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Experimental Investigation of Concrete Enhanced with Biochar

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Abstract

The construction industry is a major contributor to global carbon emissions, primarily due to cement production. To address this challenge, this study explores the incorporation of biochar, a carbon-rich byproduct of biomass pyrolysis, into concrete as a sustainable alternative. The biochar used in this research was derived from coconut shells and processed to pass through a 150-micron IS sieve to ensure uniformity in the concrete mix. The primary objective of this study is to evaluate the mechanical and durability properties of biochar-enhanced concrete while assessing its environmental impact. The methodology involved preparing concrete mixes with varying biochar replacement ratios (0%, 5%, 10%, and 15%) and conducting a series of tests after 7, 14, and 28 days of curing. Compressive strength tests were performed to analyze the structural integrity, while durability assessments, including carbonation resistance, sulfate attack resistance, and water absorption tests, were conducted to evaluate the long-term performance of biochar concrete. Additionally, a carbon footprint analysis was performed to quantify the environmental benefits of biochar incorporation. The results indicate that biochar-modified concrete exhibits improved mechanical and durability characteristics at optimal replacement levels. The porous nature of biochar enhances hydration, contributing to strength development and improved moisture retention. The carbonation and sulfate resistance tests demonstrated that biochar-concrete is more resilient against environmental stressors compared to conventional concrete. Furthermore, the carbon footprint analysis revealed that replacing cement with biochar significantly reduces CO2 emissions, promoting sustainable construction practices. This research highlights the potential of biochar as an eco-friendly material that not only enhances concrete properties but also contributes to waste management and carbon sequestration. By integrating biochar into concrete, this study provides a viable solution for reducing the environmental footprint of the construction industry while maintaining structural performance.

Keywords: Biochar, Carbon Footprint, Carbon Sequestration

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1. Introduction

Concrete is the backbone of modern construction, widely utilized for its strength, durability, and versatility. However, conventional concrete production has significant environmental implications, primarily due to the high carbon dioxide emissions associated with cement manufacturing. Cement production accounts for nearly 8% of global carbon dioxide emissions, making it one of the largest contributors to climate change. The high energy consumption and depletion of natural resources further exacerbate its environmental impact, necessitating the exploration of sustainable alternatives. In response to these challenges, researchers are actively investigating eco-friendly materials that can partially replace cement in concrete without compromising its structural integrity. One such material is bio char, a carbon-rich byproduct derived from the pyrolysis of biomass. Biochar has gained attention due to its ability to enhance concrete properties while simultaneously reducing its environmental footprint. The porous structure and high surface area of biochar contribute to improved mechanical performance, reduced permeability, and increased resistance to chemical attacks. This study focuses on the integration of coconut shell biochar into concrete, analyzing its effects on compressive strength, durability, and overall sustain ability. Coconut shells, an abundant agricultural waste material, are typically discarded or burned, contributing to environmental pollution. Converting them into biochar provides an eco-friendly solution for waste management, carbon sequestration, and greenhouse gas reduction. The use of biochar in concrete not only reduces cement consumption but also enhances durability, making it a promising alternative for sustainable construction. To evaluate these potential benefits, a series of experiments were conducted, including com pressive strength testing at 7, 14, and 28 days, durability assessment under carbonation and sulfate attack conditions, water absorption testing, and a carbon footprint analysis. The incorporation of biochar is expected to improve the mechanical properties of concrete by refining its microstructure, reducing shrinkage, and enhancing its ability to withstand environmental stressors. Additionally, biochar-modified concrete could contribute to increased thermal insulation and improved fi re resistance, making it suitable for a wide range of construction applications. The findings from this research could provide valuable insights into the development of more sustainable construction materials, aligning with global eff orts to reduce carbon emissions and mitigate climate change. By promoting the adoption of biochar as a cement replacement, the construction industry can take a significant step toward greener and more environmentally responsible building practices.

1.1. Objectives of the Study

This study focuses on the following objectives:

- To Evaluate the compressive strength of biochar-enhanced concrete at 7, 14, and 28 days.
- To Assess the durability performance specifically resistance to carbonation and sulfate attack.
- To Investigate water absorption properties and permeability characteristics of bio char- modified concrete.
- To Conduct a comparative carbon footprint analysis between conventional concrete and biochar-enhanced concrete.
- To Determine the optimal biochar replacement percentage that balances performance, sustainability, and economic feasibility.

