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Biochar in Concrete: A Review of its Role as a Supplementary Cementitious Material

[1]Tanko, A., [2]Odeyemi, S.O.,[3]Atoyebi, O.D. and [4]Wilson, U.N.

[1]Department of Civil and Environmental Engineering, Kwara State University, Malete, Nigeria.
[2]Department of Civil and Environmental Engineering, Kwara State University, Malete, Nigeria.
[3]Department of Civil Engineering, Landmark University, Omu-Aran, Kwara State, Nigeria.
[4]Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria

Corresponding Author Email: [1]tankoabdulrasheed1@gmail.com; Tel:08161345716

Abstract
Biochar, produced from biomass pyrolysis, is gaining attention as a sustainable supplementary cementitious material (SCM). At dosages below 5% cement replacement, biochar enhances concrete properties across key parameters. Mechanical strength improves via nucleation and accelerated hydration, while durability benefits from reduced permeability and ion penetration. Its porous structure acts as an internal curing agent, lowering shrinkage and cracking, and decreases thermal conductivity for better insulation. Biochar also supports carbon sequestration, reducing emissions and fostering a circular economy. Performance depends on particle size, feedstock, and pyrolysis conditions, with long-term effects on pH and reinforcement corrosion requiring further study.

Keywords: Concrete mixer, material handling, workability slump, mix design

Introduction
The environmental impact of cement production is a significant concern, with greenhouse gases like carbon dioxide (CO_2) contributing to global warming and climate change. Cement production alone accounts for approximately 8% of global CO_2 emissions, largely from the calcination of limestone and the energy-intensive clinkering process (Andrea et al., 2020). Organic waste management further exacerbates this problem by releasing methane and other harmful emissions through decomposition. Addressing these environmental challenges requires innovative solutions, with the construction industry focusing on supplementary cementitious materials (SCMs) as a viable path toward sustainability.

Biochar, a carbon-rich product derived from the pyrolysis of organic biomass in low-oxygen conditions, has emerged as a promising SCM (Akinyemi & Adesina, 2020). In addition to reducing waste and utilizing renewable resources, biochar offers the advantage of carbon sequestration, making it suitable for circular economy applications (Kamini et al., 2023). Unlike traditional SCMs like fly ash and slag, biochar originates from various biomass feedstocks, which range from agricultural residues to forest by-products, enhancing its accessibility and renewability (Akinyemi & Adesina, 2020). Research shows that biochar not only improves concrete's mechanical properties but also reduces its thermal conductivity, making it applicable to a range of structural environments (Sansores et al., 2022) .

Current studies indicate that biochar can be incorporated into concrete at dosages typically below 5% of the total cement content to optimize its benefits (Gupta et al., 2018a). However, biochar's effectiveness varies based on production parameters, particle size, and feedstock type. Future studies must focus on establishing standardized guidelines for biochar production and integration in concrete to maximize its environmental and material benefits (Khitab et al., 2021). As a novel supplementary cementitious material (SCM) shown in Figure1, biochar aligns with global efforts to reduce carbon emissions and fosters sustainable practices in construction.

Figure 1. Raw forms of (a) wheat straw, (b) rice straw, (c) sugarcane bagasse, and (d) forest residues (Khitab et al., 2021)

Materials and Methods

The production of biochar involves the thermal decomposition of organic biomass through a process known as pyrolysis. In a controlled, low-oxygen environment, biomass is heated to temperatures typically between 350°C and 700°C, producing a stable carbon-rich material with a unique porous structure (Kamini et al., 2023). This process, also known as gasification, when conducted at higher temperatures, results in a lightweight black carbon residue with potential applications in concrete (Suarez-riera et al., 2020)

Different types of biomass feedstocks, including agricultural waste (e.g., rice and wheat straw, sugarcane bagasse) and forestry residues, are commonly used for biochar production. Feedstock selection and pyrolysis conditions significantly affect biochar's properties, such as surface area, porosity, and nutrient content. Higher pyrolysis temperatures generally increase biochar's surface area and porosity, enhancing its water retention and adsorption capabilities, which are essential in construction applications (Akinyemi and Adeshina, 2020).

