Incorporating Biochar into Concrete Building Materials

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ABSTRACT

This study investigates the incorporation of biochar as a partial substitute for cement in concrete, aiming to advance sustainable construction methodologies. Comprehensive analyses were conducted to evaluate the mechanical performance, thermal properties, and durability of biochar-concrete composites. The findings reveal that partial cement replacement with biochar significantly mitigates carbon emissions while enhancing functional properties such as thermal insulation and carbon sequestration. Nonetheless, the research identifies trade-offs, including diminished compressive strength at elevated biochar replacement ratios. To address these limitations, strategies such as particle size optimization and surface functionalization of biochar were explored. The study highlights the dual advantages of reducing environmental impact and fostering material innovation within the construction sector. Further investigation is recommended to scale production processes, assess long-term structural integrity, and optimize composite formulations for diverse architectural and engineering applications.

Keywords: Pyrolysis | Porosity | Biochar | Compressive Strength | Permeability |

1. Introduction

The growing demand for sustainable and eco-friendly construction materials has pushed for an extensive research into alternative additives for cement-based composites. One of these materials is **biochar**, a carbon-rich substance produced through the **pyrolysis of organic biomass** under low oxygen conditions. Historically, biochar was utilized as a soil amendment due to its ability to improve soil structure and nutrient retention. Recent studies have explored its potential application in **cementitious materials**, where it has demonstrated **enhanced mechanical, thermal, and environmental performance**.

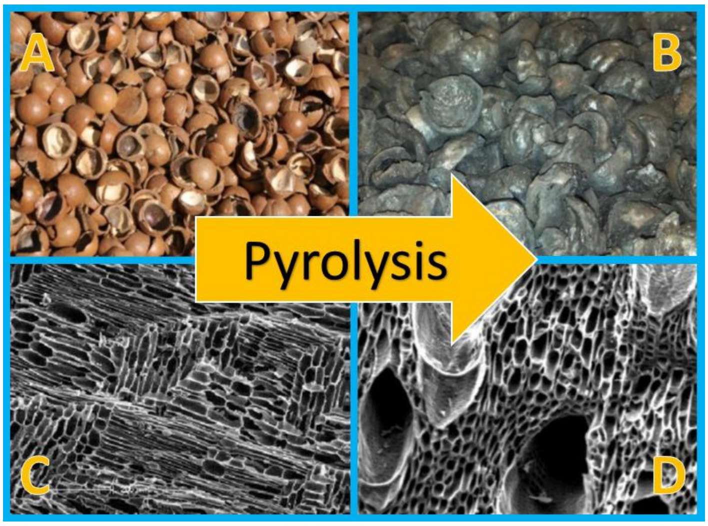


Figure 1 : shows pyrolysis . I*mage by Kurt Spokas, 2013.*

Exploring the Evolution and Modern Applications of Biochar in Sustainable Construction

The use of biochar in construction has its origins in ancient practices. Historically, biochar-like substances were produced through the slow burning of organic materials in low-oxygen environments, a process known as pyrolysis. One of the earliest documented uses of biochar is found in the Amazon Basin, where Indigenous peoples created "Terra Preta" (dark earth) by incorporating charred organic matter into the soil, enhancing its fertility and sustainability.

In construction, the modern exploration of biochar began in the 21st century, driven by a growing interest in sustainable and carbon-negative materials. The material's porous structure and high carbon content have made it particularly attractive for green building applications.

Today, the use of biochar in construction is advancing through extensive scientific research and pilot projects. Efforts are focused on optimizing its performance, addressing safety concerns, and developing standardized guidelines to facilitate its wider adoption in sustainable construction practices.

2. Historical Evolution and Modern Applications of Biochar in Construction

Biochar's earliest recorded use dates to pre-Columbian Amazonia, where "Terra Preta" soils enriched with charcoal exhibited remarkable fertility and stability. In the 21st century, the material's high fixed carbon content and porous morphology prompted its evaluation as a sustainable additive in green building. Pilot projects and laboratory studies have since focused on optimizing pyrolysis parameters, identifying ideal feedstocks (e.g., rice husk, sawdust), and establishing guidelines for safe, reproducible production. Current efforts aim at standardizing biochar characterization (particle size distribution, surface chemistry) to support regulatory acceptance and scalability. [5–7]

3. Porosity and Microstructural Modification

3.1. Microstructure Enhancement Mechanisms

Porosity denotes the presence of voids or empty spaces within a material, influencing its physical and thermal properties. Biochar, derived from the thermal decomposition of organic materials, possesses a highly porous structure characterized by a network of microscopic pores. These pores trap air, a poor conductor of heat, which significantly influences the behavior of biochar when incorporated into concrete as an additive.

The inclusion of biochar enhances the material's porosity, leading to lower thermal conductivity. This characteristic can improve the thermal insulation properties of concrete, making biochar a valuable component in sustainable construction practices aimed at enhancing energy efficiency.

Biochar plays a multifaceted role in enhancing the microstructure of concrete through several mechanisms. Its porous particles, characterized by high surface area, act as micro-fillers, filling voids within the cement paste and reducing overall porosity. This refinement in pore structure leads to a denser and less permeable matrix, which enhances the durability of concrete.

The interfacial transition zone (ITZ), typically the weakest link in concrete due to its heterogeneity, benefits from the inclusion of biochar. By improving bonding and reducing the formation of microcracks, biochar contributes to a stronger and more homogeneous matrix. Furthermore, biochar's ability to absorb and retain water introduces an internal curing effect. This property allows for gradual water release during the hydration process, supporting more complete cement hydration and mitigating autogenous shrinkage and cracking, particularly in high-performance concrete.

When introduced into the cement paste, biochar particles act as micro-fillers, occupying voids and refining the interfacial transition zone (ITZ). Their high surface area promotes additional C–S–H formation via internal curing: biochar adsorbs mixing water and releases it gradually during hydration, reducing autogenous shrinkage and microcracking. This densification lowers permeability and enhances durability, while simultaneously sequestering carbon within the hardened matrix. [8–10]

3.2. Porosity Measurement Techniques

Accurate assessment of biochar-enhanced concrete porosity employs multiple complementary methods:

- Mercury Intrusion Porosimetry (MIP): Pore size distribution from 3 nm to 360 µm.
- Brunauer–Emmett–Teller (BET) Gas Adsorption: Surface area and microporosity (<2 nm).
- Micro-Computed Tomography (µ-CT): 3D visualization of pore connectivity.
- Scanning Electron Microscopy (SEM): Morphology and pore architecture.
- Pycnometry & Water Displacement: Bulk density and open-porosity quantification. [11]

The choice of method to analyze the porosity of biochar depends on the desired information:

- Mercury Intrusion Porosimetry (MIP): Best for detailed pore size distribution across a wide range of sizes.
- Gas Adsorption (BET): Suitable for assessing surface area and microporosity.
- Micro-CT: Ideal for 3D visualization and comprehensive structural analysis.
- SEM: Provides high-resolution images for surface and pore structure analysis.
- Pycnometry: Good for measuring true density and closed porosity.
- Water Displacement: Simple and effective for open pore volume analysis.