1.2. Scope of the Study

This study explores the feasibility of replacing cement with coconut shell biochar in M20-grade concrete. The scope includes:

- To analyze biochar’s physical and chemical properties for concrete applications.
- To evaluate compressive strength development at 7, 14, and 28 days.
- To assess durability by examining resistance to carbonation and sulfate attack.

- To investigate the impact of biochar on moisture retention, permeability, and durability.
- To estimate carbon emission reductions by comparing biochar-enhanced and conventional concrete.

2. Materials and Methods

2.1 Materials Used

The various materials used in the experimental program are described below.

Biochar

Biochar, a carbon-rich material produced from the pyrolysis of organic biomass like coconut shells under limited oxygen, offers significant environmental and performance benefits when used in concrete. In this study, coconut shell biochar produced at 500 °C was used to replace cement at 0%, 5%, 10%, and 15% by weight, aligning with sustainability goals by reducing carbon emissions and promoting waste valorization. Its high stability enables long-term carbon sequestration, while its porous structure enhances concrete durability, water retention, and internal curing, reducing shrinkage and cracking. Biochar also lowers cement usage—helping cut CO_2 emissions—improves resistance to chemical attacks, and boosts thermal insulation and structural efficiency. Despite challenges in standardization and mix optimization, biochar-modified concrete presents a promising path toward greener, high-performance construction.

Figure 1: Biochar

Cement

Cement, particularly Ordinary Portland Cement (OPC) 53 grade, is a key binding material in concrete, valued for its high early strength and long-term durability due to the formation of calcium silicate hydrates during hydration. However, cement production is highly energy-intensive and accounts for about 8% of global CO_2 emissions, prompting the search for sustainable alternatives. Supplementary cementitious materials (SCMs) like biochar, fly ash, silica fume, and GGBFS are being explored to reduce cement use and environmental impact. Biochar, in particular, enhances concrete's mechanical and durability properties while lowering carbon emissions. The use of SCMs and advancements in blended cement technology support eco-friendly construction by conserving resources and improving performance. As the industry moves toward sustainability, integrating biochar and other SCMs offers a promising path to reducing the environmental footprint of traditional cement while supporting resilient infrastructure development.

Figure 2: Cement

Fine Aggregate

Fine aggregate, or sand, is essential in concrete for filling voids and enhancing workability. This study used manufactured sand (M-Sand) instead of river sand to ensure quality, consistency, and sustainability. Produced by crushing hard granite, M-Sand offers better gradation, reduced impurities, and improved particle packing, leading to increased compressive strength, durability, and resistance to environmental stressors. Its angular texture enhances interlocking and bonding with cement paste, improving mechanical performance and structural integrity. M-Sand also reduces water demand and shrinkage-related cracking due to its low silt and clay content. Unlike river sand, which harms ecosystems through over-mining, M-Sand supports eco-friendly construction by minimizing environmental impact and promoting consistent, high-performance concrete mixes.

Figure 3: M-Sand

Coarse Aggregate

Coarse aggregates are vital in concrete, providing bulk, strength, and stability, with sizes typically ranging from 4.75 mm to 40 mm. In this study, 20 mm crushed angular aggregates were used for their superior interlocking properties, which enhance load-bearing capacity and overall strength. Their angular shape and rough texture improve bonding with cement paste, increase internal friction, and reduce segregation, resulting in cohesive, durable concrete. Well-graded aggregates contribute to better compaction, higher density, and improved resistance to impact, abrasion, and environmental stressors like freeze-thaw cycles. The use of high-quality crushed stone aggregates ensures optimal mechanical performance and long-term durability, making them ideal for modern structural applications.