The versatility of biochar has been demonstrated in various industries, ranging from agriculture to wastewater treatment. Its role in construction is emerging, with research highlighting its effectiveness as a supplementary material in cementitious composites (Gupta et al., 2019). Given its stable carbon content, biochar is increasingly recognized for its carbon sequestration potential, contributing to long-term climate change mitigation. By harnessing waste biomass through pyrolysis, biochar production offers both environmental benefits and a pathway for integrating sustainable practices within the construction sector. Research and development are required to optimize biochar's production processes and standardize its application in concrete for widespread industry adoption.

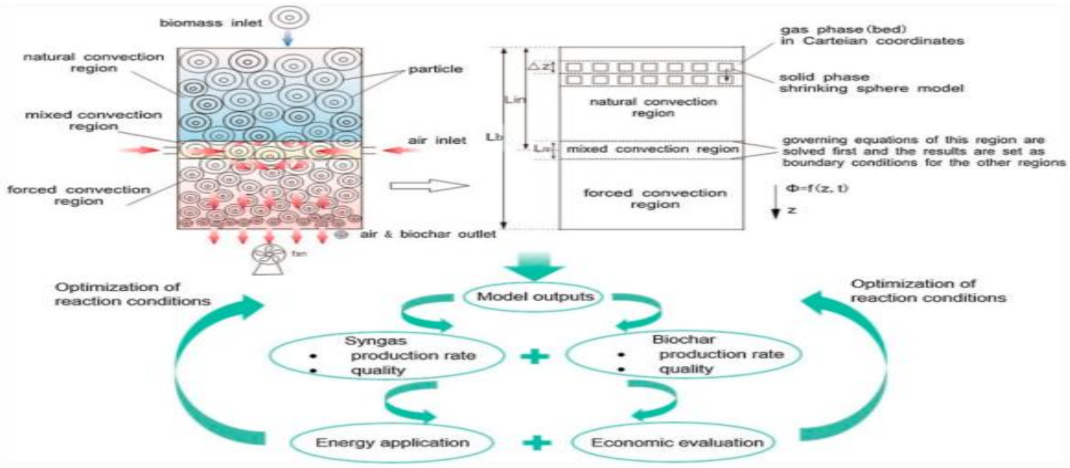

Figure 2. Gasification method of biochar production. (Barbhuiya et al., 2024)

Biochar's properties vary widely depending on the type of biomass feedstock used and the pyrolysis process conditions, influencing its performance as a cementitious material. Key physical properties include porosity, bulk density, surface area, and pH level. The porous structure of biochar provides a large surface area that can enhance water retention, nutrient storage, and the durability of cementitious composites (Akinyemi and Adesina, 2020). These characteristics contribute to its role as an internal curing agent in concrete, where it aids hydration and reduces shrinkage (Gupta et al., 2017).

Biochar's chemical properties, including elemental composition and the presence of functional groups like hydroxyl and carboxyl, contribute to its reactivity and interactions in the concrete matrix. High temperatures during pyrolysis often result in increased carbon content and fewer volatile compounds, producing a biochar that is more stable and resistant to degradation. Additionally, higher pyrolysis temperatures tend to enhance biochar's surface area and porosity, optimizing its performance in cement-based materials (Khitab et al., 2021) .

Chemical composition also affects biochar's alkalinity and cation exchange capacity (CEC), which can influence concrete properties. Biochar derived from certain feedstocks, such as hardwoods, tends to have a higher CEC, which improves its ability to absorb and retain nutrients. This feature is especially valuable in concrete applications, where biochar can improve hydration reactions and strengthen the bond within the matrix (Barbhuiya et al., 2024). Collectively, these physical and chemical properties make biochar a valuable material for enhancing concrete performance while supporting environmental sustainability.