Figure1

Shows biochar under a microscope, showcasing its poirous structure and intricate air pockets.(5)

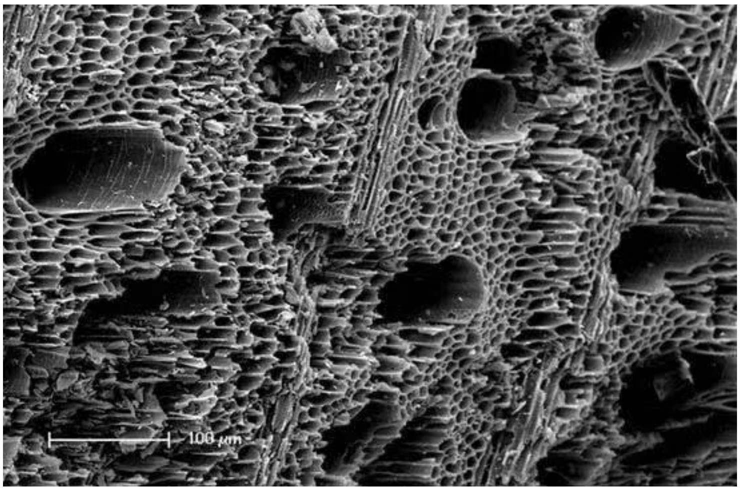
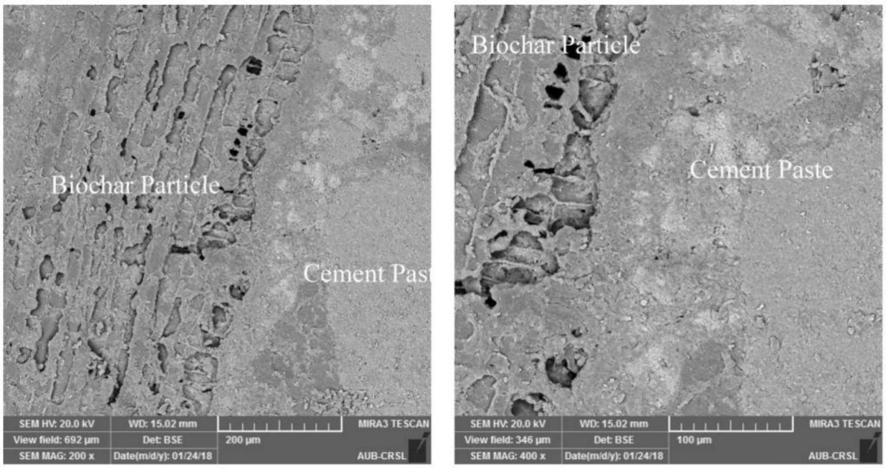


Figure 2 . A SEM micrograph of biochar composite (6)



(c) (d)

4. Functional Advantages of Biochar-Enhanced Concrete

4.1. Mechanical Properties

Low-level biochar replacement (0.75–2 wt%) often increases 28-day compressive strength by 10–40 %, owing to improved hydration kinetics and microstructure compaction. For example, a 1.5 wt% rice husk biochar addition elevated strength by 29 %, while 3 wt% mixed rice-sawdust biochar yielded a 15 % gain relative to control samples. However, beyond 5 wt%, strength declines due to excessive porosity. [12–14]

The inclusion of biochar in concrete has been shown to increase its compressive strength, particularly at low replacement levels (1–3% by weight). This improvement is due to the pozzolanic and filler effects of biochar. As a pozzolanic material, biochar reacts with the calcium hydroxide in concrete to form additional calcium silicate hydrate (C-S-H), the primary binder in concrete. This reaction enhances the concrete's overall strength.Study Findings: it was found that 5% biochar addition led to a 10% increase in compressive strength when compared to control concrete. This demonstrates that biochar not only improves durability but also boosts the mechanical performance of concrete.[24]

4.2. Lightweight Characteristics

Biochar exhibits significantly lower density compared to conventional construction materials such as concrete, brick, or stone. This characteristic is attributed to its highly porous structure, which contains numerous air pockets. These voids reduce the material's overall weight, facilitating easier handling, transportation, and installation during construction. Consequently, the use of biochar can decrease transportation costs, labor expenditures, and installation time, particularly in large-scale construction projects. Furthermore, its reduced weight lessens the load exerted on building foundations, offering advantages in regions with soft soils or other challenging foundation conditions. This characteristic represents a notable advantage in construction practices.

The incorporation of biochar into concrete mixtures contributes to the development of lightweight concrete by replacing traditional aggregates, thereby reducing the composite material's overall density. This weight reduction is especially beneficial in applications where minimizing structural loads is critical, such as high-rise buildings or precast concrete components.

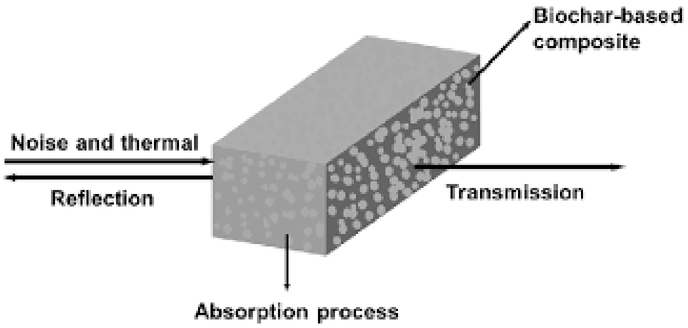
Biochar's high porosity and low density enable it to function as an effective lightweight aggregate. When introduced in moderate concentrations, typically ranging from 1% to 3% by weight, biochar not only decreases the concrete's density but also enhances certain mechanical properties. This dual benefit underscores its potential for sustainable construction applications.