Figure 4: Coarse Aggregate

2.2 Methodology

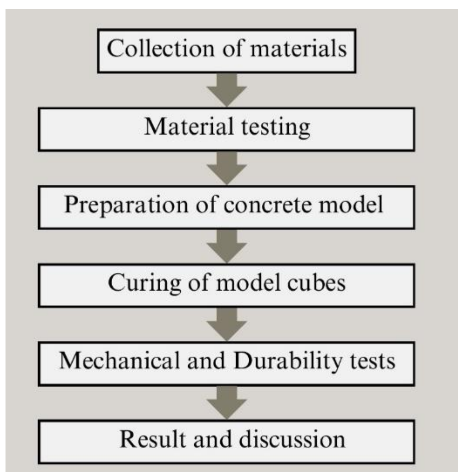

Figure 5: Methodology

3. Results and Discussion

3.1 Compressive Strength

3.1.1 7-Day Compressive Strength

The 7-day compressive strength results indicate that concrete with 5% biochar replace- ment exhibited the highest strength, reaching an average of approximately 13.81 MPa. The control mix (0% biochar) had slightly lower strength, averaging around 13.18 MPa. How- ever, as the biochar content increased beyond 5%, a decline in compressive strength was observed. The 10% biochar mix showed a slight reduction in strength, averaging 13.01 MPa, while the 15% replacement mix exhibited the lowest strength, averaging around 11.57 MPa. This trend suggests that moderate biochar replacement (5%) may enhance early strength, but higher replacement levels can reduce it, likely due to increased porosity and reduced cementitious content.

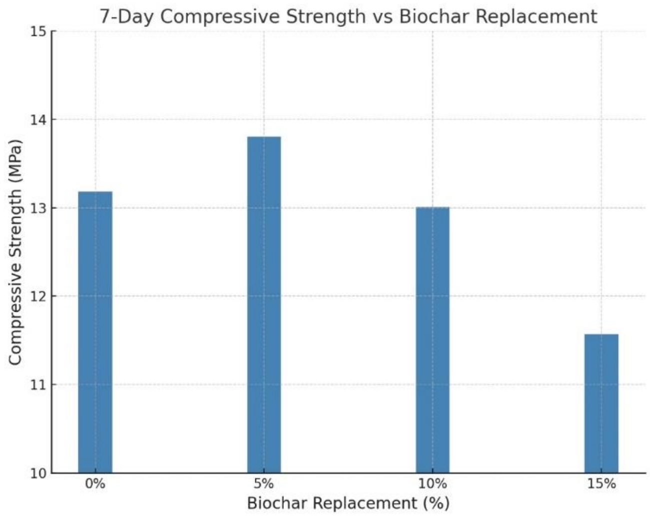

Figure 6: 7-Day Compressive Strength

3.1.2 14-Day Compressive Strength

The 14-day compressive strength results indicate that concrete with 5% biochar replace- ment exhibited the highest strength, reaching an average of approximately 17.24 MPa. The control mix (0% biochar) had slightly lower strength, averaging around 16.25 MPa. How- ever, as the biochar content increased beyond 5%, a decline in compressive strength was observed. The 10% biochar mix showed a slight reduction in strength, averaging 16.20 MPa, while the 15% replacement mix exhibited the lowest strength, averaging around 14.05 MPa. This trend suggests that moderate biochar replacement (5%) may enhance strength development at 14 days, but higher replacement levels can reduce it, likely due to increased porosity and reduced cementitious content.

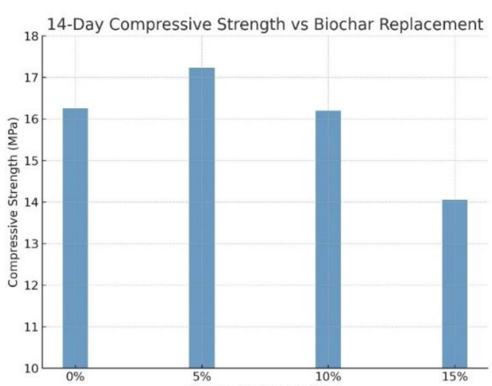

Figure 7: 14-Day Compressive Strength

3.1.3 28-Day Compressive Strength

The 28-day compressive strength results show a similar trend to the 7-day test. The control sample (0% biochar) achieved an average compressive strength of 19.98 MPa. At 5% biochar replacement, the strength slightly improved to an average of 20.68 MPa, suggesting that biochar contributes positively to long-term strength development at lower percentages. However, at 10% replacement, the strength started decreasing, averaging 19.39 MPa, and at 15% replacement, it dropped significantly to 16.53 MPa. This decline in strength at higher replacement levels could be attributed to a dilution eff ect, where the reduction in cementitious material outweighs the benefi ts provided by biochar, leading to a weaker matrix.

