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BIOCHAR-BASED CONCRETE BLOCKS FROM RICE HUSK: A SUSTAINABLE SOLUTION FOR LOW-CARBON CONSTRUCTION

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Abstract

This study investigates rice husk biochar (RHB) as a partial cement replacement in concrete blocks to enhance sustainability and reduce the environmental footprint of construction materials. RHB, produced via pyrolysis of agricultural residues, offers high porosity, silica content, and carbon sequestration potential, making it a promising additive. Experimental mixes were prepared with 5–30 wt. % RHB, using Ordinary Portland Cement, natural siliceous sand, and tap water. Tests included compressive and flexural strength, ultrasonic pulse velocity (UPV), water absorption, permeability, and thermal conductivity. Results showed that replacing 20–30 wt. % cement with RHB increased compressive strength by up to 15% when pre-mixed in a water-super plasticizer solution, while 20% replacement improved flexural strength by ~30%. UPV readings (~3 km/s) indicated no significant compromise in material integrity. Pre-soaked biochar reduced water absorption by up to 41% at 30% replacement, due to reduced porosity. Thermal conductivity decreased steadily with higher biochar content, confirming its insulation benefits. However, replacement levels above 15% in load-bearing applications led to strength reductions, indicating the need for optimal proportioning. Environmental assessment confirmed substantial carbon sequestration potential, with literature reporting up to 870 kg CO_2-eq mitigation per ton of dry feedstock. Additionally, using RHB supports waste valorization, reduces landfill pressure, and lowers embodied carbon. The mix designs required no specialized production methods, enabling immediate adoption in industry. These findings demonstrate that RHB-based concrete blocks offer mechanical adequacy, improved thermal performance, and significant environmental benefits, making them suitable for non-load-bearing and energy-efficient applications. Future work should optimize mixes for structural uses and assess long-term performance under real-world conditions.

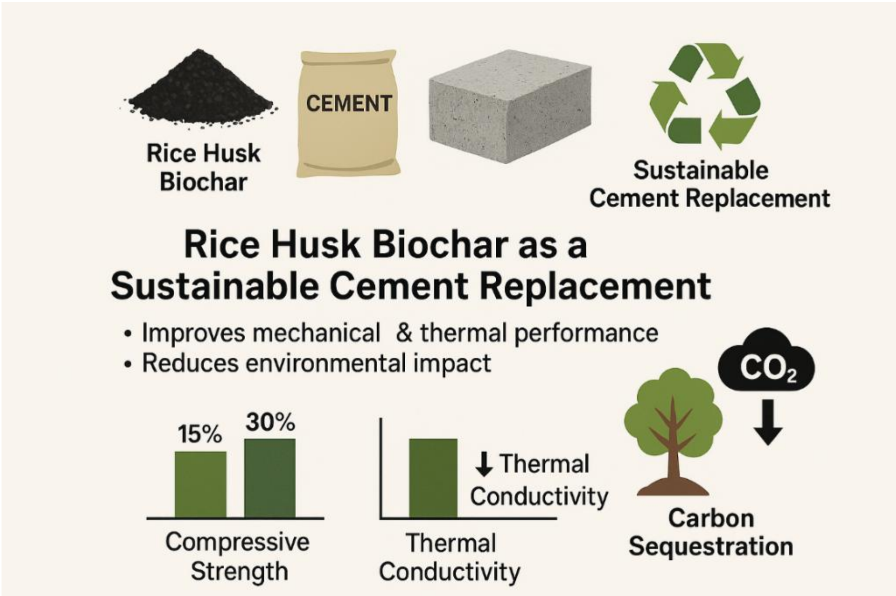

Figure 1. Graphical Abstract

1. INTRODUCTION

One of the largest consumers of natural resources and producers of greenhouse gases is the construction industry, with the production of cement being a primary contributor to CO2 emissions. Researchers are developing new ways to reduce the carbon footprint of construction in response to the growing demand for sustainable and eco-friendly building materials. Using biochar, a type of charcoal derived from organic materials, in place of cement in concrete is one possible remedy. Because of its high water absorption capacity and low heat conductivity, biochar is a useful additive for improving the sustainability, durability, and mechanical strength of concrete [1,2]. In order to create more sustainable and long-lasting building materials, this study investigates the potential of biochar derived from gasification treatment waste as a filler product and a replacement for regular Portland cement in cement paste and mortar compositions. The use of biochar, a type of charcoal made from decomposed organic materials at high temperatures without oxygen, has been the subject of my research. Because of its unique qualities, such as its high capacity to absorb water and low heat conductivity, biochar is a material that can be used in a wide range of applications. Furthermore, biochar's high surface area and reactivity make it a great additive that can improve the bond between aggregate and cement paste, giving concrete greater durability and mechanical strength.