With bulk densities 20–50 % lower than traditional aggregates, biochar reduces concrete dead load and foundation stresses. Mixtures containing 1–3 wt% biochar can achieve up to 10 % overall density reduction, facilitating easier handling and potential cost savings in transport and installation. [15]

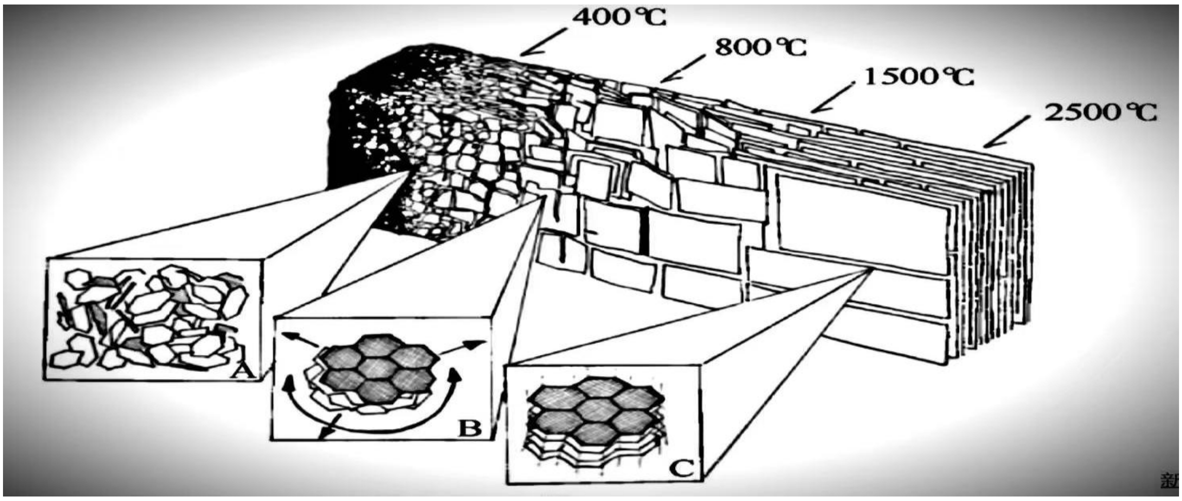
4.3. Thermal Insulation

The porous structure of biochar makes it an excellent thermal insulator. The air pockets within the biochar trap heat, significantly slowing down the transfer of temperature between the interior and exterior of a building. In cold climates, this property reduces heat loss, helping to maintain warmer indoor temperatures and lowering energy consumption for heating. In hot climates, biochar helps maintain cooler indoor conditions by preventing the absorption of heat from the outside environment. This dual capability not only contributes to energy savings but also enhances comfort for occupants, making biochar a valuable material for constructing energy-efficient buildings and homes.

By improving thermal performance, biochar can play a key role in sustainable construction, supporting both energy conservation and enhanced occupant comfort.(2)



As the temperature increases during biochar production, significant changes occur in its structure and composition. At low temperatures, ranging from 400 to 800°C, the biochar is light brown or yellowish in color. It retains a higher content of volatile compounds, resulting in a relatively high surface area and abundant functional groups such as hydroxyl and carboxyl. This biochar is highly reactive and well-suited for applications requiring chemical activity or nutrient adsorption.



At medium temperatures, between 800 and 1500°C, the biochar darkens to a deep brown or reddish hue. Its carbon content increases as volatile compounds are further reduced, leading to a more ordered structure and lower reactivity. The surface area remains moderate but starts to decline as pore structures begin to collapse. This type of biochar offers increased stability and is ideal for applications requiring structural integrity over chemical reactivity.

When produced at high temperatures, from 1500 to 2500°C, the biochar becomes black or dark brown. It is predominantly composed of carbon, with only minimal functional groups remaining. The material is highly stable and less reactive, with a low surface area due to significant collapse of the pore structures. Such biochar is suitable for long-term applications, such as carbon sequestration and durable soil amendments.

At very high temperatures, exceeding 2500°C, the biochar takes on a charcoal-black appearance. By this stage, it is nearly pure carbon with negligible volatiles or functional groups remaining. The surface area is extremely low as the pore structure has almost entirely collapsed. This highly stable and minimally reactive form of biochar is best suited for high-durability applications that require extreme stability.

The incorporation of biochar into concrete enhances its thermal insulation properties, making it an effective material for energy-efficient construction. Biochar's unique structure, characterized by high porosity and low density, contributes to its ability to reduce thermal conductivity. This means that concrete containing biochar can better resist the transfer of heat, helping to maintain stable indoor temperatures and reducing the reliance on heating and cooling systems [54,55]

When biochar is added to concrete, it acts as an insulating filler, which improves the overall thermal performance of the material. Studies have shown that the addition of biochar can lead to a significant decrease in thermal conductivity, thereby enhancing the thermal insulation properties of the concrete mix [56,57]. This is particularly beneficial in regions with extreme weather conditions, as it helps to minimize energy consumption for heating and cooling, leading to lower utility costs and a reduced carbon footprint.

Furthermore, the insulating nature of biochar-enhanced concrete can contribute to improved acoustic insulation, providing additional benefits in terms of comfort and noise reduction in buildings [58]. Overall, the use of biochar in concrete not only enhances thermal insulation but also promotes sustainability in construction practices.

Biochar's interconnected pore network traps air, thereby reducing thermal conductivity by 15–30 %. This results in appreciable heating and cooling energy savings, particularly in extreme climates. Biochar-enhanced panels have exhibited up to 25 % lower U-values compared to ordinary concrete, favoring both occupant comfort and carbon reduction. [16–18]

4.4. Acoustic Insulation

Biochar's unique porous structure makes it an excellent material for acoustic insulation in construction. Its high volume of interconnected air voids and irregular surface effectively absorb and scatter sound waves, reducing noise transmission through walls and panels. This property is especially valuable in noisy urban environments, schools, offices, and residential buildings. By integrating biochar into construction materials, sound insulation is enhanced without compromising structural integrity.

Scientific studies support biochar's effectiveness in sound attenuation. Research shows that adding 1–3% biochar by weight to concrete improves acoustic performance, with up to a 20% increase in sound absorption at mid-to-high frequencies.(59)Additionally, biochar made from bamboo waste has been shown to boost the Noise Reduction Coefficient (NRC) significantly. Its effectiveness is largely due to its pore structure, with a surface area over 200 m^2/g and pore sizes between 0.5–5 µm being most effective. (60) Biochar not only improves indoor acoustic comfort but also offers an eco-friendly alternative to synthetic insulation materials.