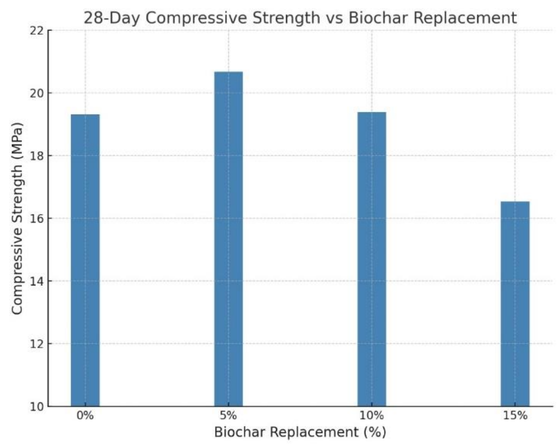

Figure 8 :28-Day Compressive Strength

3.2 Water Absorption

The water absorption test results indicate a clear trend of increasing water absorption with higher biochar replacement percentages. At 0% biochar, water absorption values range between 0.35% and 0.45%, demonstrating minimal porosity. As the biochar content increases to 5%, water absorption rises to a range of 0.85%–0.95%, suggesting a slight increase in porosity due to biochar's porous nature. At 10% biochar replacement, the absorption further increases to 1.1%–1.3%, and at 15%, it reaches the highest values, ranging from 1.6% to 1.8%. This trend suggests that biochar incorporation enhances the material's water retention capability, likely due to its high internal porosity, which can affect concrete durability and permeability.

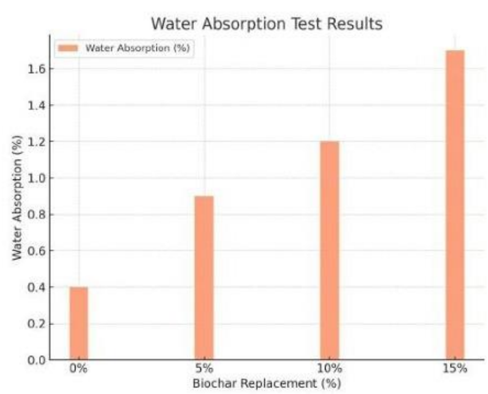

Figure 9: Water Absorption Test

3.3 Sulfate Attack Test

The sulfate attack test on cement mortar cubes with varying levels of biochar replace- ment revealed a clear trend in weight loss, compressive strength reduction, and visual degradation. The control samples (0% biochar) exhibited the least weight loss (1.5- 2%) and retained around 87.5% of their initial compressive strength. The addition of 5% biochar showed slightly better strength retention compared to the control, but weight loss increased slightly due to higher porosity. The 10% biochar replacement resulted in compressive strength values similar to the control, demonstrating stability under sulfate exposure. However, at 15% biochar replacement, weight loss rose to approximately 3.5%, and strength reduction reached 15% (from 28.8 MPa to 24.5 MPa), indicating a decline in sulfate resistance. Visual inspection further supported these fi ndings, with the 0% and 5% biochar samples showing minor surface erosion, the 10% biochar samples exhibit- ing moderate scaling and minor cracks, and the 15% biochar samples displaying visible cracks and surface disintegration due to sulfate attack. These results suggest that while low biochar content may improve or maintain sulfate resistance, higher replacement levels lead to increased vulnerability.

