical hydration characteristics of M30 concrete.
2. **Specimen 2 (5% Coconut Fibre):**
   - At 5% fiber content, the 7-day strength increases to roughly 24.8 N/mm², and the 28-day strength rises to 40.5 N/mm².
   - This indicates a positive effect of moderate coconut fiber content on compressive strength, likely due to improved crack bridging and fiber-matrix interaction.
   - The slump values remain nearly constant (105–106 mm), suggesting that workability is maintained despite increased fiber content.
3. **Specimen 3 (6% Coconut Fibre):**
   - The specimen with 6% fiber shows a 7-day strength of around 23.6 N/mm² and 28-day strength of 39 N/mm², slightly lower than the 5% fiber specimen.
   - This demonstrates that excessive fiber content may marginally reduce compressive strength, possibly due to fiber clustering, void formation, or reduced compaction efficiency.
   - Despite the slight reduction, the strength is still higher than the 4% fiber specimen, indicating a non-linear relationship between fiber content and strength.
4. **Curing Age Effect:**
   - For all specimens, compressive strength increases from 7 days to 28 days, confirming normal cement hydration and strength development.
   - The increase is approximately 70–75% from 7 days to 28 days, consistent with standard concrete curing behavior.
   - This confirms that coconut fiber does not hinder the hydration process significantly.
5. **Effect of Fiber Content on Strength Trend:**
   - The graph shows that moderate coconut fiber addition (around 5%) yields the maximum 28-day strength, while lower (4%) or higher (6%) content leads to slightly lower values.
   - This suggests the optimum coconut fiber content for M30 concrete lies close to 5%, balancing strength gain, workability, and fiber distribution.

- Excess fiber content beyond the optimum may cause inhomogeneity, negatively affecting compressive strength.

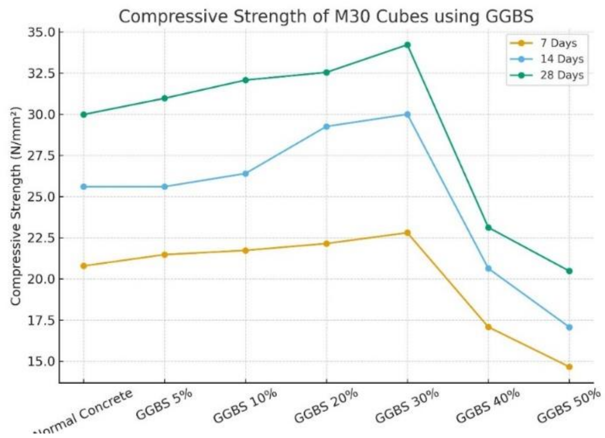
6. **Workability Consistency:**
   - Slump values for all specimens range from 104–111 mm, indicating good workability despite fiber addition.
   - Stable workability ensures proper compaction, which contributes to consistent compressive strength values.
7. **Practical Implications:**
   - Incorporating coconut fiber in M30 concrete enhances crack resistance and toughness without drastically compromising compressive strength.
   - For structural or rigid pavement applications, maintaining fiber content around 5% is ideal for optimizing performance.
   - Excessive fiber addition (6% or more) should be avoided to prevent reduced strength due to poor fiber dispersion and potential voids.
8. **Consistency Across Samples:**
   - Minor variations in 7-day and 28-day strength across the three replicates for each specimen indicate good reproducibility of the experimental procedure.
   - This reliability reinforces the validity of the observed trends in strength performance with varying fiber content.

3.4 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) has the potential to enhance the stability characteristics of concrete when compared to a control mix. This project focuses on evaluating the impact of replacing cement with varying percentages of GGBS, specifically at 0%, 10%, 20%, 30%, 40%, and 50%. By incorporating GGBS as a partial substitute for cement, the study aims to assess its influence on the strength, durability, and overall performance of concrete. The use of GGBS not only contributes to sustainability by utilizing an industrial byproduct but also enhances various properties of concrete, such as reduced heat of hydration, improved workability, and long-term strength development. The investigation will include a comparative analysis of the control mix and GGBS-modified concrete to determine the optimal replacement level that ensures structural stability while promoting eco-friendly construction practices.