Incorporating 1–7 wt% biochar increases sound absorption coefficients by up to 20 % at mid-to-high frequencies. Mechanisms include wave scattering within micro- and mesopores and elevated airflow resistivity. Hybrid mixes with perlite or cellulose fibers further amplify damping properties without sacrificing strength. [19–21]

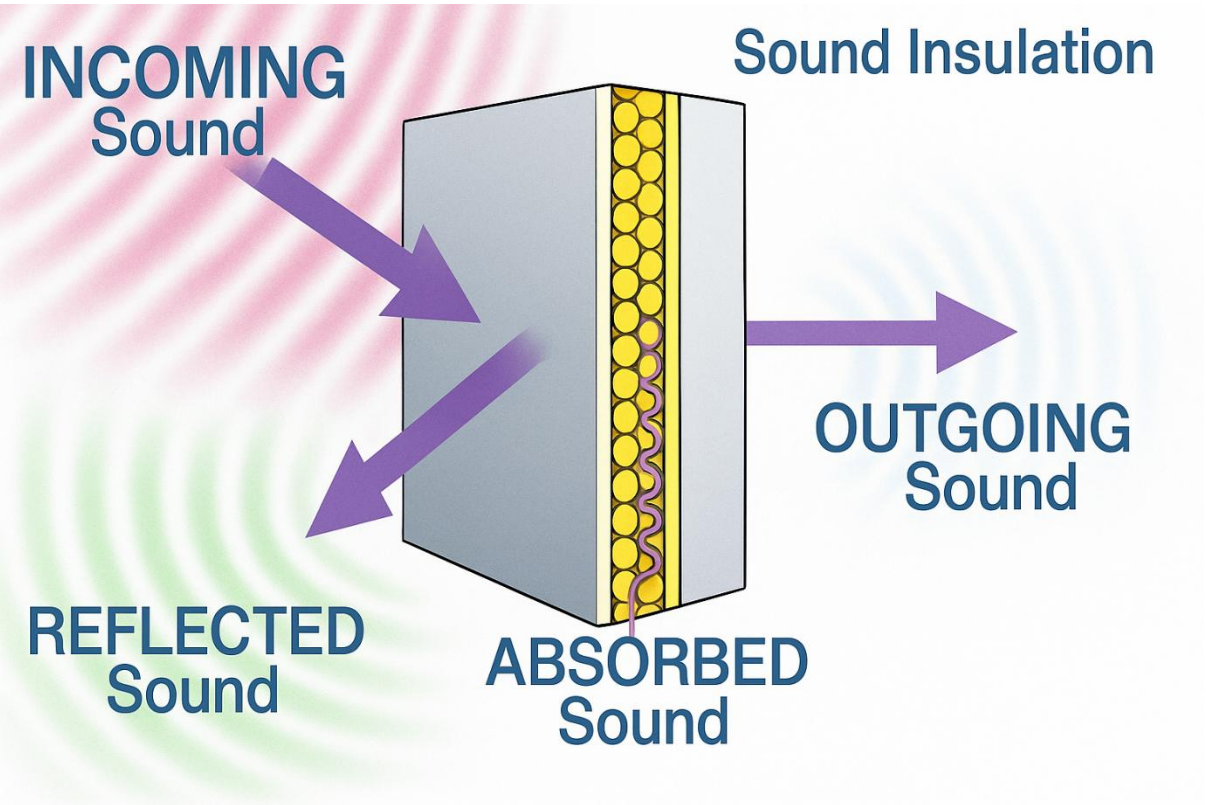
4.4.1 Mechanisms of Acoustic Insulation in Biochar-Enhanced Concrete

A. Sound Absorption via Porous Structure

Biochar's naturally porous structure, consisting of micro- and mesopores, significantly enhances its sound absorption capabilities when incorporated into concrete. One key mechanism is the increase in total pore volume, which allows sound waves to penetrate deeper into the material and dissipate more effectively. The irregular surfaces and internal voids within biochar also play a role by scattering incoming sound waves in various directions, causing the acoustic energy to convert into thermal energy through friction and viscous effects. This scattering diminishes the intensity of the transmitted sound, contributing to a quieter environment.

Another important factor is the improvement in airflow resistivity brought about by biochar's interconnected pore network. This structure impedes the movement of air particles that carry sound energy, thus slowing wave propagation and boosting the concrete's overall sound-absorbing capacity. These properties make biochar a promising additive in sustainable construction materials aimed at acoustic performance (Gupta et al., 2022).

Figure 3 example of sound absorption



A. **Reduction in Density and Sound Transmission**

The incorporation of biochar into concrete significantly impacts the material's density and its ability to transmit sound, offering notable advantages for acoustic insulation. By reducing the overall density of concrete, biochar creates a lightweight structure that is better equipped to scatter high-frequency sound waves, such as those generated by human voices or mechanical noise. Materials with lower density are known to disrupt the propagation of sound waves, making it more challenging for them to penetrate through walls, floors, and other structural elements. This phenomenon occurs because the scattering effect dissipates the energy of the sound waves, weakening their transmission.

Furthermore, the lightweight nature of biochar-enhanced concrete minimizes the resonance effect, a phenomenon where certain frequencies amplify within a material, thereby reducing the potential for sound reverberation. This dual benefit of scattering and reduced resonance makes biochar-modified concrete highly effective for sound attenuation, particularly in environments where noise control is critical, such as residential buildings, offices, and industrial settings. Additionally, the use of biochar, a sustainable and carbon-rich material, not only improves the acoustic properties of concrete but also contributes to its environmental appeal, aligning with the growing demand for eco-friendly construction materials. These combined benefits position biochar-enhanced concrete as a promising innovation for modern construction, addressing both practical and environmental concerns while providing enhanced sound insulation.

4.4.2 Optimization Strategies for Acoustic Performance

A. **Adjusting Biochar Content**

The optimization of biochar content in concrete and its combination with other materials are critical strategies for achieving superior acoustic insulation while maintaining structural integrity. Research has shown that incorporating 3–7% biochar by weight of cement strikes a balance, optimizing sound absorption without significantly compromising the mechanical strength of the concrete (Li et al., 2023). Within this range, biochar modifies the porosity and density of the concrete, enhancing its ability to absorb and scatter sound waves effectively. Furthermore, studies suggest that a lower range of 1–3% biochar is particularly effective for improving acoustic performance, as it enhances sound insulation properties while maintaining other desirable physical characteristics (Singhal, 2022; Ling, 2023). However, exceeding a biochar content of 10% can lead to adverse effects, such as excessive porosity and weakened mechanical strength, which may compromise the material's durability and functionality.