Moreover, the porous nature of biochar can contribute to decreasing the water content for mixing concrete, which can result in enhanced workability and decreased shrinkage. This has been explored the application of biochar in construction materials, especially as a concrete admixture or additive/replacement in cement-based composite [3]. This study builds on earlier research that showed encouraging results when using biochar to increase concrete's mechanical strength and durability. In my study, I used biochar made from waste from gasification treatment as a filler and investigated whether it could be used in cement paste and mortar mixtures in place of regular Portland cement. This study shows that adding 30 weight percent biochar can have a positive impact on the properties of cementitious mixtures. Additionally, this study supports earlier studies that showed the feasibility of adding biochar to concrete to improve its mechanical strength, water tightness, and durability. It is observed that optimal mix proportion and source of biochar have an important role in influencing results, and it reflects the possibility for more investigation in this field. In total, this study adds to the body of evidence regarding the advantages of biochar application in construction materials. Through the examination of new uses and the design of mixes to optimize, the potential of biochar have capacity to provide more sustainable and long-lasting building material [1].

Table 1. Literature Review

Sr. #	Year	Authors	Objective	Method	Material	Conclusion
1	2024	[4]	Effects of biochar as partial replacement	Literature review and technology assessment	Biochar and other carbon-neutral technologies	Highlighted biochar's role in emission's reduction and building material innovation.
2	2024	[5]	Biochar concrete	Experimental analysis of product characteristic and energy efficiency	Biomass as a raw material	Enhanced understanding of product efficiency in green technologies

3	2023	[6]	Investigate biochar as cement additive	Experimental study	Cement composites	Biochar reduces carbon footprint and improves material properties
4	2019	[1]	Improve lightweight concrete performance	Comparative study of biochar	Carbonized peach and apricot shells	Biochar enhance concrete performance metrics

5	2022	[7]	Pyrolysis of E-waste	Cleaner Production		A comprehensive review on pyrolysis of E-waste and its sustainability
6	2022	[8]	Properties of biochar concrete	Mechanical and durability properties	Mechanical and durability properties of biochar concrete	
7	2024	[9]	Analysis of environmental performance indicators		CO_2 emissions and water	Analysis of Environmental performance metrics for concrete block production: embodied energy, carbon dioxide emissions, and water usage.
8	2020	[10]	Life cycle assessment of biochar	Partial replacement to Portland cement.		Life cycle assessment of biochar as a partial substitute for Portland cement
9	2024	[11]	Rice husk biochar for carbon sequestration		Soil fertility and plant health	Rice husk biochar for carbon sequestration, enhancement of soil fertility, and improvement of plant health