Results and Discussion

Fresh Concrete properties

Biochar positively influences both the fresh and hardened properties of concrete. The incorporation of biochar in concrete mixes has been shown to reduce both fresh and hardened densities, which can be beneficial in applications where lightweight materials are desired (Akinyemi and Adesina, 2020). Moreover, biochar's high water absorption capacity enables it to act as an internal curing agent, enhancing hydration and reducing drying shrinkage. This property is particularly advantageous in mixes with low water-to-cement ratios, as biochar gradually releases stored water, improving hydration (Gupta et al., 2018a; Dixit et al., 2019). However, biochar's high absorption rate can reduce workability, necessitating the use of superplasticizers to achieve the desired consistency.

Biochar also serves as a nucleation site, where hydration products form, accelerating the hydration process and increasing early-age strength (Supunsala et al., 2023). Studies suggest that optimal biochar dosages are typically below 5%, as higher amounts may introduce excessive porosity and weaken the concrete matrix (Gupta et al., 2019).

The impact of biochar on concrete's thermal properties is also noteworthy. Its low thermal conductivity can reduce heat transfer, improving the energy efficiency of buildings in extreme climates. Given these combined benefits, biochar presents a promising approach to enhancing concrete's physical and mechanical properties. However, variability in biochar's properties based on feedstock and production conditions remains a challenge, underscoring the need for standardized guidelines in concrete applications.

The mechanical performance of biochar-modified concrete generally improves at lower biochar dosages, with enhanced compressive and tensile strengths observed in several studies (Sansores et al., 2022). These improvements are attributed to biochar's ability to absorb and retain water, fostering continuous hydration and increased cohesion within the concrete matrix. As an SCM, biochar's particle-packing effect increases matrix density, while its high-water retention further optimizes the hydration process (Gupta et al., 2019a).

Biochar's influence on crack propagation also contributes to improved mechanical properties. Research shows that adding fine biochar particles can alter crack patterns, increase fracture energy and reduce brittleness (Restuccia & Ferro, 2016). This is partly due to biochar's inhomogeneities, which act as barriers to crack growth, requiring greater energy for fracture and enhancing the material's toughness (Turovaara, 2022). Additionally, biochar can enhance the flexural strength of concrete by providing additional reinforcement within the matrix, improving resistance to bending and shear forces (Barbhuiya et al., 2024).

However, high dosages of biochar can dilute cement content, leading to reductions in strength if not carefully managed (Andrea et al., 2020). Optimal biochar content is essential to balance the benefits of enhanced hydration and particle packing with the challenges of maintaining workability and preventing excessive porosity. Studies generally suggest that dosages of 2-5% yield the best results, balancing improved mechanical performance with adequate workability and durability. Future research should focus on identifying the optimal biochar characteristics and dosages for different types of concrete applications to maximize mechanical performance while minimizing potential drawbacks.

Biochar's effect on concrete durability is a focal point of research, given its potential to improve resistance to environmental degradation. By reducing permeability, biochar-modified concrete is less susceptible to water ingress and ion penetration, which are major contributors to reinforcement corrosion and freeze-thaw damage (Gupta et al., 2018a). The high-water retention of biochar contributes to a denser matrix, effectively reducing voids and enhancing resistance to environmental stressors.

However, biochar dosage is crucial in achieving optimal durability. Research by Gupta et al., 2018a showed that adding small amounts (1-2%) of food and wood-waste biochar to cement mortar as a sustainable admixture helps lower its permeability, while higher amounts (5% and above) may introduce excessive porosity, potentially reducing durability. . Furthermore, biochar's electrical conductivity has piqued interest for self-sensing applications, where it could provide real-time feedback on structural health and crack development (Barbhuiya et al., 2024).

