Journal of Asian Concrete Federation
Vol. 11, No. 2, pp. 15-37, June 2025
ISSN 2465-7964/ eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2025.11.2.15

Review Paper

Biochar Concrete: A state–of–the–art review

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(Received: 15-May-2025; Revised: 15-May-2025; Accepted: 18-May-2025; Published online: 25-Jun-2025)

Abstract: This paper reviews the studies on using biochar in concrete. An introduction to the environmental impact of cement production and the need for sustainable alternatives was first discussed, highlighting biochar's potential as a partial cement replacement. Then, the effect of biochar on cement hydration, workability, mechanical properties, durability, and microstructure was examined, with emphasis on its role in carbon sequestration. Notably, this review interrogates biochar's contributions to compressive strength enhancement, permeability reduction, and volumetric stability via shrinkage mitigation-performance dimensions, in addition to elucidating the synergistic mechanisms between biochar and supplementary cementitious materials (e.g., fly ash, GGBS). Despite the promising results, challenges related to biochar's long-term performance and optimisation for concrete applications remain. The paper concludes by emphasising the need for further research into the durability, structural behaviour, and environmental impact of biochar-concrete composites.

Keywords: Alkali-activated concrete; compressive strength, porosity, machine learning; multi-objective optimization

1. Introduction

Concrete is the most used construction material, with cement being one of its key components [1, 2]. The cement clinker manufacturing process involves a series of complicated operations in which raw materials, primarily limestone and clay, such as kaolin, shale, or marl, along with other additives, are subjected to approximately 1400℃ calcination. This process results in considerable CO_2 emissions [3]. The cement industry is a significant source of global carbon emissions, contributing 5-8% of total emissions and representing the second-largest industrial sector for CO_2 emissions, accounting for approximately 27% of all direct emissions worldwide [1]. The adverse environmental effects of cement manufacturing are anticipated to rise. According to the International Energy Agency (IEA), up to 4.4 billion tonnes of cement will be produced annually by 2050, with an increase of 12% to 23% expected in the coming decades. Thus, reducing CO_2 emissions from cement usage and concrete production is essential for mitigating and addressing climate change [4].

The application of green concrete materials is an important part of this transition. Green concrete can be defined as concrete that has less embodied energy and carbon compared to conventional concrete, as it ultimately incorporates waste, recycled, and environmentally friendly materials as either binders or aggregates [5-7]. Incorporating supplementary cementitious materials (SCMs), e.g., ground granulated

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blast furnace slag (GGBS), fly ash (FA), silica fume (SF), metakaolin (MK), alongside biochar derived from industrial by-products as a partial substitution for cement, are examples of green concrete development [8]. Also, recycled aggregates from construction and demolition wastes are successfully commercialised for concrete production.

Among these waste materials, using biochar has been proven a safe and promising way to achieve carbon neutrality for the construction industry. Biochar is a carbon-rich material made by pyrolysing various waste biomass materials, such as rice straw, wood waste, food waste, and sludge, in an environment with limited oxygen [9]. This process stabilises and stores carbon, making it an effective method for reducing greenhouse gas emissions. Although biochar is generally classified as a lightweight aggregate or microfiller in concrete matrices rather than a true hydraulic binder, its lightweight and highly porous characteristics make it suitable for use as a lightweight aggregate in cement-based composites [10]. It plays an important role in modifying the bulk density, refining the pore structure, and enhancing the internal curing and moisture retention. In addition, biochar's porous nature enhances the CO_2 capture capacity of biochar concrete. During the service life of concrete, one ton of biochar can absorb about 2.72 tonnes of CO_2 equivalent [11]. Thus, buildings constructed with biochar concrete can act as long-term carbon sinks, aiding in climate change mitigation. On the other hand, the appropriate addition of biochar may accelerate cement hydration and result in enhanced structural properties of concrete [12].

For instance, various studies have demonstrated that biochar can improve concrete properties as a cementitious material, enhancing chemical stability, storage capacity, and low thermal conductivity while also serving as an internal curing agent and carbon absorbent [13] [14]. The varied pore sizes in biochar facilitate water absorption and retention, allowing it to provide an internal curing effect in cement-based composites. The water absorbed by biochar, which is not chemically bonded to its carbon structure, is released during the cement hydration process, aiding early-age hydration. This water retention capability fosters favourable curing conditions, improving concrete microstructure, durability, and material properties. Additionally, it reduces water evaporation, mitigating shrinkage, similar to self-curing agents [15].

Furthermore, biochar positively influences the mechanical and fracture characteristics of biochar cementitious mixes [16]. The fracture resistance and bending capacity of biochar-based cement composites may increase due to the ability of biochar particles to absorb cracking forces within the cementitious matrix [17]. Biochar-enhanced concrete can exhibit higher compressive strength due to the acceleration of cement hydration facilitated by the nucleation effect. Additionally, biochar has been shown to improve resistance to chemical attacks, such as sulfate and chloride-induced corrosion, although the long-term effects require further investigation. The composition and structure of the C-S-H gel in biochar cement composites are still being studied and have not been fully explored [18].

Despite these benefits of biochar-augmented concrete, challenges remain regarding its long-term performance, durability, and optimal composition. This review aims to explore biochar-concrete composites as a sustainable construction solution, examining their properties, production methods, sustainability aspects, benefits, and applications. However, existing reviews are limited in exploring the interactions between biochar and supplementary cementitious materials (SCMs), the effects of varying biochar dosages on concrete properties, and the lack of comprehensive life cycle assessments evaluating its environmental impact. By addressing these topics, the review seeks to contribute to the advancements and wider adoption of biochar-concrete, promoting carbon sequestration and reducing environmental impact in the construction industry.

2. Biochar production

2.1 Raw Materials

Biochar is a carbon-rich material produced from biomass through pyrolysis at temperatures between 200 °C and 1200 °C in an oxygen-limited environment [19]. Biomass feedstocks such as food waste, wood, animal manure, and crop residues can be used [20]. Its carbon content ranges from 60 to 85%, depending on pyrolysis conditions and feedstock [21, 22]. The choice of biomass impacts biochar properties and yield, with low moisture content being ideal, as high moisture can lead to tar formation, clogging processes, and reducing yield [23, 24]. Biochar's surface chemistry varies based on these factors, affecting its hydrophilic, hydrophobic, and acidic properties [3, 25]. Given the significant impact of biomass feedstock on biochar yield and properties, various feedstocks can be used:

Agricultural Waste Biomass: Agricultural waste biomass includes crop residues (e.g., corn stover, rice straw, peanut shells, sugarcane bagasse) and byproducts (e.g., rice husk, coconut shells, dairy manure). As lignocellulosic residues, they contain cellulose, hemicellulose, and lignin, as shown in Fig.1. These residues can be broken down into sugars used for biofuels and organic products [26]. Crop type and composition influence biochar yield and quality. Agricultural waste biomass has lower ash content, higher calorific values, and fewer voids than woody and organic biomass. It has a higher carbon content than organic waste but lower than woody biomass, and a higher nitrogen content than woody biomass but lower than organic waste [27].