The reviewed literature collectively underscores the growing recognition of biochar as a viable additive or partial replacement for cement in sustainable construction materials. Wazir (2024) highlighted, through a literature review and technology assessment, biochar's potential to reduce emissions while driving innovation in building materials. Barbhuiya et al. (2024) provided experimental evidence on the efficiency of biochar–concrete composites, particularly in enhancing product performance and energy efficiency when biomass-derived raw materials are used. Lin et al. (2023) demonstrated, via experimental studies, that biochar incorporation in cement composites not only reduces the carbon footprint but also improves material properties. Earlier work by Senadheera et al. (2019) confirmed that carbonized agricultural residues such as peach and apricot shells enhance the performance metrics of lightweight concrete. Taken together, these studies form a consensus that biochar can contribute simultaneously to environmental sustainability and mechanical performance improvement in cementitious composites, while supporting circular economy principles through waste valorization. The large-scale implementation of RHB-based concrete can be facilitated through public–private partnership (PPP) models, which have proven effective in enhancing resource mobilization and project delivery in Pakistan [12]. Such collaborations could accelerate the adoption of sustainable materials in mainstream construction. The integration of RHB-based concrete into sustainable construction practices aligns with broader green building strategies that combine alternative binders and natural fibers for enhanced environmental performance. Similar to approaches merging fly ash and hemp for eco-friendly concrete [13], this study reinforces the potential of renewable, low-carbon materials to advance green construction objectives. The development of RHB-based concrete supports the ongoing pursuit of sustainable construction solutions, complementing previous efforts to enhance the strength and workability of green concrete [14]. Both approaches highlight the importance of optimizing material performance while reducing environmental impact. The utilization of RHB in concrete aligns with prior research on agro-industrial waste valorization, such as the use of sugarcane bagasse ash and silica fumes as supplementary cementitious materials [15], reinforcing the role of waste-derived additives in reducing cement consumption and promoting sustainability.

Building on this consensus, the present study aims to extend the application of biochar specifically rice husk biochar (RHB), as a partial replacement for cement in concrete blocks, with a focus on quantifying both mechanical and environmental benefits. The objectives are twofold: (1) to assess the potential of RHB in lowering carbon emissions and advancing environmental sustainability in the construction sector, and (2) to investigate its material properties, thermal insulation benefits, and economic viability in contributing toward a carbon-neutral future. The novelty of this research lies in its holistic approach, combining multiple performance assessments mechanical, thermal, and environmental within a single experimental framework. Unlike many prior studies that focus narrowly on one property, this work integrates carbon footprint reduction, thermal insulation potential, waste management benefits, economic feasibility, and material versatility, providing a comprehensive evaluation of RHB concrete for both industry adoption and sustainability impact.

While previous studies have demonstrated the promise of biochar in cementitious composites, few have systematically evaluated rice husk biochar across a full spectrum of mechanical, durability, thermal, and environmental parameters using standardized testing protocols. This research addresses that gap by delivering a unified dataset that links performance trends directly to practical application guidelines, enabling both scientific understanding and real-world implementation.

2. MATERIALS AND METHODS

This study employed an experimental approach to evaluate the feasibility of using rice husk biochar (RHB) as a partial replacement for Ordinary Portland Cement (OPC) in concrete block production. The methodology was designed to assess both the mechanical and environmental performance of RHB-based concrete across varying replacement levels. The research process encompassed material selection and preparation, mix proportioning, specimen casting and curing, and a series of standardized tests to measure compressive strength, flexural strength, water absorption, permeability, thermal conductivity, and ultrasonic pulse velocity. In parallel, an environmental assessment was carried out to estimate the potential carbon footprint reduction and CO_2 sequestration benefits of incorporating RHB. Each methodological step was informed by relevant ASTM standards.

Ordinary Portland Cement (OPC) conforming to ASTM C150, natural siliceous sand with a silica content above 98%, and tap water were used as base materials. Rice husk biochar is a porous, carbon-rich material produced by pyrolysis (heating under no oxygen conditions) of rice husks, which are typical agricultural residues. It is light in weight, possesses high surface area, and has silica and fixed carbon and is thus a desirable additive to building materials [16, 17]. Rice husk biochar is a viable, sustainable concrete block additive for sustainable concrete blocks. With appropriate mix design and utilization, it presents a combination of thermal performance, weight savings, and sustainability and is thus well-suited to non-structural and energy-saving construction [18, 19]. The biochar additive was produced from rice husks via pyrolysis under oxygen-limited conditions at 400–700 °C [20], resulting in a lightweight, porous, silica-rich material. Before mixing, the rice husk biochar (RHB) was sieved to obtain a uniform particle size and, for selected batches, pre-soaked in water for 24 hours to assess the influence of moisture conditioning on porosity and durability performance.

The experimental program involved partial replacement of OPC with RHB at weight proportions of 10%, 20%, and 30%. Two mixing strategies were adopted: the Water–Superplasticizer Pre-Mix Method, where RHB was dispersed in a water–superplasticizer solution before combining with cement and sand; and the Dry Blend Method, where RHB was dry-mixed with cement prior to water addition. The water-to-cementitious materials ratio was kept constant for all batches.