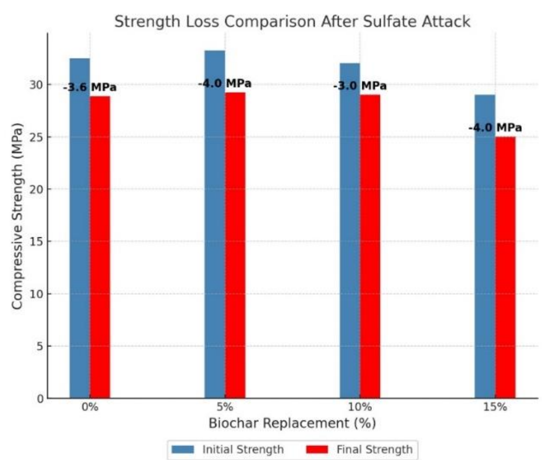

Figure 10: Comparison of strength loss after sulfate attack

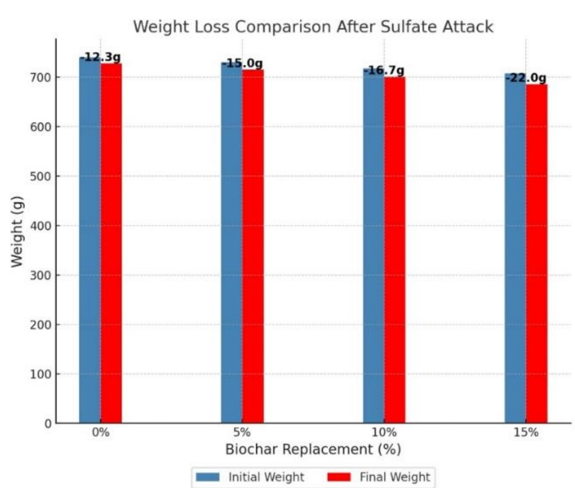

Figure11: Comparison of weight loss after sulfate attack

3.4 Carbon Footprint Analysis

The sulfate attack test on cement mortar cubes with varying levels of biochar replace- ment revealed a clear trend in weight loss, compressive strength reduction, and visual degradation. The control samples (0% biochar) exhibited the least weight loss (1.5- 2%) and retained around 87.5% of their initial compressive strength. The addition of 5% biochar showed slightly better strength retention compared to the control, but weight loss increased slightly due to higher porosity. The 10% biochar replacement resulted in compressive strength values similar to the control, demonstrating stability under sulfate exposure. However, at 15% biochar replacement, weight loss rose to approximately 3.5%, and strength reduction reached 15% (from 28.8 MPa to 24.5 MPa), indicating a decline in sulfate resistance. Visual inspection further supported these fi ndings, with the 0% and 5% biochar samples showing minor surface erosion, the 10% biochar samples exhibit- ing moderate scaling and minor cracks, and the 15% biochar samples displaying visible cracks and surface disintegration due to sulfate attack. These results suggest that while low biochar content may improve or maintain sulfate resistance, higher replacement levels lead to increased vulnerability.

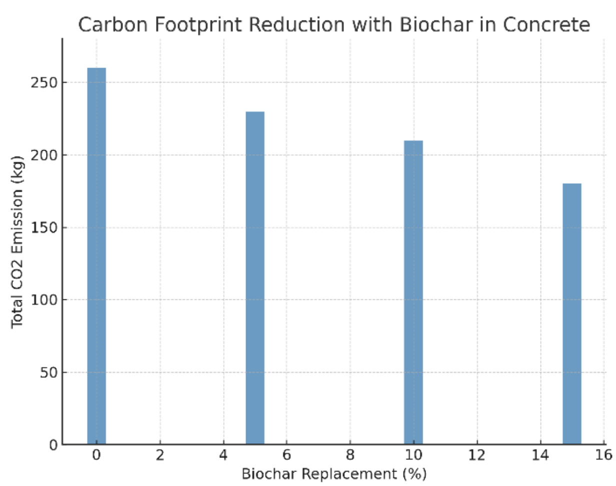

Figure 12: Carbon Footprint reduction with biochar in concrete

4. Conclusion and Future Scope

4.1 Conclusion

- This study evaluated the effects of partially replacing cement with coconut shell biochar in M20-grade concrete and cement mortar. The performance of differ- ent biochar replacement ratios (0%, 5%, 10%, and 15%) was assessed based on carbonation resistance, water absorption, and sulfate attack resistance.
- The carbonation test results indicated that all samples remained uncarbonated, demonstrating that biochar did not compromise carbonation resistance.
- The water absorption test showed an increase in absorption with higher biochar content, confirming increased porosity.
- The sulfate attack test revealed a slight reduction in compressive strength with higher biochar content, along

with minor weight variations. However, no significant cracks were observed, indicating durability against sul
fate exposure.

- Based on the findings, 5% biochar replacement emerged as the optimal percentage, balancing strength, durability, and sustainability benefits. This study confirms that coconut shell biochar can serve as a sustainable and eco-friendly partial cement replacement, contributing to reducing the carbon footprint of concrete production.

4.2 Future Scope

- Extended Durability Studies: This study was limited to 28-day evaluations; future research should assess long-term durability by conducting tests at 90 days and beyond for better insight into strength and performance variations over time.
- Porosity Reduction and Strength Enhancement: The increased porosity observed with higher biochar content suggests the need for admixtures or supplementary materials to optimize permeability and strength.
- Microstructural Analysis: Advanced techniques like SEM (Scanning Electron Mi- croscopy) and XRD (X-ray Diffraction) can be employed to analyze the impact of biochar on concrete at a microscopic level.
- Field Applications and Real-World Testing: Large-scale trials in different environ- mental conditions will help validate laboratory findings and determine the practical feasibility of biochar-enhanced concrete.
- Economic and Life Cycle Assessment: A detailed cost-benefit analysis and life cycle assessment (LCA) should be conducted to evaluate the economic and environmental advantages of using biochar in commercial concrete production.

5. References

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