Algae and Aquatic Biomass: Algae and aquatic biomass such as seaweed can produce biochar with high nutrient content of nitrogen, ash, and inorganic components, which in terms beneficial for soil amendment in agriculture and as a bio-adsorbent in water treatment due to its multitude of organic functional groups in addition to inorganic minerals. Algal biochar has lower carbon content and surface area but higher cation exchange compared to biochar derived from agricultural biomass [29].

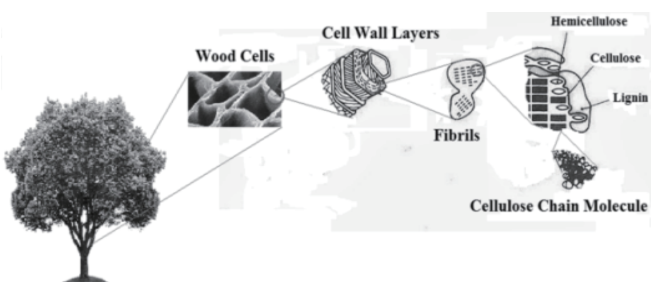


Fig. 1. Wood is Composed of Cellulose [28].

Woody Biomass: Woody biomass, such as wood chips, branches, wood pellets, and sawdust, is widely utilised in pyrolysis and is well known for its high carbon content and low moisture, high calorific value, and fewer voids, which makes it appropriate for different applications [30]. Additionally, biochar derived from wood feedstock often has a higher surface area and greater aromaticity, making its carbon content more stable and resistant to degradation compared to grass biochar [31].

Dedicated Energy Crops: Dedicated energy crops are cultivated for energy applications without replacing food production. Rich in sugars protein, and fibres, they serve as sources of chemicals, renewable energy, and materials [32]. They are classified into herbaceous crops (e.g., switchgrass, energy cane, miscanthus) and short-rotation woody crops (e.g., eucalyptus, hybrid poplar) with faster harvest cycles [33].

Municipal Solid Waste (MSW): MSW refers to waste from municipal, commercial, and manufacturing activities, including food waste, paper, plastics, metals, sewage sludge, and more [34]. MSW pyrolysis produces biochar, with its composition influenced by waste content and contaminants. The resulting biochar mainly consists of carbon, low ash, inorganic materials, and trace metals, making it a potential alternative fuel. It also contains essential soil amendment elements like calcium (Ca), potassium (K), and magnesium (Mg) [35].

Poultry Litter and Animal Manure: Poultry Litter and Animal Manure consist of feathers, excreta, leftover feed, and absorbent bedding materials like sawdust, rice hulls, and woodchips. It includes waste from meat chickens, egg layers, turkeys, ducks, and quails. Pyrolysis is the most common way of converting animal manure into biochar with a higher yield [36]. Poultry litter biochar is nutrient-rich, highly porous, and has a large surface area with high cation exchange capacity, supporting microbial growth in composting [37]. Its high ash and low carbon content enhance soil health by improving nutrient retention [35].

Thus, to achieve the desired biochar quantity and quality, the production method must be suitable for the specific type of biomass. Pyrolysis is the most common thermochemical process, converting biomass into bio-oil, syngas, and biochar by heating organic materials above 400°C in an oxygen-free environment [38]. The product yield depends on parameters such as temperature, heating rate, inert gas flow, and residence time as shown in Fig.2.

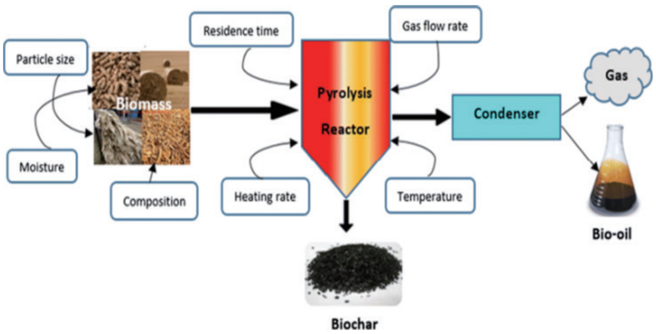


Fig. 2 Conventional pyrolysis process [39].

Pyrolysis is classified into fast and slow types based on operating conditions. Fast pyrolysis (~500°C, ~2 sec) maximises bio-oil yield (~75%), with 12% biochar and 13% gas [40]. Slow pyrolysis (300–500°C, 5–30 min) produces a higher biochar yield (25–30%) with 30–50% bio-oil and 35% gas [41]. Various reactors, including wagon reactors, paddle kilns, agitated drums, fluidised beds, and rotating kilns, are used for both types [42]. In addition to pyrolysis, several thermochemical methods, including traditional kilns, retort kilns, hydrothermal carbonisation (HTC), gasification, torrefaction, and microwave pyrolysis, are employed for biochar production, each offering distinct advantages and drawbacks. Retort kilns and microwave pyrolysis enhance biochar quality, while HTC converts wet biomass into hydrochar with improved properties [43]. Gasification typically produces less biochar, often with contaminants [44]. Whereas torrefaction enhances biomass energy density [29]. Higher pyrolysis temperatures (>500°C) increase biochar stability, surface area, and carbon content. In comparison to fast pyrolysis, slow pyrolysis results in biochar with higher carbon, ash, iron, and nitrate content [45].

2.2 Biochar Properties

Biochar characterisation is essential for understanding its elemental composition, surface area, functional groups, stability, and CO_2 adsorption capacity. Techniques such as SEM, FTIR, TGA, XRD, BET analysis, Raman spectroscopy, NMR, and volumetric sorption are used to assess these properties. This section reviews the physical, chemical, and biological characteristics of biochar.

2.2.1 Physical Properties

Biochar is a black, lightweight, finely grained material with high porosity and surface area, which impacts properties like nutrient binding, soil water retention, and microbial activity [46]. During pyrolysis, biomass loses water and releases volatile components, forming pores of varying sizes, from nanometres to micrometres. These pores are classified as micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [47]. Pore distribution is essential for adsorption processes, as its presence significantly influences the relationship between surface area and porosity.