Table 3.4: Compressive Strength of M30 Cubes using GGBS

Mix Type	Sample	7 Days (M30)	14 Days (M30)	28 Days (M30)
Normal Concrete	1	20.80	25.60	30.00
	2	20.65	25.45	29.85
	3	20.90	25.75	30.10
GGBS 5%	1	21.46	25.60	30.96
	2	21.60	25.75	31.05
	3	21.35	25.45	30.90
GGBS 10%	1	21.73	26.40	32.08
	2	21.85	26.55	32.20
	3	21.60	26.25	31.95
GGBS 20%	1	22.13	29.28	32.54
	2	22.25	29.40	32.70
	3	22.05	29.10	32.40
GGBS 30%	1	22.80	30.00	34.22
	2	22.95	30.10	34.35
	3	22.65	29.90	34.10
GGBS 40%	1	17.07	20.65	23.12
	2	17.20	20.75	23.25
	3	16.95	20.50	23.00
GGBS 50%	1	14.66	17.05	20.47
	2	14.80	17.20	20.60
	3	14.50	16.95	20.35



Graph 3.4: Compressive strength of M30 grade concrete at various % of Ground Granulated Blast Furnace Slag (GGBS)

Observations from the Graph:

1. **Normal Concrete (0% GGBS):**
   - The baseline concrete shows a 7-day strength of approximately 20.8 N/mm², a 14-day strength of 25.6 N/mm², and a 28-day strength of 30 N/mm².

- This establishes the reference for comparing the effect of GGBS replacement on compressive strength.

2.GGBS 5% Replacement:

- At 5% GGBS replacement, the 7-day strength slightly increases to around 21.46 N/mm², while the 28-day strength rises to 30.96 N/mm².
- This indicates a minor improvement in strength due to the pozzolanic reaction of GGBS, which contributes to additional cementitious compounds over time.

3.GGBS 10% Replacement:

- With 10% GGBS, the 7-day strength is approximately 21.73 N/mm² and 28-day strength 32.08 N/mm², showing a clear positive trend compared to normal concrete.
- The 14-day strength also improves slightly, reflecting accelerated early-age strength gain due to optimum GGBS replacement.

4.GGBS 20% and 30% Replacement:

- At 20% GGBS, the 28-day strength reaches 32.54 N/mm², while at 30% it reaches 34.22 N/mm², marking the peak compressive strength among all replacements.
- This trend demonstrates that moderate GGBS replacement (20–30%) enhances long-term strength due to the additional calcium silicate hydrate formation from the pozzolanic reaction.

5.High GGBS Replacement (40–50%):

- At 40% replacement, the 28-day strength drops sharply to 23.12 N/mm², and at 50% it further decreases to 20.47 N/mm².
- This reduction occurs because excessive GGBS reduces the cement content too much, limiting the early-age hydration and resulting in a weaker matrix.
- Although GGBS contributes pozzolanic action, its effect cannot compensate for the reduced cement content at very high replacements.

6.Curing Age Effect:

- For all replacement levels, compressive strength increases consistently from 7 days to 28 days.
- The greatest strength gain is observed in mixes with 20–30% GGBS, reflecting the long-term pozzolanic contribution.
- Lower or excessive replacement levels show slower or limited strength gain over time.

7.Overall Trend:

- The graph shows a bell-shaped trend, where compressive strength first increases with increasing GGBS content (up to 30%) and then decreases at higher replacements.
- This indicates an optimum GGBS replacement level of around 20–30% for maximizing compressive strength in M30 concrete.