Research also shows that biochar's pyrolysis conditions and feedstock can influence its impact on durability. High-temperature biochar tends to be more resilient, while biochar with increased alkalinity can support carbonation, enhancing concrete's resistance to sulfate attacks (Barbhuiya et al., 2024). Additionally, biochar can improve resistance to alkali-silica reaction (ASR) by mitigating the availability of reactive silica species (Andrea et al., 2020). Although biochar offers promise in durability improvement, standardized testing is required to fully understand its performance across varied environmental conditions. Long-term studies are necessary to evaluate biochar-modified concrete's behavior under real-world exposure scenarios, ensuring its reliability and effectiveness in enhancing concrete durability. Biochar's ability to absorb and release water makes it an effective internal curing agent, particularly in low water-to-cement ratio mixes where maintaining hydration is challenging. As biochar releases moisture during the hydration process, it prevents drying shrinkage, reducing cracking and improving overall concrete durability (Barbhuiya et al., 2024). This internal curing effect has been observed to enhance cement hydration and decrease shrinkage, especially in mixes exposed to air curing or limited external curing conditions (Gupta & Kua, 2018).

Moreover, biochar's CO_2 adsorption capability adds another dimension to its application in concrete. Upon incorporation in concrete, biochar can undergo carbonation, where CO_2 reacts with calcium hydroxide to form calcium carbonate. This process contributes to additional strength development but may also result in microcracking due to volume expansion (Supunsala et al., 2023). Gupta et al., (2018b) found that pre-treated biochar can facilitate carbonation without compromising concrete's compressive strength, though the impact on reinforcement corrosion warrants further investigation. The internal curing and carbonation effects of biochar offer a twofold advantage, enhancing durability and supporting carbon sequestration in concrete. However, standardized protocols are needed to fully capitalize on these benefits while addressing potential risks to structural integrity. Biochar's ability to retain and gradually release water ensures continuous hydration, reducing the likelihood of thermal and drying cracks. Additionally, the carbonation process, while beneficial for strength, requires careful management to prevent adverse effects such as pH reduction, which can lead to corrosion of embedded steel reinforcement.

Further research should explore the optimal biochar properties and dosages to maximize internal curing benefits while controlling carbonation effects. Understanding the interplay between biochar-induced internal curing and carbonation will enable the development of concrete mixes that are both durable and environmentally sustainable. Integrating biochar into concrete aligns with global sustainability goals, offering a pathway to reduce the carbon footprint of the construction industry while enhancing material performance. Internal carbonation is a crucial process in cementitious materials, where CO_2 is absorbed and reacts with calcium hydroxide to form calcium carbonate. This process not only contributes to the strength development of concrete but also plays a significant role in carbon sequestration, aligning with global efforts to mitigate climate change. Biochar, with its high surface area and porous structure, enhances the internal carbonation process in cement mortar, offering a dual benefit of improved material properties and environmental sustainability.

The incorporation of biochar into cement mortar facilitates the absorption of CO_2, promoting the formation of calcium carbonate. This reaction contributes to the densification of the cement matrix, thereby increasing compressive and tensile strengths (Gupta et al., 2018b). Additionally, the carbonation process can lead to a reduction in porosity and permeability, enhancing the durability of the mortar by making it less susceptible to water ingress and ion penetration. However, the carbonation process must be carefully managed to prevent potential drawbacks, such as pH reduction, which can compromise the passive layer protecting embedded steel reinforcement from corrosion (Supunsala et al., 2023)

Studies have shown that pre-treating biochar with CO_2 can enhance its carbonation capacity without adversely affecting the mechanical properties of the cement mortar. For instance, Gupta et al. (2018b) demonstrated that mortar mixes containing CO_2-treated biochar exhibited improved compressive strength compared to those with untreated biochar. This improvement is attributed to the enhanced carbonation reaction facilitated by the pre-treated biochar, which provides additional nucleation sites for calcium carbonate formation. However, excessive carbonation can lead to microcracking and debonding within the mortar matrix, potentially offsetting the strength gains (Akinyemi & Adesina, 2020).