Specimens were cast in standard cube molds for compressive strength testing and prism molds for flexural strength testing. All specimens were demolded after 24 hours and cured in tap water at 23 ± 2 °C until testing ages of 7 and 28 days.

Mechanical and durability performance were assessed through compressive strength (ASTM C39), flexural strength (ASTM C78), water absorption (ASTM C642), and permeability tests including primary and secondary capillary absorption. Thermal conductivity was measured using a steady-state guarded hot plate apparatus (ASTM C177). Ultrasonic Pulse Velocity (UPV) testing (ASTM C597) was conducted to assess internal material integrity and uniformity.

All results were based on triplicate specimens, and averages were calculated to minimize variability. Data were compared against the control mix and contextualized using recent literature findings. Environmental performance was evaluated using literature-based CO_2 sequestration coefficients, estimating potential carbon mitigation per ton of RHB used.

RESULTS and DISCUSSION

The experimental results confirm that rice husk biochar (RHB) can serve as a viable partial cement replacement, delivering both performance and environmental benefits when applied within optimal dosage ranges. Flexural strength improvements of up to 30% were achieved at 20% RHB replacement, likely due to enhanced crack-bridging and tortuous fracture

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paths induced by the porous biochar particles. Compressive strength results were more nuanced: while 5–15% RHB maintained strength within acceptable limits for non-load-bearing applications, replacements exceeding 20–25% required pre-soaking treatments and optimized mixing to avoid strength loss. These findings align with several recent studies, though reported optimal percentages vary depending on feedstock type and pyrolysis conditions.

Thermal conductivity decreased consistently with increasing RHB content, confirming the material's insulating potential and its suitability for energy-efficient building envelopes, especially in hot climates where thermal resistance contributes to operational energy savings. Water absorption results demonstrated the importance of pre-soaking RHB to reduce porosity-driven sorptivity. UPV values (~3 km/s) confirmed that biochar incorporation, at the tested levels, did not significantly compromise internal material integrity. From an environmental perspective, the partial cement replacement directly reduces embodied carbon and indirectly contributes to waste valorization by upcycling agricultural residues. Literature-based estimates suggest potential CO_2 mitigation up to 870 kg CO_2-eq per ton of feedstock, though this figure should be validated experimentally for the specific RHB and curing conditions used here. Industrial feasibility is reinforced by the fact that the production process requires no specialized equipment or modifications to existing concrete block manufacturing methods. The detailed results are discussed below.

.1.Compressive Strength

The compressive strength test results of biochar-based concrete blocks are shown in Figure. The error bars represent the range of values from the mean. For concrete blocks samples, incorporation of 30% biochar in the water-super plasticizer solution yielded over a 15% increase in compressive strength than pure cement. But when biochar was blended with cement powder, a reduction in strength of 8% was noticed. This research found that a proportion of biochar in excess of 25-30% of the total cement volume increase the compressive strength of the mix, independent of the pyrolysis temperature

Figure 2. Concrete block testing in UTM machine

The results are consistent with [21], whereas, other studies indicate that the best content of biochar can differ based on biomass and pretreatment conditions[22, 23]. Compared to that, mortar samples had a negligible loss of resistance of 2% when subjected to 30% biochar [24] When biochar was previously mixed with cement powder, the compressive strength increased by more than 10% [25] In addition, when biochar was utilized as a cement replacement, there was a minimal reduction in strength of just 2%, whether the biochar was blended with water or cement powder.

These results consistent with existing studies, such as [26] which indicated a slight decrease in fracture strength when biochar obtained from coconut shell was added. Nevertheless, the effect of biochar on flexural strength is also influenced by the feedstock it is obtained from, as indicated by [27] who found a 47% increase in flexural strength at 7 days due to the addition of biochar derived from hazelnut shell.