8.Practical Implications:

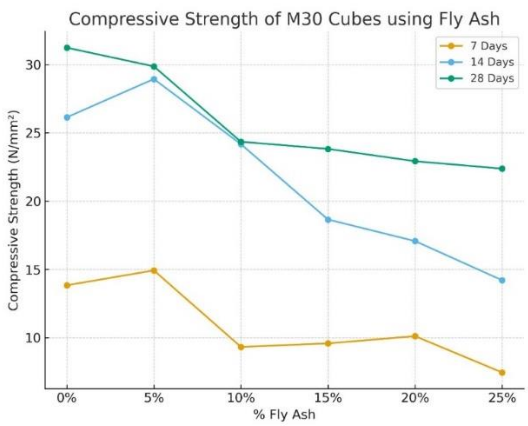
- Moderate GGBS replacement improves durability and long-term strength while also reducing cement usage, contributing to sustainable concrete practices.
- Excessive replacement (>40%) should be avoided in structural applications due to significant strength reduction.

3.5 Fly Ash

Fly ash, a waste generated by thermal power plants, poses a significant environmental concern due to its disposal challenges and potential ecological impact. This study investigates the use of fly ash in cement concrete as a partial replacement of cement and as an additive, aiming to provide a sustainable and environmentally friendly approach for its disposal and reuse. The research focuses on incorporating fly ash in concrete mixtures by replacing cement at varying levels from 5% to 25%, in incremental steps of 5%. The study is conducted as a case study for the Koradi Thermal Power Plant in Nagpur, Maharashtra, assessing the feasibility and advantages of using fly ash in concrete production. The goal is to demonstrate the potential of fly ash as a supplementary cementitious material, reducing dependence on conventional cement and promoting sustainable construction practices. In this investigation, M30 grade concrete was prepared using a nominal mix design according to IS 456-2000, with a water-cement ratio of 0.5. Fly ash was blended into the cement at replacement levels of 5%, 10%, 15%, 20%, and 25% by weight of cement. For compressive strength testing, concrete samples were cast in 15 cm × 15 cm × 15 cm molds, ensuring the top surface was properly leveled. A total of 18 cubes were prepared, with six specimens corresponding to each fly ash replacement level. The freshly cast cubes were covered with wet gunny bags for 24 hours to prevent premature drying and then submerged in a curing tank for the designated period. After curing, the specimens were removed from water and immediately tested for compressive strength using a Universal Testing Machine, providing data on the influence of fly ash content on concrete performance.

Table 3.5: Compressive Strength of M30 Cubes using Fly Ash

% Fly Ash	Sample	7 Days	14 Days	28 Days
0%	1	13.86	26.12	31.27
	2	13.70	26.25	31.15
	3	13.95	26.05	31.30
5%	1	14.93	28.98	29.86
	2	14.85	28.75	29.95
	3	15.00	29.10	29.80
10%	1	9.32	24.17	24.35
	2	9.25	24.00	24.20
	3	9.40	24.35	24.50
15%	1	9.59	18.66	23.83
	2	9.50	18.50	23.75
	3	9.65	18.80	23.90
20%	1	10.13	17.07	22.92
	2	10.00	16.95	22.85
	3	10.20	17.20	23.00
25%	1	7.45	14.21	22.39
	2	7.40	14.10	22.30
	3	7.50	14.30	22.45



Graph 3.5: Compressive strength of M30 grade concrete at various % of Fly Ash

Observations from Graph:

1. **Normal Concrete (0% Fly Ash):**
   - The control concrete shows consistent 7-day strength values ranging from 13.70 to 13.95 N/mm², 14-day strength between 26.05 and 26.25 N/mm², and 28-day strength from 31.15 to 31.30 N/mm².
   - This provides the baseline for comparing the effect of Fly Ash replacement on compressive strength.

2.Fly Ash 5% Replacement:

- At 5% replacement, the 7-day strengths increase slightly to a range of 14.85–15.00 N/mm², showing a minor improvement in early strength compared to normal concrete.
- The 14-day strengths range between 28.75 and 29.10 N/mm², and 28-day strengths are around 29.80–29.95 N/mm².
- This indicates that small amounts of Fly Ash contribute positively to early strength due to its filler effect, though 28-day strength is slightly lower than the control concrete.