The biochar pore volume, related to pore size and porosity, the surface area, and total pore volume of biochar typically fall within the ranges of 8–132 m^2/g and 0.016–0.083 cm^3/g, respectively, as shown in Fig. 3. When appropriate precursors and optimal pyrolysis conditions are employed, the surface area of biochar can attain up to 490.8 m^2/g, while its total pore volume can reach 0.25 cm^3/g [48]. In contrast, the volume of macropores in biochar is determined by the type of feedstock used [49]. For instance, Kajina and Rousset [50] found that biochar derived from sugar cane leaves exhibited a larger pore size of 0.1 m^2/g and significantly higher surface area of 253.2m^2/g compared to biochar obtained from coconut shells, which had a total pore size of 0.1 m^2/g and a specific surface area of 25.8m^2/g.

Similarly, El-Gamal, et al. [51] reported that biochar derived from sugarcane exhibited a higher pore size of 0.1 m^2/g and a greater specific area of 185.6 m^2/g compared to rice husk biochar, which had a similar pore size of 0.1 m^2/g but a lower surface area of 154.7 m^2/g. The specific surface area of biochar is influenced by feedstock composition and ash content, with lower ash content typically resulting in a higher surface area. For example, Ronsse, et al. [52] found that an increased ash content in biomass feedstocks is inversely related to the specific surface area of biochar. Gupta, et al. [53] further demonstrated that feedstock selection critically governs biochar's pore structure and surface properties. In their comparative analysis of lignocellulosic (sorghum, cotton stalk, wood, dairy manure) and non-lignocellulosic (algae) biochars, high-carbon, low-ash biochars (e.g., wood-derived) exhibited up to 50% greater surface area and pore volume compared to high-ash variants. These improvements were associated with accelerated cement hydration kinetics,10-12 % enhancement in compressive strength. Among different types, Wood-based biochar exhibited the highest specific surface area (127.0 m²/g) due to its low ash content (0.2%). In comparison, straw, green waste, and algae biochars had surface areas of 22.0 m²/g, 46.0 m²/g, and 19.0 m²/g, respectively, with ash contents of 7.9%, 3.5%, and 38.4%.

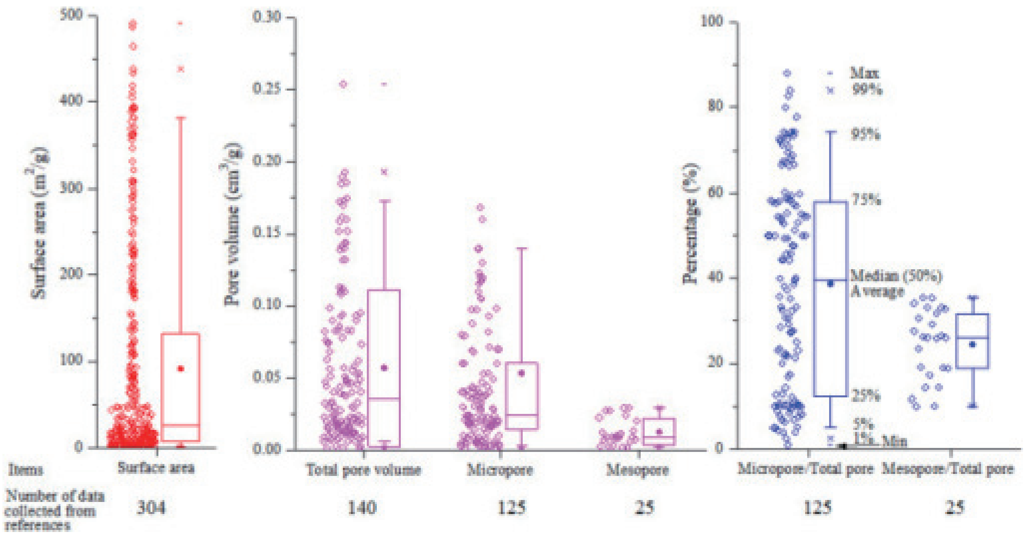


Fig. 3 The surface area and porosity of biochar [48].

2.2.2 Chemical Properties

Biochar is primarily composed of carbon, with varying amounts of oxygen, hydrogen, nitrogen, and other elements depending on the feedstock. Its chemical composition is influenced by pyrolysis temperature and feedstock type, as shown in Table 1. It primarily consists of SiO_2 , Al_2O_3, K_2O, CaO, Fe_2O_3, Na_2O, and MgO. For instance, rice husk biochar at 500 °C has a high SiO_2 content (89.27%) [54] Thermo-mechanical behavior of cementitious material with partial replacement of Class-II biochar with Accelerated Carbonation Curing (ACC, while waste wood biochar contains significant CaO (54.51%) and moderate MgO (13.83%) [55]. These variations highlight the impact of feedstock and pyrolysis conditions on biochar's chemical composition and properties. In addition to the elemental compositions, biochar's chemical properties, including pH, electrical conductivity, and cation exchange capacity, determine its application suitability. Proximate analysis measures carbon, ash, and volatile matter, while ultimate analysis focuses on organic and inorganic compositions [49]. Carbon transforms into more stable structures during pyrolysis, improving stability and density. Higher pyrolysis temperatures enhance carbon stability and heat resistance [56]. The main chemical properties are:

Functional groups: The carbonisation process thermally decomposes biomass, releasing oxygen and hydrogen while detaching functional groups. This produces biochars with low hydrogen-to-carbon (H/C) ratios, reduced functional groups, and more stable aromatic structures, which are essential for long-term applications. [57]. Common functional groups on biochar surface include hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and phenolic (-C_5H_5OH). These functional groups significantly enhance biochar's chemical reactivity, making it effective for several applications, whether in concrete or soil. [3].

The formation of these aromatic structures depends on the feedstock type and carbonisation temperature.

pH values: Biochar's pH is influenced by manufacturing temperature and atmosphere. Under a nitrogen atmosphere, pH increases with temperature, peaking at 10.18 at 700 °C. In an air-limited environment, pH decreases at lower temperatures (~250 °C) before rising significantly with higher temperatures. pyrolysis conditions significantly impact biochar's pH, which is crucial for various applications [58].

Cation Exchange Capacity (CEC): CEC measures the ability of a material to hold exchangeable cations (e.g., Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+); CEC depends on the material's surface structure and area, with functional groups serving as surface charges. The measurement varies depending on the solution pH and solvents used (e.g., distilled water, NaOH, HCl), with a higher pH often increasing CEC. Pyrolysis conditions, such as temperature and feedstock choice, influence the surface functional groups of biochar, affecting its cation exchange capacity (CEC), as biochar produced at lower temperatures typically exhibits a higher CEC due to an increased surface area and the retention of functional groups. [59].