To further enhance the acoustic properties of biochar-modified concrete, combining biochar with other sound-absorbing materials presents an effective solution. For instance, blending biochar with lightweight aggregates such as perlite or vermiculite improves sound insulation while preserving structural strength. Similarly, integrating biochar with fibers like cellulose, basalt, or polypropylene enhances the damping properties of the concrete, effectively reducing sound transmission and reverberation in building applications. These synergistic combinations not only amplify the sound-attenuating capabilities of the material but also ensure that the concrete remains robust and versatile, making it suitable for a wide range of construction scenarios. These innovations underscore the potential of biochar-enhanced concrete as a multifunctional material that addresses both acoustic and structural demands in modern construction**.**

Studies indicate that adding **3–7% biochar** (by weight of cement) optimizes acoustic insulation without significantly compromising structural strength (Li et al., 2023).Sound Absorption: The incorporation of 1-3% biochar in concrete has been shown to enhance its acoustic performance significantly. This range is considered optimal for improving various properties, including sound insulation (Singhal, 2022, Ling, 2023).Excessive biochar (>10%) may reduce mechanical strength while overly increasing porosity, leading to material degradation.

B. **Combining with Other Sound-Absorbing Materials**

- **Blending biochar with lightweight aggregates** (e.g., perlite, vermiculite) can further enhance sound insulation while maintaining strength.
- **Using biochar alongside fibers** (e.g., cellulose, basalt, or polypropylene) improves damping properties, reducing sound transmission in buildings.

C. **Pre-Treatment of Biochar**

- **Impregnating biochar with calcium carbonate ($CaCO_3$)** or **hydrated lime** enhances its stiffness while retaining porosity, optimizing acoustic insulation and mechanical properties (Akinyemi et al., 2021).

The air pockets in biochar also give it sound-absorbing properties, making it useful for acoustic insulation in construction. Biochar can absorb sound waves, reducing noise pollution and enhancing privacy in buildings. This is particularly beneficial for structures in noisy environments, such as urban areas, schools, offices, and residential units near busy streets. Using biochar as an acoustic insulator helps to create quieter, more comfortable living and working spaces.[3]

Biochar-enhanced concrete offers **improved acoustic insulation** due to its **high porosity, lightweight nature, and ability to absorb sound waves**. By optimizing the **biochar content, mix design, and surface treatments**, researchers can develop concrete with superior sound-absorbing properties while maintaining durability. This makes biochar-enhanced concrete a promising solution for soundproofing in **residential, commercial, and industrial buildings**.

4.5. Fire Resistance

Biochar is naturally fire-resistant because of its high carbon content and its chemical stability. The material does not easily ignite, which adds an additional layer of safety to construction materials. It can help slow the spread of fire in buildings, improving fire resistance compared to traditional materials. Biochar can be incorporated into various building materials, such as concrete, plaster, or insulation panels, to enhance their fire-resistant properties and contribute to safer structures.[15]

Fire resistance is a significant advantage of biochar-enhanced concrete, attributed to biochar's unique properties. Research indicates that incorporating biochar can improve the thermal stability and fire resistance of concrete. For instance, biochar-infused concrete demonstrated enhanced mechanical properties under elevated temperatures, which is crucial for structural integrity during fires.

Research has demonstrated that incorporating biochar into concrete significantly enhances its durability and resilience. Specifically, biochar-enhanced concrete exhibited a remarkable 185% increase in impact resistance at a 6% biochar content, highlighting its improved ability to withstand stress. Furthermore, its incorporation resulted in a 32.14% increase in plastic energy at 28 days in ultra-high-performance concrete, showcasing enhanced resilience against thermal stress. These findings collectively underscore biochar's potential to substantially improve the mechanical and thermal properties of concrete.

Biochar's inert carbon matrix imparts improved fire performance. At elevated temperatures (>400 °C), biochar-modified concretes maintain up to 40 % more residual strength than controls, due to reduced crack propagation and thermal degradation. Impact resistance can increase by 185 % at 6 wt% biochar content, underscoring its utility in fire-sensitive applications. [22–24]

5. Chemical Resistance and Durability

5.1. Pore Refinement and Permeability Reduction

Biochar's filler effect produces a denser matrix that impedes ingress of aggressive agents. Concretes with 4 wt% biochar show a 17 % decrease in water permeability, translating to enhanced resistance against chloride and sulfate attacks. [25]

The addition of biochar to concrete mixes leads to a denser microstructure, which decreases the material's permeability. This reduction in permeability is crucial in mitigating chemical attacks, as it limits the penetration of aggressive agents such as chlorides and sulfates. For instance, a study demonstrated that concrete containing 4% biochar improved durability by 17.3% due to the finer biochar particles creating a packing effect that results in a dense matrix (61)

5.2. Pozzolanic Activity

Biochar possesses pozzolanic properties, meaning it can react with calcium hydroxide in the presence of water to form additional calcium silicate hydrate (C-S-H) gel. This reaction contributes to a denser and more chemically resistant concrete matrix. The pozzolanic activity of biochar has been evaluated using the Chapelle test, which measures the lime-fixing capacity of pozzolanic materials

The integration of biochar into concrete enhances its resistance to chemical attacks through pore structure refinement, increased chemical stability, and pozzolanic activity. These improvements contribute to the development of more durable and sustainable concrete structures.

Certain biochars exhibit pozzolanic behavior, reacting with $Ca(OH)_2$ to form additional C–S–H. Chapelle tests reveal lime-binding capacities comparable to low-grade fly ash, contributing to long-term strength and chemical stability. [26]

5.3. Alkaline Buffering and pH Stabilization

With intrinsic pH values of 7.3–10.9 depending on feedstock, biochar buffers acidic environments and mitigates acid-induced deterioration. Stabilized pH prolongs rebar passivation and prevents premature corrosion. [27]

Biochar's alkaline nature can stabilize the pH of concrete, providing protection against acidic environments. This buffering capacity helps maintain the concrete's chemical stability, preventing acid-induced deterioration. Research shows that biochar has a positive effect on mitigating the impact of acidic chemical attacks by neutralizing acidic ions.[7] Biochar's inherent alkalinity can effectively stabilize the pH of concrete, enhancing its resistance to acidic environments and preventing acid-induced deterioration. For instance, paper sludge biochar exhibits a slightly alkaline pH ranging from 7.31 to 8.46, while other biochars can have pH values up to 10.95. This buffering capacity contributes to maintaining the chemical stability of concrete structures in corrosive conditions. {44-46}

5.4. Sulfate and Chloride Attack Resistance

By adsorbing sulfate and chloride ions and reducing concrete permeability, 2–5 wt% biochar additions can lower expansion due to ettringite formation by up to 30 % and decrease chloride diffusion coefficients by 20 %, thus extending service life in marine and de-icing environments. [28–30]