3.Fly Ash 10% Replacement:

- At 10% replacement, the 7-day strength drops significantly to 9.25–9.40 N/mm², reflecting a slower early-age hydration due to partial cement replacement.
- The 14-day strength is 24.00–24.35 N/mm², and 28-day strength is 24.20–24.50 N/mm², showing that moderate Fly Ash replacement decreases both early and late-age compressive strength compared to normal concrete.

4.Fly Ash 15% Replacement:

- For 15% Fly Ash, 7-day strengths are slightly higher than 10% replacement (9.50–9.65 N/mm²), but 14-day strength drops sharply to 18.50–18.80 N/mm².
- The 28-day strength is 23.75–23.90 N/mm², indicating that higher Fly Ash content slows hydration initially and reduces strength development over time.

5.Fly Ash 20% Replacement:

- At 20% Fly Ash, 7-day strengths improve slightly to 10.00–10.20 N/mm², but 14-day strength decreases further to 16.95–17.20 N/mm².
- 28-day strength is 22.85–23.00 N/mm², showing that excessive Fly Ash replacement reduces compressive strength compared to lower replacement levels and normal concrete.

6.Fly Ash 25% Replacement:

- With 25% replacement, 7-day strengths drop significantly to 7.40–7.50 N/mm², 14-day strengths are only 14.10–14.30 N/mm², and 28-day strength is 22.30–22.45 N/mm².

- This demonstrates that very high Fly Ash replacement negatively impacts both early and long-term compressive strength due to insufficient cementitious material for hydration.

7.Curing Age Effect:

- For all replacement levels, compressive strength increases with curing age from 7 days to 28 days.
- The highest strength gain with curing time is observed in normal concrete (0% Fly Ash) and low Fly Ash replacement (5%).
- Higher replacement levels (10–25%) show slower strength gain and lower final strength, indicating that Fly Ash delays early hydration.

8.Overall Trend:

- The data shows that low Fly Ash replacement (5%) can slightly improve early strength, while moderate-to-high replacements (10–25%) reduce both early and 28-day compressive strength.
- Optimal Fly Ash replacement for maintaining strength in M30 concrete appears to be very low, around 5%.

9.Practical Implications:

- Small amounts of Fly Ash improve sustainability and slightly enhance early strength.
- High Fly Ash replacements (>15%) should be avoided in structural concrete where early and 28-day strength is critical.

4. CONCLUSION

The present research on sustainable materials in rigid pavement construction provides significant insights into the potential of alternative resources such as bamboo fiber, coconut fiber, human hair fiber, fly ash, and ground granulated blast furnace slag (GGBFS) as partial replacements and reinforcements for conventional rigid pavement materials, and the outcomes of the experimental program clearly demonstrate that the incorporation of these materials not only contributes to addressing pressing environmental concerns such as waste management, reduction of greenhouse gas emissions, and conservation of natural resources, but also leads to noticeable improvements in the mechanical, durability, and functional performance of pavement concrete; the study has established that bamboo fiber, coconut fiber, and human hair fiber act as effective reinforcing agents, enhancing tensile strength, flexural performance, crack resistance, and post-cracking ductility, while supplementary cementitious materials such as fly ash and GGBFS significantly improve workability, long-term strength gain, and resistance against aggressive environmental conditions, thereby producing a synergistic effect that results in sustainable and resilient pavement mixes. Furthermore, the study highlights that the use of these materials reduces the overall carbon footprint of pavement construction by minimizing dependence on cement and virgin aggregates, which are energy-intensive and environmentally damaging in their extraction and production, thereby aligning infrastructure development with global sustainability goals; in addition to the environmental advantages, the cost-effectiveness of these sustainable alternatives was also observed as the utilization of waste materials like human hair and coconut fiber, as well as industrial by-products such as fly ash and GGBFS, significantly reduces raw material expenses, lowering construction costs without compromising on structural integrity.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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