Table 1 Chemical composition (%) of different types of biochar

Types of biochar	Pyrolysis temperature (℃)	SiO_2	Al_2O_3	K_2O	CaO	Fe_2O_3	MgO	P_2O_5	SO_3	TiO_2	Na_2O	Ref.
Corn straw	300	4.46	1.39	0.58	1.36	1.68	3.68		-		23.18	
	400	4.71	1.67	0.61	1.46	1.91	3.57	1.7			20.54	
	500	4.66	1.49	0.69	1.53	2.02	3.54	7.24			21.53	
	550	4.50	1.37	0.73	1.61	2.05	3.37	7.24			21.98	
								9.45				
Bamboo	650-750	44.2	15.04	12.8	9.6	9.29	2.73	1.11	1.59		-	
Sewage sludge	500	49.4	17.5	2.65	3.91	12.0	3.48	-	-		-	
Waste wood	500	4.48	7.46	2.11	54.51	2.23	13.83	-	-		0.98	
Rice husk	500	89.27	0.95	3.19	1.8	1.21	-	-	1.86		-	
Rice stubble	450	68.67	1.66	9.08	10.85	1.99	2.74	-	0.79		1.15	
Forest waste	400-500	49.7	2.36	13.5	19.6	3.12	4.63	-	1.39		1.63	
Bagasse	500	4.33	-	57.97	13.44	3.83	-	2.12	2.21	-	4.33	
Cornstalk	500	34.52	-	26.67	18.19	12.42	-	5.15	8.69		34.52	
Saw dust	500	-	-	9.14	60.68	4.99	-	2.73	-		-	
bagasse	500	16.62	-	20.68	12.79	3.65	0.14	3.17	2.42		-	
Coconut husk	500	12.1	-	17.75	17.53	6.14	0.26	7.88	5.25		-	
Peanut husk	500	17.67	-	21.46	12.69	4.77	0.16	4.17	1.44		-	
Rice husk	500	18.54	-	13.71	16.28	0.48	0.07	-	2.31		-	
Wheat husk	500	10.7	-	23.14	12.32	2.05	0.50	7.88	3.60		-	
Woodchips	900	4.15	-	19.25	60.49	0.55	6.16	4.17	0.98		0.42	
Waste boards	500	20.03	6.26	0.62	63.57	2.59	2.68	-	2.01		0.33	
Coconut husk	500	49.38	3.95	14.82	5.25	5.72	2.48	0.56	2.32		11.43	
Waste wood	500	7.68	2.02	3.71	9.68	2.22	7.01	16.9			1.30	

2.3 Biochar Concrete Mix Design and Production Considerations

Incorporation of biochar into concrete requires pre-treatment due to its low density and high porosity compared to traditional aggregates. A widely adopted approach involves saturating the biochar with water equivalent to approximately 25% of its mass, which helps maintain slump and workability [2]. This prevents excessive moisture absorption from the cement paste, maintaining the mix's rheological properties [70]. Moreover, the pre-wetting process facilitates internal curing, as the water retained within biochar is gradually released during cement hydration, enhancing strength development and minimizing shrinkage. Gupta and Kua [71] found that wood waste-derived biochar, pre-soaked with water, not only improved compressive, flexural, and split-tensile strength by 40–50% compared to other mix formulations, but also demonstrated superior internal curing effectiveness in mortar. Similarly, Kua and Tan [72] observed that pre-soaked biochar contributed to enhanced carbonation efficiency in mortar, further demonstrating the role of pre-soaked biochar in both strength development and carbonation curing. To ensure proper dispersion and homogeneity in the mix and prevent segregation, biochar is typically added after the initial mixing of cement and aggregates, followed by mechanical mixing, with the addition of a proper superplasticizer and viscosity-modifying agents to further enhance the performance and consistency of the biochar-concrete composites [73].

3. Biochar in cement–based composites

Biochar has gained attention as a partial replacement for cement in concrete, with optimal dosages ranging from 1% to 3% by binder weight [74]. It is cost-effective, reduces carbon emissions, and enhances early strength by absorbing mixed water, lowering the water-cement ratio. Biochar can also exhibit pozzolanic behaviour, reacting with calcium hydroxide during hydration to form additional cementitious compounds, improving mechanical properties, and reducing permeability [75]. This reaction also sequesters carbon, contributing to lower greenhouse gas emissions. Biochar enhances thermal conductivity, water retention, and early hydration, promoting strength development as shown in Fig. 4. However, its flammability raises fire safety concerns [76]. Thus, both the composition and chemical stabilisation are essential in the formation of cementitious materials. Biochar can be used in ready-mix and precast concrete, but precast production offers more control due to its sensitivity to mix design and curing conditions. Precast concrete is widely preferred in construction for its exceptional durability and versatility [77]. Recent advancements have led to the market availability of biochar-concrete products, including precast elements and paving blocks [78]. Integrating biochar into precast concrete reduces carbon footprint and material cost by partially replacing cement. However, a thorough cost-benefit analysis is needed to evaluate long-term impacts, considering biochar production, operational changes, and addressing challenges [77].

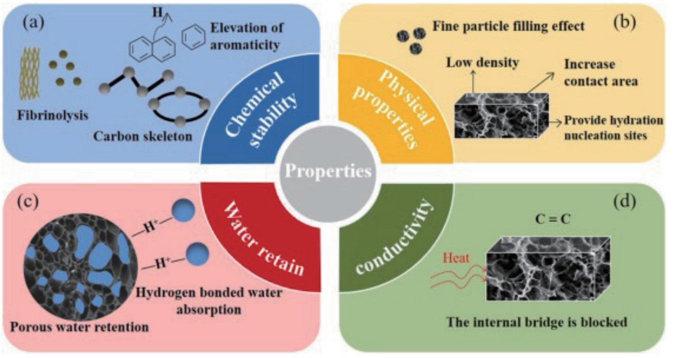


Fig. 4 Performance advantages of biochar [76].

3.1 Biochar Effect on Cement Hydration

Cement hydration is the reaction between cement and water that causes hardening. Initially, clinker phases disintegrate, releasing ions. When the solution becomes oversaturated, nucleation occurs on the clinker surface. This complex process is affected by different factors, such as solubility variations and concentration changes, particularly in forming calcium silicate hydrate (C-S-H) gel, which is the main product of hydration [79]. The formation of C-S-H is crucial for the strength and durability of cementitious materials, and this is where the properties of biochar can significantly impact hydration. Biochar's surface area, pH, porosity, and morphology play vital roles in enhancing the performance of cementitious materials. Biochar addition improves the hygro-mechanical behavior of cementitious materials by modifying their pore structure and moisture distribution, leading to enhanced strength, durability, and resistance to chloride infiltration and carbonation [80].