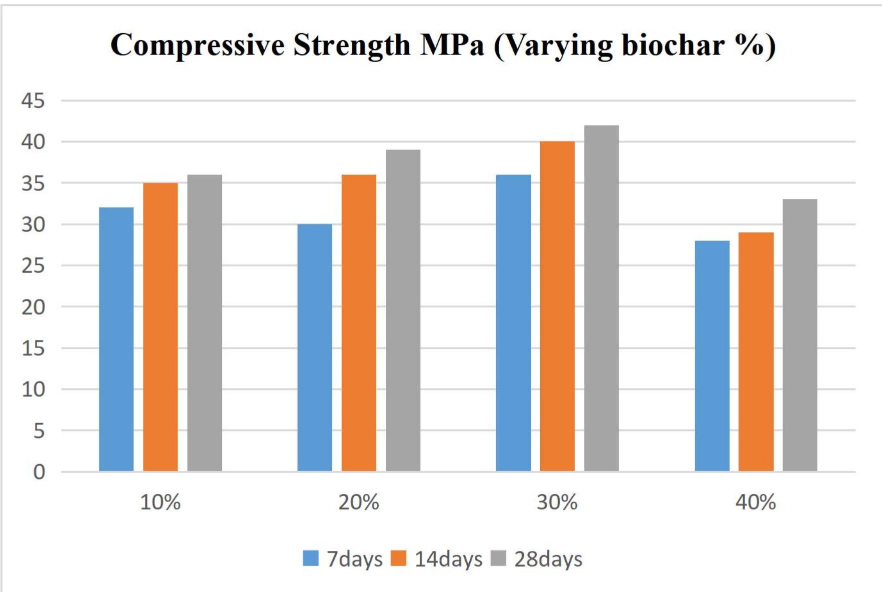

Figure 3. Compressive Strength of Biochar based concrete blocks

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Biochar incorporation can influence their elastic modulus and mechanical strength. Covalent bonding among carbon atoms when pyrolyzed can enhance the elastic moduli and hardness of such composites, especially at elevated pyrolysis temperatures. It's also noted, however, that a rise in the proportion of biochar incorporated into cement-based composites can result in their elastic moduli to drop [8]. While this could seem to be a drawback, it could be beneficial in constructing earthquake-resistant materials for use in earthquake zones, where stress-distributing and stress-absorbing capacities are very much needed [21, 28]. Overall, these results indicate that biochar is a valuable component for cement-based composites, with potential to develop more sustainable and resistant building materials. On the basis of understanding the impact of biochar on elastic modulus and mechanical strength, material that is tailored to have certain performance requirements can be manufactured.

The ultrasonic pulse velocity (UPV) test measures the quality and integrity of concrete. The test involves the measurement of the velocity of ultrasonic pulses through the concrete, which can reflect the presence of defects, e.g., cracks, voids, or poor-quality areas [29]. The UPV test results for the 30% biochar concrete block was promising with an average pulse velocity of about 3.5 km/s. This indicates that adding biochar to the mixture did not much compromise the quality or integrity of the material. The 3 km/s average pulse velocity shows that the biochar concrete block possesses a relatively good uniformity and density, which is critical in achieving the structural performance and durability of the concrete structures. These findings are promising, as they show that biochar can be employed as a sustainable, environmentally friendly, and good additive to be incorporated into concrete manufacturing without compromising material quality. Whereas, the results are not aligned with other studies [30, 31].

3.2. Ultrasonic Pulse Velocity (UPV) Test Results

Figure 4. Ultrasonic Pulse Velocity (UPV)