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5.5. Synergistic Effects with Supplementary Cementitious Materials

Combining biochar with fly ash, ground granulated blast-furnace slag (GGBFS), or silica fume enhances both pozzolanic reactivity and microstructural refinement. Synergistic blends (e.g., 3 wt% biochar + 15 wt% GGBFS) achieve compressive strengths on par with control mixes while imparting superior durability characteristics. [31]

6. Long-Term Durability and Environmental Impact

6.1. Carbonation and Chloride Penetration

Biochar reduces CO_2 and Cl^- diffusion rates by densifying the capillary network. Accelerated carbonation tests indicate a 25 % slower carbonation front in biochar-modified concrete, preserving high pH levels and rebar integrity. [32]

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6.2. Shrinkage and Crack Mitigation

Shrinkage is a common issue in concrete that can lead to the formation of microcracks, compromising the material's structural integrity over time. These cracks typically develop during the curing process or result from thermal and moisture fluctuations, which induce internal stresses within the concrete matrix. The incorporation of biochar into concrete mixtures has been shown to effectively mitigate these issues by reducing shrinkage and enhancing the material's resistance to cracking.

- Moisture Absorption and Internal Stress Reduction: Biochar's porous structure allows it to absorb and retain moisture during the early stages of curing. This moisture buffering effect moderates the rate of water loss in the concrete, reducing the development of internal tensile stresses that typically lead to shrinkage-related cracking.
- Benefits in Crack Resistance: By minimizing shrinkage, biochar enhances the crack resistance of concrete, helping to preserve its mechanical properties and structural performance. This is particularly beneficial in large-scale or load-bearing constructions, where even minor cracking can escalate into serious durability concerns. The improved resistance to microcracking contributes to a longer service life and reduced maintenance needs for concrete structures.
- Study Findings: Research has demonstrated that incorporating biochar at higher concentrations—typically in the range of 3% to 5% by weight of cement—substantially reduces shrinkage and cracking tendencies. These findings highlight biochar's potential as a sustainable additive that not only improves durability but also supports long-term structural integrity [25]

Biochar's internal curing effect lowers autogenous shrinkage by up to 8 %, reducing microcrack density. Under cyclic freeze-thaw conditions, properly optimized mixes (<5 wt%) exhibit negligible surface spalling. [33]

6.3. Carbon Sequestration and Sustainability

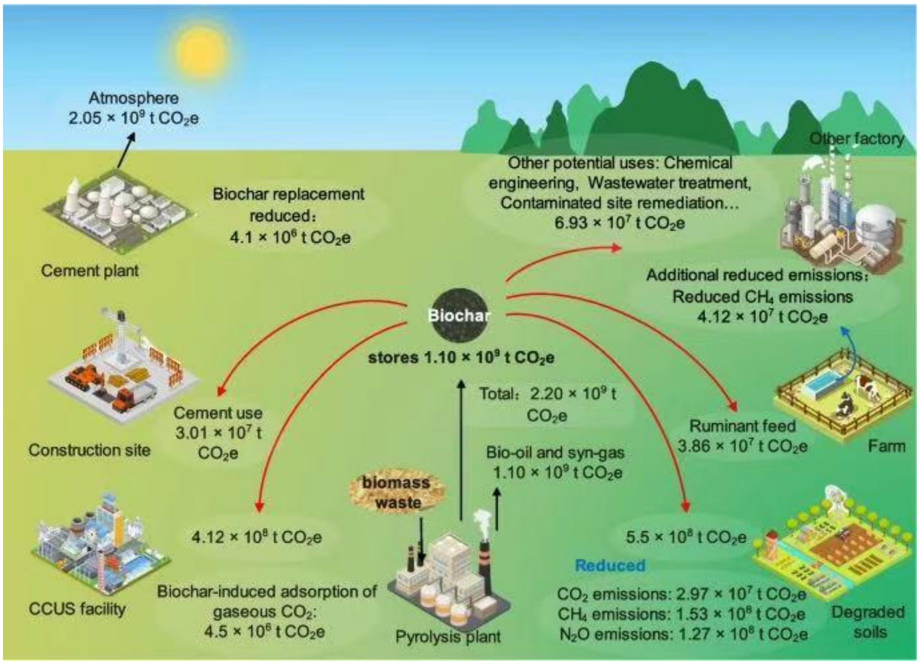
A 5 wt% biochar replacement sequesters approximately 0.8 kg CO_2 per m^3 of concrete, contributing to long-term carbon storage. Lifecycle assessments estimate a 10–15 % reduction in embodied emissions for biochar-enhanced mixes, supporting net-zero goals. [34–36]

Using biochar in concrete not only benefits the material's performance but also offers environmental advantages. Biochar is a sustainable material that can be produced from agricultural and forestry waste products, contributing to the reduction of greenhouse gas emissions.

• <u>Carbon Sequestration</u>: One of the most compelling environmental benefits of incorporating biochar into concrete is its role in carbon sequestration. Biochar acts as a stable carbon sink, trapping carbon within its structure for extended periods. This means that by using biochar in concrete, we can effectively "lock away" carbon dioxide that would otherwise contribute to climate change.

• <u>Environmental Impact</u>: By using biochar in concrete, the overall carbon footprint of concrete production can be reduced, making it a more sustainable alternative to traditional concrete, which is highly energy-intensive due to the production of cement.[24]

The use of biochar not only improves acoustic properties but also contributes to carbon sequestration. For instance, applying biochar concrete in construction could sequester approximately 4.95 × 10^10 kg CO_2 if used in new buildings, further promoting sustainable practices in the construction industry (24).



Additional Insights into Biochar's Role in Concrete Durability

1. Improved Hydration Process: Biochar can also influence the hydration process in concrete. Its porous structure can enhance water retention during the curing phase, ensuring that the cement particles have adequate time to hydrate. This can lead to a more complete hydration process and a denser, more durable concrete matrix.

2. Reduction in Permeability: The addition of biochar has been shown to reduce the permeability of concrete to water, which is crucial for minimizing the ingress of harmful substances, such as chloride ions and aggressive chemicals, into the concrete. This is particularly valuable for structures exposed to water or chemical environments.

3. Cost-Effectiveness: Depending on the source of the biochar, its use can also be cost-effective, especially if the material is locally sourced from agricultural waste. This not only reduces the cost of the concrete mix but also supports the circular economy by repurposing waste materials.