A larger surface area is associated with other beneficial properties of biochar, such as cation exchange capacity and water retention capacity [81]. The impact of biochar on cement hydration is primarily influenced by its specific surface area and mineral composition, which can vary based on the types of feedstocks and the conditions during pyrolysis [74]. These properties are vital during the hydration of cement, as they impact the availability of water and ions required for hydration reactions. The surface area of biochar is largely determined by its porous structure, which differs from other conventional fillers. This unique porosity offers additional surface area within the cement paste, aiding in regulating effective water content, facilitating internal curing, and providing sites for the condensation of hydration products [82].

Moreover, past studies have shown that the micro-pores and macro-pores in biochar, ranging from 5 to 30 μm, have a significant role in water absorption and retention. This capacity allows biochar particles to initially store water, which can later be released into the mortar paste, promoting the internal curing action [83]. This internal curing mechanism has been shown to help sustain hydration in low-water cement mixtures, leading to increased C-S-H gel formation over time and enhanced strength development. For instance, a study conducted by Haris Javed, et al. [65] investigated the potential of using five different types of biochar - bagasse biochar, coconut husk biochar, peanut husk biochar, rice husk biochar, and wheat husk biochar - as a partial replacement for cement (1-5 wt%). The research assessed the effect on hydration characteristics, including setting time, water demand, and water absorption. The results found that incorporating biochar into cement pastes demands slightly more water due to biochar's porous nature, leading to cohesive mixes. Biochar also accelerates setting time and results in lower water absorption and porosity compared to the control pastes, due to enhanced hydration product formation.

Biochar can act as a carbon-based additive in cement, similar to materials such as carbon nanotube (CNT) and graphite nanoplatelets (GNP), in enhancing cement hydration by refining the pore structure and promoting C-S-H formation. Huang, et al. [19] examined the effect of carbon nanotube (CNT) and graphite nanotube (GNP) at 0.3% by mass of binder on the composition and mechanical properties of C-S-H in ultra-high-performance concrete. The addition of 0.3% CNT and GNP increased compressive strength by approximately 20 MPa, attributed to the nucleation and filling effects that refined the pore structure. Increasing CNT and GNP content from 0-3% raised the proportion of high-density C-S-H from 65% to 90%, enhancing the C-S-H elastic modules by 20%.

On the other hand, other studies have indicated that biochar may not significantly impact cement hydration. For example, a study conducted by Schmidt, et al. [84] examined the effect of biochar derived from woody feedstock as a partial replacement for cement (5 - 30 wt%). The findings indicated that biochar did not significantly interfere with cement hydration at early ages; however, the water retained in the biochar particles caused a slight retarding effect on hydration. Given these mixed results, further research is needed to understand biochar's effect on cement hydration and its potential as a sustainable alternative, focusing on optimal types, dosage, and interaction mechanisms.

3.2 Biochar Effect on Workability

Concrete workability refers to the ease with which freshly mixed concrete can be handled, placed, and compacted without compromising its uniformity, affecting the consistency, flowability, permeability, compactability, and hardness of a concrete mix, making it essential for producing high-quality concrete [85]. Adequate workability in cementitious composites is necessary for proper placement and compaction; it is closely linked to rheological properties, including yield stress and viscosity. The incorporation of biochar into cement paste notably influences these properties, primarily through its water absorption, which varies with the particle size, porosity, and type of biochar [11].

Various studies have highlighted that the porous nature of biochar can reduce workability during the initial curing stage, leading to decreased flowability in biochar-cement mixtures. As biochar content increases, the reduction in workability becomes more pronounced, as its high carbon content may demand additional water for optimal performance. [86]. For instance, Yang and Wang [87] Investigated the replacement of cement with rice husk biochar at 2% and 5% levels for ordinary Portland cement (OPC). Their study found that the workability decreases with an increase in the biochar replacement ratio, primarily due to the high porosity of biochar, which absorbs water during mixing, as shown in Fig.5. The workability decreases with higher biochar levels, as shown by reductions in flow diameter (200mm for Control-Mortar (C-M) to 180 mm for 5 % Biochar–Mortar (B5-M) and relative flow (100% to ~90%).

A study conducted by Tan, et al. [88] observed that increasing biochar content in cement mortar decreased fluidity due to its porous structure and high cation exchange capacity, with a 3% reduction in workability when biochar pyrolysed at 400 °C was used. To mitigate workability challenges, limiting biochar replacement to 5% is recommended [86], along with the use of superplasticisers to enhance flow and adjust the water-cement ratio [18]. Additionally, biochar particle size and distribution are critical for workability. Smaller particles increase water demand, reducing fluidity, whereas larger particles enhance flow but may compromise uniformity. Optimal particle size improves packing density, flowability, and mechanical properties [3].

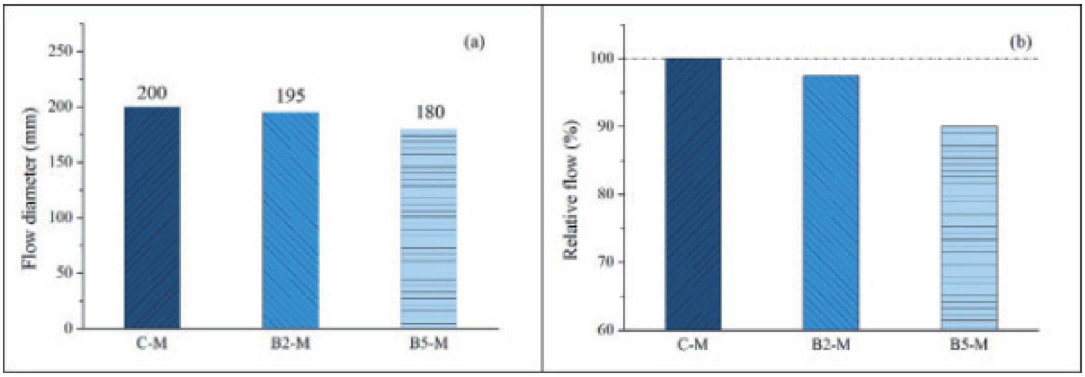


Fig. 5 (a) flow diameter (b) relative flow of blended mortars [87].