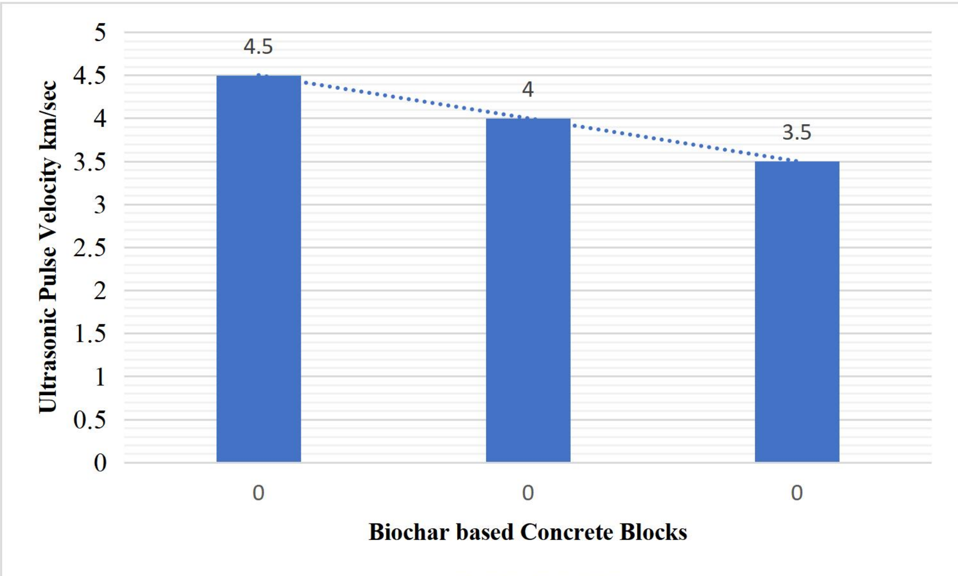

Figure 5. Ultrasonic Pulse Velocity km/sec

The results of this study emphasize the potential of biochar as a sustainable and performance-improving additive in concrete block manufacturing. The cement utilized was Ordinary Portland Cement (OPC), and fine aggregates were regular river sand. The most significant innovation was the addition of biochar derived from pyrolyzed agricultural residues [32, 33], which acted as a partial replacement for cement by weight in varying percentages. One of the most important results was the obvious effect of biochar on thermal insulation. As the proportion of biochar rose, we found a steady decrease in thermal conductivity in all samples [34]. This confirms the theory that the porous nature of biochar is an insulator, holding air in and preventing heat from passing through [35]. This characteristic makes these blocks ideal for application in climates where thermal performance plays a major role in energy savings in buildings. This trend indicates that although biochar is beneficial to thermal and environmental conditions, its replacement level has to be properly optimized in order to maintain structural reliability. The continual reduction in strength can be explained by lower binding capability of biochar as opposed to cement, as well as its high surface area that might interfere with the hydration process.

3.3. Water Absorption

In this study of cement mixers, found that water absorption is an important parameter in evaluating durability. This is noted that the amount of macrospores in the cement mix increases with increased biochar content, which can result in increased sportively and penetration depth. It's found that pre-soaking biochar in water before mixing it with cement considerably lowered water absorption levels. Particularly, this study demonstrated that cement mortar cast with 30% biochar had a 41% decrease in water absorption rate when the biochar was pre-wetted with water. This decrease is due to the compaction effect on the mortar paste that lowers the porosity. However, a subsequent study this conducted yielded different results [36] biochar produced from rice husk without pre-soaking it in water, the water absorption rate of the cement mortar was comparable to that of the control sample [37]. This findings highlight the importance of pre-soaking biochar in water to enhance its performance in concrete mixes. The water absorption properties of concrete are critical to its durability, and understanding the effects of biochar treatment can inform its optimal use in construction materials. Water absorption tests revealed a minimal porosity increase with increased biochar content. Although this could be of concern when it comes to durability, particularly in wet conditions, the values were still within acceptable limits for internal partitioning and dry climate use. The low bulk density of the biochar blocks, as seen through their lower bulk density, is also an added value by providing ease of handling and transportation [38]. This property, along with thermal insulation, makes it suitable for these blocks to be employed in prefabricated building modules or emergency tents.

3.4. Flexural Strength

In this study of the flexural strength of biochar-concrete composites, the biochar based concrete block with 20% cement replacement 30% increase in flexural strength for both the 7-day and 28-day tests was achieved. Also, there was an enhancement in fracture energy because of tortuosity in the crack path induced by the biochar within the cement matrix [8]. The results are consistent with previous research such as author observed that adding 1% biochar (hazelnut shell and peanut shell) by weight to cementitious composites can enhance their toughness and flexural strength by preventing crack propagation [39]. Other researchers have also reported similar results, such as a 26% increase in flexural strength when using poultry litter-based biochar to replace sand [40]. In general, this analysis indicates that biochar can improve the flexural strength of cement composites depending on its type and quantity. By balancing the type and proportion of biochar, more durable and green building materials can be manufactured [41].