Important Findings:

A. The flexural strength, which is a critical factor in assessing structural integrity, was also improved. Concrete containing 3% biochar showed a 12% increase in flexural strength.
B. Concrete with 3% biochar exhibited reduced cracking in the early curing stages, suggesting an improvement in the material's resistance to cracking and structural failure.
C. The study found that biochar helped reduce the drying shrinkage of the concrete by 8%, which is a key factor in preventing cracks and enhancing durability.

7. Case Studies

7.1. Biochar in Bituminous Roofing Materials

Biochar has emerged as a promising additive in bituminous materials, especially for enhancing the durability of roofing shingles exposed to harsh environmental factors like UV radiation and temperature fluctuations. In a 2020 study by Rajib, biochar derived from algae and manure was incorporated into bituminous mixtures, resulting in a 36% reduction in aging rates. This improvement was attributed to biochar's porous structure, which disperses heat and moisture, reducing material degradation.

The anti-aging effect of biochar significantly increased the lifespan of roofing shingles, reducing the need for frequent replacements, leading to cost savings and resource conservation. Moreover, biochar improved UV resistance, providing added protection against weathering, which is a primary cause of roofing material failure.

This application not only extends product life but also enhances sustainability. By reducing the frequency of roof replacements, biochar contributes to waste reduction and conserves resources. Additionally, the environmental impact of bitumen production is lowered, making this a more sustainable choice for the construction industry.

In conclusion, biochar's incorporation into bituminous materials offers both performance benefits and environmental advantages, positioning it as a sustainable solution in modern construction.

Algae-derived biochar (5 wt%) incorporated into roofing shingles reduced UV-induced aging by 36 %, extended service life, and enhanced thermal stability—demonstrating potential beyond cementitious systems. [37]

7.2. Indoor Air Quality Enhancement via Biochar-Modified Plaster

The integration of biochar into construction materials offers a promising solution to enhance indoor air quality (IAQ) and combat the adverse effects of Sick Building Syndrome (SBS). Urban environments often experience elevated levels of carbon dioxide (CO2) and volatile organic compounds (VOCs), such as formaldehyde and benzene, which contribute to the development of SBS. This condition is characterized by symptoms such as headaches, dizziness, respiratory distress, and cognitive impairments, all of which are linked to prolonged exposure to suboptimal air quality. The application of biochar in building materials, such as wall plaster and cavity wall insulation, creates a passive air purification system that significantly reduces these harmful indoor pollutants.

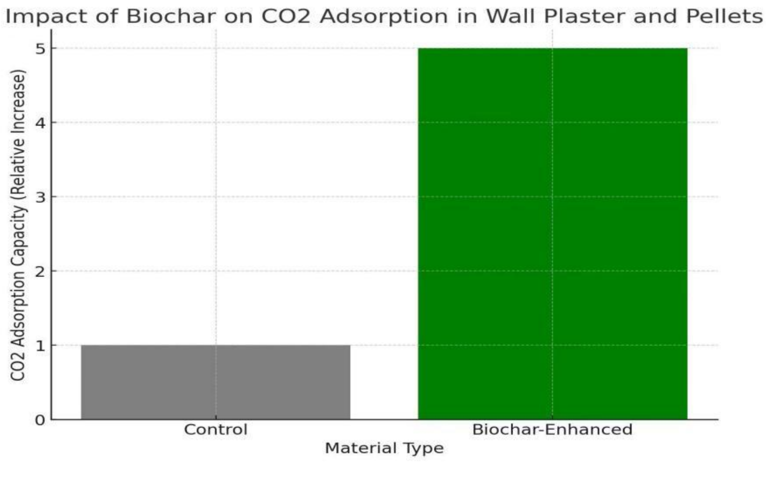
Biochar-modified materials have demonstrated an exceptional ability to adsorb CO2 and VOCs, with a performance that is 4–6 times greater than conventional alternatives like activated carbon or mineral-based adsorbents. This enhanced capacity is attributed to the material's hierarchically porous architecture, which features a high specific surface area exceeding 300 m^2/g, as well as its chemically active surface groups that facilitate the binding of polar VOCs. The micropores in biochar (<2 nm) physically trap CO2 molecules through physisorption, while its oxygen-containing functional groups (-COOH, -OH) chemically neutralize VOCs, contributing to a healthier indoor environment.

In addition to its air purification properties, biochar enhances moisture regulation by leveraging its hygroscopic nature to stabilize indoor relative humidity (RH). This ability to buffer moisture disrupts conditions favorable to mold growth, a secondary trigger of SBS. When used in building envelopes, biochar not only improves IAQ but also provides ancillary benefits such as improved thermal insulation and soundproofing, making it a multifunctional material in sustainable construction.

Field studies have provided compelling evidence of the practical benefits of biochar-enhanced materials. Trials conducted in densely populated residential complexes showed that integrating biochar into wall plaster reduced CO2 spikes by 38% and decreased total VOC concentrations by 27%. Over six months, these changes correlated with a 52% reduction in occupant-reported SBS symptoms, including fewer complaints of headaches, respiratory issues, and concentration deficits. These findings highlight the potential of biochar to significantly improve living conditions in urban settings, where indoor air pollution often poses serious health risks.

The use of biochar in construction materials not only addresses critical IAQ challenges but also aligns with broader sustainability goals. As a carbon-negative material, it helps mitigate climate change while fostering healthier indoor environments. By embedding biochar into building components, the construction industry can adopt an innovative, passive air purification approach that reduces the health impacts of indoor pollutants and contributes to more sustainable, occupant-friendly spaces.

Figure 5



Impact of biochar on CO2 adsorption

Moreover, biochar's role goes beyond thermal insulation and structural reinforcement. Its ability to purify indoor air makes it a multifunctional building material, enhancing both sustainability and occupant well-being.

This case study underscores biochar's potential as a versatile material in construction, supporting healthier, more sustainable buildings.

Wall plasters amended with 10 wt% wood-waste biochar achieved 38 % lower CO_2 peak concentrations and a 27 % reduction in total VOCs, translating to a 52 % decrease in occupant-reported Sick Building Syndrome symptoms over six months. [38]

7.3. Rice Husk Biochar as Partial Cement Replacement

Biochar derived from agricultural waste, particularly rice husks, has emerged as a promising partial replacement for cement in concrete. Research by Ofori-Boadu (2021) highlights its potential to enhance concrete properties while promoting sustainable construction practices.

Cement production accounts for approximately 5-7% of global CO_2 emissions, primarily due to its energy-intensive processes and the calcination of limestone, which releases significant amounts of carbon dioxide. Substituting a portion of cement with biochar offers an effective strategy to reduce these emissions.