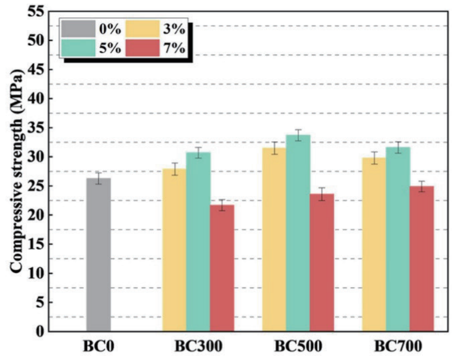
3.3 Biochar Effect on Mechanical Properties

Mechanical properties such as strength, elasticity, ductility, and toughness are vital for the performance and stability of civil engineering materials, especially in structural applications [89]. The addition of biochar to cement mixtures enhances mechanical properties and durability [82, 86, 87]. Optimising biochar dosage improves the pore structure of cementitious materials, leading to increased compressive and flexural strength, toughness, and ductility. Moreover, pre-saturating biochar particles before mixing enables moisture release during curing, acting as an internal curing agent that improves hydration and overall material performance[66]. Improves the pore structure of cementitious materials, increasing compressive and flexural strength, toughness, and ductility.

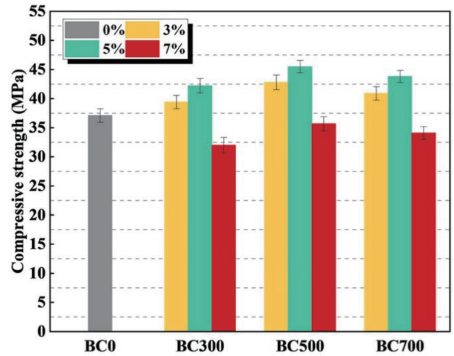
Different studies highlight the impact of biochar type and dosage on cementitious materials. Gupta, et al. [90] reported that 2% mixed wood sawdust biochar reduced setting time and enhanced early compressive strength and ductility, although it did not notably affect flexural strength. [91] found that bamboo biochar at 0.08% replacement increased compressive strength before declining at higher dosages, while flexural strength and toughness improved by 66% and 103%, respectively. Similarly, Khushnood, et al. [92] observed that 1% hazelnut and peanut shell biochar significantly enhanced flexural strength and toughness.

The mechanical performance of biochar-cement composites depends on feedstock type and production conditions. Gupta, et al. [93] found that 1–2 wt% food and rice waste biochar maintained strength, while food waste biochar improved impermeability. Wood waste biochar provided the most sustainable enhancement, increasing compressive and tensile strength by 20%, reducing water absorption, and improving ductility. Biochar production methods also impact performance. Sirico, et al. [66] reported that wood biochar from gasification at 2.5% dosage maintained strength with a slight increase in fracture energy. Similarly, Suarez-Riera, et al. [94] found that 2% gasified wood biochar reduced flexural strength but improved fracture energy, shifting failure behaviour from brittle to ductile. Collectively, biochar enhances mechanical strength and significantly improves fracture energy in cement-based materials by altering crack propagation and increasing energy absorption before failure[66].

A meta-analysis of 606 observations shows that plant-based biochar (excluding rice and hardwood) increases 28-day compressive strength by 3–13%. Pyrolysis temperature impacts porosity, with 500°C yielding more pores than 350°C, while temperatures above 600°C cause pore wall collapse. Biochar produced above 450°C with smaller particle sizes is most effective, and an optimal dosage below 2.5% by binder weight improves strength while maintaining rheological properties [2]. For example, Wang, et al. [95] found that 1% waste wood-derived biochar enhanced compressive strength by 8.9%, with 700°C pyrolysed biochar outperforming 500°C. Similarly, Chen, et al. [96] reported that 5% corn straw biochar improved mortar strength most when pyrolysed at 500°C, compared to 300°C and 700°C, as shown in Fig.6. Liu, et al. [97] studied the effect of adding soybean dregs biochar produced at 300 °C, 500 °C, and 700 °C, finding that high temperature pyrolysis enhanced pore structure and surface area, which enhanced the concrete's microstructural compactness, and improved the mechanical performance with a 12.32% Increase in compressive strength and a 16.42% increase in tensile strength compared to the control samples.



(a) Compressive strength at 3 days of ACC



(b) Compressive strength at 28 days of ACC

Fig. 6 Compressive strength at 3 days and 28 days [96].

Table 2 provides a summary of various studies investigating the effect of different types and dosages of biochar on the mechanical properties of cementitious materials. This table compares the impact of different biochar types and dosages on compressive and flexural strength, toughness, and ductility across various studies. In summary, incorporating biochar into cementitious materials can enhance mechanical properties at lower dosages by improving water retention and facilitating pozzolanic reactions.

The presence of silica and aluminum in certain biochars promotes these reactions by interacting with calcium hydroxide to form additional binding phases, thereby increasing strength [81]. However, higher biochar dosages may lead to strength reduction due to increased porosity and alterations in the cement matrix. Additionally, larger particle sizes and higher porosity can influence the microstructure, while excessive biochar content may induce early-stage drying shrinkage, potentially compromising long-term durability [98]. Therefore, careful selection of biochar type and dosage is essential for optimising mechanical performance.

Table 2 Overview of biochar's effect on mechanical properties

Reference	Biochar Type	Biochar Dosage by Cement Weight	Effect on Compressive Strength	Effect on Flexural Strength	Effect on Toughness/Ductility	Other Notes
[93]	food waste, rice waste, and wood waste)	1-2%	Food & rice waste: no significant change. Wood waste: increased compressive and tensile strength by up to 20%	Food &rice waste: no significant change. Wood waste: increased	Improved ductility For wood waste Sorptivity reduced by 38%	Wood waste: reduced water penetration by 60% improved impermeability and improved tensile strength.
[91]	Bamboo	0.05, 0.08, 0.2%	Increased at 0.08wt% by 25%	Increased by 66%	Improved toughness at 0.08% by 103%	Compressive strength decreased at high dosage
[66]	Wood waste	1, 2.5%	Equal to control samples	Slightly decreased (5-10%) for 2.5 wt%	improved fracture energy by 5-15 % at 7 &28 days, no significant change on ductility	Improved crack propagation and energy absorption
[95]	Wood waste	1%, 5%	Increased at 1wt% by 8.9%	No direct mention	No direct mention	The 700°C pyrolysis biochar is more effective than 500°C
[87]	Rice husk	2%, 5%	12.8% Decrease at 3 days;5.5% at 28days	No direct mention	No direct mention	Higher biochar dosage reduced compressive strength
[90]	Mixed sawdust wood	2%	Improved early compressive strength by up to 15-25%	No significant effect	Improved ductility, reduced water permeability up to 50%	No effect on flexural strength reduced sorptivity up to 40%
[92]	Peanut, and hazelnut shells	Up to 1%	No direct mention	Increased by 80% (max value was 5.44 MPa at 0.2wt%) Control was 2.96 MPa	0.5wt% hazelnut shells & Increase fracture energy, and improved in toughness	Fracture/toughness improved due to crack deflection and bridging by the angular particles for biochar. Hazelnut shells provided greater improvements
[94]	Wood waste	2%	30-40% decrease	Slightly decreased about 2%	Improved fracture energy and improved ductility for 2% biochar	Enhanced fracture energy, no effect on strength