3.5. Permeability

Incorporating 20–30 weight percent biochar into cement mortar can lower its water permeability, according to several studies [4, 42]. Reduced permeability might lead to more durability and resistance to degradation. Additionally observed is that adding biochar can slow down the mass gain brought about by sodium chloride adsorption. The studies on the capillary absorption of cement-based materials using biochar came to the conclusion that they could be split into primary and secondary absorption. It occurs as main absorption in the first 24 hours and as secondary absorption over one day. This work has shown that biochar can lower the initial absorptivity; significant decreases have been recorded at 30 weight percent of biochar content. The findings highlight the possibilities of biochar as a great additive to cement-based materials, so improving their resistance to degradation and durability. Correct biochar proportion and composition will help us create stronger and more environmentally friendly building materials [9].

.6.Environmental Benefits of Biochar-Cement Composites (Carbon Sequestration)

The use of biochar as a material also has high sustainability advantages. It comes from biomass waste, reducing landfill pressure and carbon sequestration. It partially replaces cement, [3] which is high in energy use and high emissions of CO_2, the carbon footprint of the concrete overall is greatly reduced. This works perfectly with global construction trends driving demand for cleaner substitutes. In practical terms, mix designs employed within this research did not need to have any specialized manufacturing methods. Conventional methods of casting were employed to produce the blocks, so biochar-based concrete can be implemented at industry level without the need to alter current manufacturing procedures [22]. However, further study is required on the curing process, as biochar's absorption and interaction with water can influence hydration and setting times [29]. In conclusion, the materials used and outcomes attained are in support of the use of biochar-based concrete blocks in green building. Though compromises have to be made mostly compressive strength at increased content of biochar the thermal and environmental advantages create a strong argument for their uptake in targeted uses. Further work will involve improvements to mix design, investigation of surface treatments for minimizing porosity, and assessments under actual climatic conditions to maximize the benefits of this sustainable technology. Biochar-cement composite provides substantial environment benefits, including carbon sequestration. Biochar carbon becomes included in material embodied carbon and has various aspects that affect the same, namely feedstock, pyrolysis conditions, and use of other co-products.

According to [43], Biochar might cut net greenhouse gas emissions by around 870 kg CO_2 equivalent per ton of dry feedstock. Additionally, [44] fixed carbon in biochar-cement composites can further minimize future constructions' embodied carbon. This is particularly important in the case of the cement industry, which is the largest green gas emitter and generates severe environmental consequences. The carbon fixation within biochar-cement composites is subject to the adsorptive ability of the biochar, diffusion of CO_2 along the pore system in the hydrated cement matrix, and carbonatable products. The biochar is used as sites for nucleation of hydration to produce more additional hydration products which can be subjected to reaction with CO_2 in order to give calcium carbonate [45]. Studies [11, 45] have indicated that biochar enhances the capacity for CO_2 capture through its high surface area and micro-pore volume. Incorporation of biochar has the potential to enhance the CO_2 uptake of cementitious materials, which will result in greater carbon sequestration[46]. This is attributed to the physical and chemical properties of biochar, which allow it to adsorb and store CO_2.

Accelerated carbonation curing (ACC) is a procedure that entails exposure of prefabricated cementitious materials to high levels of CO_2, between 1-20% (1000-200,000 ppm), at controlled humidity and temperature levels during the initial 24-48 hours of casting. This causes the reaction between CO2 and calcium-bearing phases to form calcium carbonate minerals. Studies [43] have demonstrated that ACC can lead to large-scale carbon sequestration and enhanced mechanical performance of cement-based materials. The use of biochar can further augment the carbon sequestration potential of ACC, resulting in enhanced durability and strength of cement-based materials.

A number of studies have examined the impact of biochar on the carbon sequestration capacity of cement-based materials. For instance, [47] reported that at 7 and 28 days of age, the carbonate mineralization increased by 3-6% when 3 weight percent of biochar was added in comparison to the control. Another study by [31] determined that incorporation of 20% fly ash and 2-4% biochar synthesized from corn stover led to greater mass gain after 2 hours of carbon dioxide exposure than when the mortar had only fly ash (control). This was due to enhancement of the mineralization of carbonates due to the incorporation of biochar.