The effectiveness of biochar in promoting internal carbonation is influenced by several factors, including the biochar's surface area, porosity, and chemical composition. Higher surface areas and porosity enhance the biochar's ability to absorb and retain CO_2, thereby accelerating the carbonation process (Barbhuiya et al., 2024). Additionally, biochar's alkalinity, which can be modified through pyrolysis conditions, plays a significant role in the carbonation reaction. Alkaline biochar surfaces attract acidic CO_2 molecules, enhancing the efficiency of the carbonation process and contributing to stronger, more durable mortar.

Integrating biochar for internal carbonation in cement mortar presents a promising approach to improving both the mechanical properties and environmental sustainability of concrete. However, further research is needed to optimize biochar's properties for controlled carbonation, ensuring that the benefits are maximized while minimizing potential risks. Understanding the balance between carbonation-induced strength gains and the prevention of microcracking is essential for the successful application of biochar in cementitious materials. Future studies should explore the long-term effects of biochar-induced carbonation on the structural integrity and durability of concrete, providing comprehensive guidelines for its practical implementation in the construction industry.

Biochar's ability to absorb gases and water is primarily due to its microporous structure, which is influenced by feedstock, pyrolysis temperature, and pressure. Physical adsorption, based on van der Waals forces, allows biochar to capture CO_2, making it valuable for carbon sequestration (Supunsala et al., 2023). Increasing the pyrolysis temperature expands pore size, enhancing biochar's adsorption capacity and making it suitable for applications in concrete (Khitab et al., 2021).

Studies show that the carbon content of biochar influences its CO_2 adsorption capacity, with higher carbon content supporting stronger physical adsorption forces. Alkaline biochar surfaces, produced through higher-temperature pyrolysis, improve CO_2 adsorption efficiency by attracting acidic gas molecules (Barbhuiya et al., 2024). Additionally, biochar's surface alkalinity can be modified by adding metal ions, further enhancing CO_2 capture (Akinyemi & Adesina, 2020). The absorption mechanisms of biochar present opportunities for reducing the carbon footprint of concrete. However, variability in biochar's adsorption properties based on production methods poses challenges in developing a standardized approach for its use in construction. Factors such as specific surface area, pore size distribution, and surface chemistry must be carefully controlled to optimize biochar's adsorption performance (Supunsala et al., 2023;Suarez-riera et al., 2020). Furthermore, the regeneration and reuse of biochar in adsorption applications can contribute to the economic feasibility and sustainability of its use in the construction industry.

Advanced characterization techniques, such as Brunauer-Emmett-Teller (BET) analysis and thermogravimetric analysis (TGA), are essential for understanding and optimizing biochar's adsorption properties (Supunsala et al., 2023). Future research should focus on tailoring biochar's structural and chemical properties through controlled pyrolysis processes and post-treatment modifications to enhance its adsorption capacity and stability. By optimizing these factors, biochar can be effectively integrated into cementitious materials, contributing to both improved concrete performance and environmental sustainability.

Conclusion

Biochar presents a promising SCM for sustainable concrete applications. Its use reduces environmental impact, enhances material properties, and aligns with circular economy principles. This discussion has highlighted the limitations, challenges, and research opportunities related to biochar in concrete. While issues like standardization, cost, and scalability remain, ongoing research is tackling these challenges. Advancements in understanding biochar's mechanisms, optimizing its formulations, and integrating it with other materials are facilitating its broader use in construction. Additionally, biochar's application aligns with the increasing demand for sustainable practices and reduced carbon emissions in the construction industry. The inclusion of sections on internal carbonation further underscores biochar's multifaceted benefits, providing a comprehensive overview of its potential in modern concrete technology. As research progresses, biochar's role in the construction sector is likely to expand, with optimized formulations contributing to lower emissions and greener infrastructure.

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