3.4 Biochar Effect on Durability

Biochar enhances durability by improving hydration and filling voids, creating a denser microstructure that blocks ions and water penetration [18]. Santhosh et al.[99] confirmed that biochar improves cement matrix homogeneity, reduces water absorption, and increases chloride resistance. Aneja, et al. [100] found that 2% and 4 % rice husk biochar reduced permeability by 9.6% and 17.3%, respectively, due to finer particles filling voids and enhancing hydration. Similarly, Gupta et al. [101] reported that 1- 2 wt% rice husk and waste wood biochar improved hydration, reduced permeability, and increased sulfate resistance. However, Yang and Wang [87] found that 2-5% biochar increased chloride diffusion, likely due to dilution effects and added porosity. This study aligns with research conducted by Cunningham and Keane [86], who investigated the use of timber biochar and Juncus waste biochar as a cement replacement ranging from 0% to 6%. The results demonstrated that incorporating biochar increased concrete permeability and chloride migration, likely due to the dilution effect and the formation of additional pores.

On the other hand, biochar's fine particles positively influence the shrinkage behaviour of cementitious composites. Smaller particle sizes are suitable for porosity to help reduce shrinkage by filling voids and improving matrix cohesion, while its water retention properties. This effect is similar to self-healing curing agents, as biochar's ability to reduce water evaporation helps alleviate both plastic and drying shrinkage, lowering the risk of cracking [15] and enabling internal curing, mitigating rapid shrinkage during early curing stages [18]. Mo, et al. [102] found that adding 2 wt% weed tree biochar to cement composites increased the internal relative humidity and a reduction of 16.3% in autogenous shrinkage at 180 hours of curing. Similarly, Dixit, et al. [103] investigated the effects of replacing 2- 5 wt% of cement with sawdust biochar in high-performance concrete. Biochar reduces shrinkage by improving internal curing.

Higher biochar content resulted in greater control over total and autogenous shrinkage. At 72 hours, 2% and 5% biochar reduced shrinkage by 21% and 32%, respectively, mitigating early-age cracking. These findings align with Gupta, et al. [104], who investigated using wood waste biochar and coconut shell biochar as a 5wt% cement replacement. The results demonstrated a reduction in autogenous shrinkage by 61% and drying shrinkage by 23% at 91 days. Despite these insights, research on the shrinkage behavior of biochar in concrete remains limited, highlighting the importance of precise dosage control. Rashid et al.[63] found that 7.5% and 10% Junglee Keekar (JK) and rice stubble (RS) biochar significantly increased drying shrinkage. JK biochar increased shrinkage by 96% and 60%, while RS biochar led to 65% and 61% increases compared to the control mix as shown in Fig.7. Similarly, Gupta, et al. [105] found that incorporating sawdust biochar as a cement replacement increased early-age drying shrinkage. However, at later stages, 1% biochar reduced shrinkage, whereas 2% led to an increase compared to the control, as shown in Fig.8, which illustrates the Shrinkage behaviour of samples with varying biochar percentages.

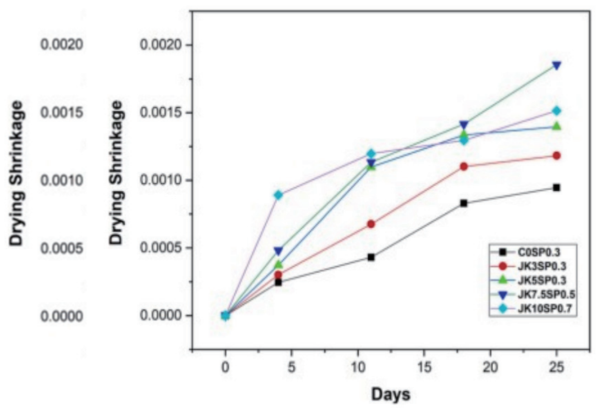


Fig. 7 Drying shrinkage results for JK biochar drying shrinkage results for RS biochar [63].

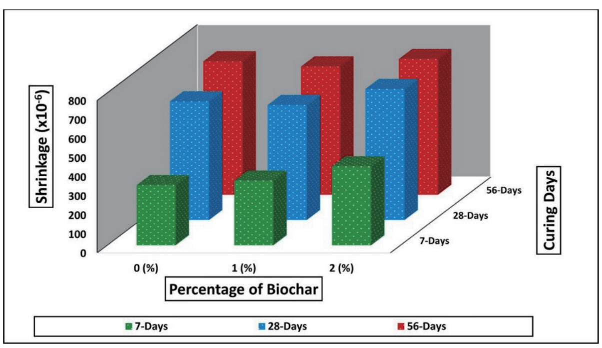


Fig. 8 Shrinkage of samples with different percentages of biochar [106].

Biochar's porous structure can increase drying shrinkage at higher concentrations. Its ability to absorb and retain moisture leads to volume shrinkage as water is released during drying. Higher biochar concentrations create more pore space for moisture retention, intensifying shrinkage effects. These findings highlight the need for careful dosage control. Overall, Further research is needed to assess biochar's impact on durability factors like chloride ion diffusion, sulfate resistance, and shrinkage in cementitious composites.

3.5 Biochar Effect on Microstructure

Concrete has a heterogeneous microstructure comprising cement paste, pore structure, and the interfacial transition zone (ITZ), which represents the boundaries between the cement paste and aggregate particles. Strengthening these components enhances mechanical properties and durability. The hydrated cement paste consists of key phrases, including calcium silicate hydrate (C-S-H), calcium hydroxide (CH), ettringite, mono-sulfate, unhydrated cement particles, and air voids [107]. Optimising the final product involves incorporating supplementary cementitious materials and additives with varying particle sizes and surface areas. Biochar from wood and food waste develops a porous structure during pyrolysis, enabling it to absorb mixing water and reduce free water in concrete [82]. This enhances the microstructure by filling pores, creating a denser matrix, and lowering the binder-aggregate ratio. As a result, the improved microstructure contributes to increased strength and structural integrity [17]. The small particle size of biochar (D90 ~45 μm) allows it to fill the interfacial transition zone (ITZ), enhancing Portland cement composites. Its large surface area provides nucleation sites, strengthening cementitious bonds and improving compressive strength [2].