4. CONCLUSION

This study demonstrates that incorporating rice husk biochar (RHB) into concrete blocks can balance environmental sustainability with functional performance when dosage levels are appropriately tailored to the intended application. The results show that:

1. Non-load-bearing and thermal insulation applications benefit most from 15–25% RHB replacement, achieving high thermal insulation, improved flexural strength, and significant carbon footprint reduction.
2. Semi-structural and load-bearing applications should limit RHB to ≤10% to maintain compressive strength while still securing moderate environmental gains.

- Enhanced flexural performance and thermal resistance.
- Reduced embodied carbon via partial cement replacement and potential carbon sequestration.
- Feasibility of adoption using existing concrete block manufacturing methods without capital investment.

Figure 6 represents the comparison control, 10% RHB, 20% RHB and 30% RHB mixes across strength, insulation, water absorption, and carbon footprint reduction. The radar chart confirms that higher RHB dosages significantly improve thermal and environmental metrics while modestly reducing compressive strength supporting the application-specific ranges of biochar based concrete blocks.

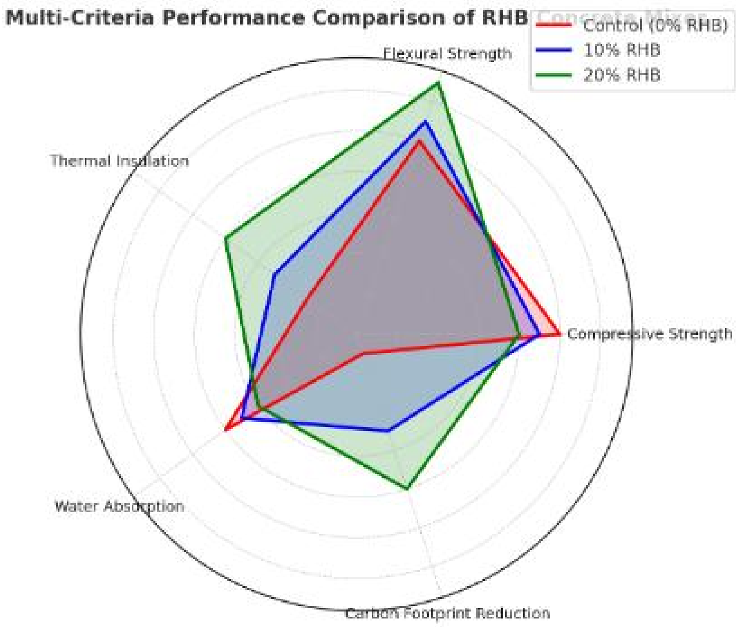

Figure 6. Multi-Criteria Radar Chart Performance Comparison of Biochar based Concrete Block

5. LIMITATIONS AND FUTURE REAEARCH DIRECTIONS

More studies need to be carried out to assess the influence of biochar on the long-term stability and properties of cement materials. Furthermore, the creation of engineered biochar with properties improved for carbon storage and other functions is still being researched. Limitations of this study include the absence of long-term durability testing (e.g., freeze–thaw, chloride ingress), lack of experimental CO_2 sequestration measurement, and no life-cycle cost analysis.More studies are required to maximize the biochar content and mix design to get even greater performance and to investigate further applications of biochar concrete in different construction works. Nevertheless, the outcomes of this study evidence the capability of biochar as a worthwhile additive in concrete mix, adding to greener and more sustainable building practices. Future research should focus on several key areas to advance the practical application of rice husk biochar (RHB) concrete. First, accelerated durability testing and field trials under diverse climatic conditions are essential to validate long-term performance and ensure suitability for different geographic regions. Second, experimental quantification of CO_2 uptake under varied curing regimes is needed to provide direct evidence of the material's carbon sequestration potential. Third, comprehensive life-cycle cost and environmental impact analyses, including the evaluation of potential carbon credit valuation, will strengthen the economic and sustainability case for industry adoption. Finally, the development of engineered biochar with tailored microstructural properties could optimize the balance between mechanical strength, thermal insulation, and durability. By addressing these areas, RHB-based concrete can progress from a promising laboratory innovation to a widely adopted green building material, making a significant contribution to global decarbonization goals.

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