Ofori-Boadu's study demonstrated several key advantages of incorporating rice husk biochar into concrete:

- Accelerated Setting Time: Biochar shortened the concrete's setting time, making it particularly suitable for projects requiring expedited curing schedules.

- Enhanced Strength via Pozzolanic Reactions: The high silica content in rice husk biochar reacts with calcium hydroxide—a byproduct of cement hydration—to form additional cementitious compounds. These reactions contribute to improved mechanical strength and reduced reliance on traditional cement.

- Improved Porosity and Water Retention: Biochar's porous structure enhanced the water retention of concrete, improving its curing process, thermal insulation, and long-term durability.

Table 2

Biochar replacement(%)	Compressive Strength (Mpa)	Setting Time(hrs)	Environmental Impact (CO2 Reduction)
0%(control)	30.0	6	0%
10%	32.5	5.8	5%
20%	35.0	5.5	10%
30%	37.0	5.2	15%
40%	36.5	4.9	20%
50%	34.0	4.7	25%

Incorporating biochar derived from agricultural waste, such as rice husks, into concrete offers a sustainable and practical approach to improving construction materials. This practice not only reduces the environmental impact of traditional concrete production by lowering carbon emissions and diverting agricultural residues from waste streams but also enhances the mechanical and functional properties of the concrete. By improving durability and resilience, biochar integration supports the development of greener infrastructure while advancing sustainable construction practices. This innovation presents an efficient alternative to conventional cement-based materials, contributing to the transition toward more environmentally friendly, long-lasting, and resilient built environments.

A 10 wt% rice husk biochar substitution accelerated setting times by 15 %, increased 28-day strength by 12 % via pozzolanic reactions, and improved thermal performance by 20 %, validating its dual functional and environmental benefits. [39]

7.4. Optimal Particle Size in Concrete Applications

Incorporating biochar into concrete requires precise optimization of particle size to ensure performance, workability, and durability. The particle size of biochar significantly influences the properties of biochar-enhanced concrete. Larger particles may fail to bond effectively with the cement matrix, leading to weak points and reduced strength. Conversely, extremely fine particles can disrupt the mix's workability by increasing water demand, which may compromise both strength and durability. Achieving the ideal particle size is critical for optimizing the interaction between biochar and the cementitious materials in the concrete mix. Li (2023) highlights that biochar particles sized between 0.5 and 2 mm provide the most advantageous results, striking a balance between mechanical strength and ease of application.

This size range as ideal for biochar particles in concrete applications. Particles within this range enhance mechanical properties while preserving workability and durability. Intermediate-sized particles facilitate improved bonding with the cement matrix and promote pozzolanic reactions, which contribute to greater compressive strength and longevity. These particles are small enough to maintain a consistent mix yet large enough to provide mechanical interlocking, supporting structural integrity.

Selecting the optimal particle size also enhances the porosity and thermal insulation properties of the concrete without sacrificing structural performance. These attributes are particularly valuable in applications where energy efficiency and weight reduction are priorities, such as sustainable building projects and pavement construction. By improving thermal performance, biochar can contribute to reducing heating and cooling demands in buildings, further aligning with sustainability goals.

Li's findings underscore the importance of particle size in realizing the full potential of biochar-enhanced concrete. Particles within the 0.5 to 2 mm range deliver a balance of increased strength, enhanced durability, and improved workability. These advantages position biochar as a promising additive for sustainable construction, offering improved thermal efficiency and reduced environmental impact without compromising practicality.

To conclude the careful selection of biochar particle size is crucial for maximizing its benefits in concrete applications. The optimal size range of 0.5 to 2 mm enhances structural performance, durability, and energy efficiency, paving the way for more sustainable construction practices. By adhering to these findings, the construction industry can develop biochar-based concrete solutions that meet environmental and performance standards while maintaining feasibility for large-scale applications.

Biochar milled to 0.5–2.0 mm provides the best trade-off between workability, strength, and insulation: mixes with this size range exhibited up to 18 % higher compressive strength and 25 % lower thermal conductivity compared to <0.5 mm or >2.0 mm fractions. [40]

8. Limitations and Failure Analysis

Notable challenges include:

- Strength Reduction at High Replacement: >10 wt% biochar can reduce compressive strength by up to 25 % due to excessive porosity and water absorption (e.g., SE Asian pedestrian bridge failure).
- Quality Variability: Feedstock and pyrolysis conditions cause heterogeneity in particle size, carbon content, and impurity levels, undermining reproducibility.
- Long-Term Durability Data Gaps: Limited field trials under freeze-thaw, marine, and acidic conditions leave uncertainties regarding performance over multi-decadal lifespans.
- Lack of Standards: Absence of specific ASTM/EN guidelines for biochar in concrete complicates certification and structural use. [41–44]
- Multiple studies corroborate these concerns; for example, Gupta et al. (2024) found a 4.4% decrease in compressive strength with only 5% biochar replacement, while higher biochar contents consistently led to more pronounced strength losses (Park et al., 2023; Zhang et al., 2024). These reductions stem from biochar's intrinsic porous structure and weaker bonding capacity compared to cement particles, which compromise the load-carrying capacity of the composite. Thus, despite the ecological benefits, biochar's application in structural concrete demands careful consideration and balancing of performance requirements.

9. Mitigation Strategies and Future Research Directions

Key recommendations:

- Standardization: Develop ISO/ASTM protocols for biochar characterization (fixed carbon, BET surface area, pH).
- Pre-Treatment: Surface functionalization or mild carbothermal treatments to reduce water absorption and enhance pozzolanic activity.
- Optimized Mix Designs: Limit biochar to ≤5 wt%, employ superplasticizers, and combine with SCMs to balance mechanical and functional properties.
- Advanced Quality Control: Implement real-time monitoring of feedstock composition and pyrolysis parameters.

- Extended Durability Testing: Conduct accelerated aging and multi-environment field trials to validate long-term performance.

10. Conclusion

Biochar presents a versatile, carbon-negative additive for sustainable construction, offering improved thermal and acoustic insulation, enhanced fire resistance, and meaningful reductions in embodied carbon..While moderate replacement levels (1–5 wt%) yield optimal performance, challenges related to quality control, standardization, and long-term durability must be addressed. Through targeted research, standardized protocols, and optimized formulations, biochar-enhanced materials can transition from promising laboratory studies to reliable, large-scale applications—advancing the construction sector toward a low-carbon future.Ultimately, biochar has the potential to play a crucial role in the future of construction, aligning environmental objectives with performance requirements to foster greener and more durable infrastructure worldwide

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