During hydration, the supersaturated pore solution infiltrates biochar's internal pores, promoting the precipitation of C-S-H gel, which enhances concrete strength and durability [87]. Ling, et al. [73] studied the effect of biochar from waste wood at cement replacement levels of 0%, 1%, 3%, 5%, and 10% on concrete's microstructure and mechanical properties. SEM and XRD analysis showed that biochar improved the concrete microstructure. Without biochar, C-S-H crystals formed a loose structure with micropores, causing cracks in the interfacial transition zone (ITZ), as shown in Fig.9.

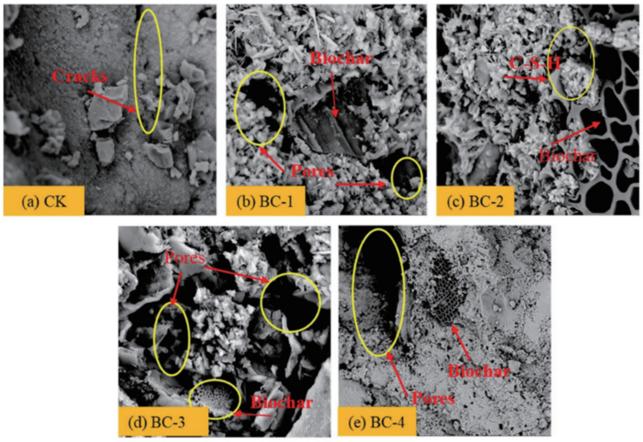


Fig. 9 SEM images of concrete of biochar with 3% content [73].

However, 3 wt% biochar acted as a micro filler, providing nucleation sites for cement hydration and resulting in a denser structure. XRD analysis of 28-day concrete with 3% biochar showed that as biochar fineness decreased, $CaCO_3$ intensity reduced, while SiO_2 and $Ca(OH)_2$ initially decreased and then increased. Biochar promotes hydration by forming C-S-H gel, improving strength. However, finer biochar adsorbs water, hindering the $Ca(OH)_2$ reaction and reducing strength. Similarly, Song, et al. [108] found that rice husk biochar (RHBC) improved the hydration and microstructure of foamed concrete at replacement levels of 1% to 7%.

Biochar promoted additional hydration products, enhancing thermal stability and mechanical properties. It refined the pore structure, increasing closed pores and density, while C-S-H gel surrounded biochar particles, filling cracks and reducing harmful pores for a more compact and stable microstructure of biochar-based concrete. Fig. 10 shows the microstructure of biochar-based concrete using SEM. (a) shows the scattered C-S-H gel and cracks, while (b) shows a clustered gel with fewer harmful pores, resulting from biochar's pozzolanic reaction. Few studies have explored biochar with supplementary cementitious materials (SCMs) in cement-based composites. Qu, et al. [109] used wood waste biochar (1 wt% to 10 wt%) in cement-GGBS blends, improving chloride immobilisation by refining the microstructure and reducing porosity. Similarly, L. Chen et al. [9] replaced fine aggregates with 10%, 20%, and 30% biochar and combined it with SCMs like metakaolin, fly ash, and GGBS. This promoted cement hydration, improving C-S-H gel formation and strength. Pang, et al. [110] produced biochar from waste synthetic eucalyptus plywood boards and replaced cement with 3 wt%, 5 wt%, and 10 wt% under elevated temperatures. They found that a 3 wt% substitution optimally enhanced micro-filling and secondary hydration, yielding strength gains and a refined microstructure, with reduced porosity, cracks, and spalling. Despite the promising advancements in biochar-modified concrete, further research is needed to fully understand the synergistic effects of biochar and SCMs in cement-based composites.

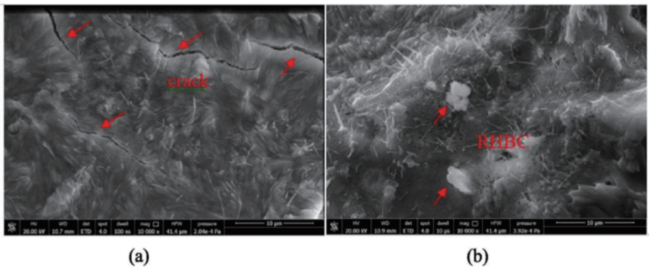


Fig. 10 SEM images: (a) control sample; (b) concrete-biochar-5% [108].

3.6 Biochar Effect on CO_2 Adsorption

Biochar's porous structure and high surface area enable efficient CO_2 adsorption, transportation, and storage. A greater surface area enhances the interaction between cement compounds and CO_2, speeding up the carbonation process [106]. Unlike other solid adsorbents, it relies mainly on its physical mechanism properties, as shown in Fig.11, which illustrates the CO_2 physisorption mechanism. Factors like pyrolysis temperature, feedstock type, and biochar activation affect its CO_2 adsorption capacity. While raw biochar has limited adsorption potential, modifications have been shown to significantly enhance its ability to capture CO_2 in various studies. Biochar's CO_2 capture is enhanced by its porous structure and high surface area, with engineered modifications like chemical, physical, impregnation, and grafting methods applied before or after pyrolysis to improve performance [111]. Micropores in biochar are crucial for enhancing its CO_2 performance [112].

Biochar is considered a carbon-negative material, as it locks carbon within its structure during preparation. It has the potential to offset up to 12% of anthropogenic CO_2 emissions by 2050, with estimated sequestration ranging from 0.3–2 Gt CO_2 per year [16]. Beyond its CO_2 adsorption properties, biochar can reduce the carbon footprint of cementitious materials by supplementing cement with biochar and enhancing capture during the curing process. Carbon sequestration during biochar production helps offset emissions from cement manufacturing [74]. According to a life cycle assessment (LCA) study by Roberts, et al. [113], the carbon-negative impact of biochar production can reach approximately 885 kg CO_2 equivalent per ton of dry feedstock, with around 62-66% of this reduction attributed to carbon sequestration in the biochar. This aligns with a study by [114] demonstrated that integrating biochar into Super Sulfated Cement (SSC) shows a significant reduction in concrete's carbon footprint. A 5% biochar dosage results in a Global Warming Potential (GWP) of 115.44 kg CO_2-eq/m³, a 75.79% reduction compared to Ordinary Portland Cement (OPC) and a 24.86% reduction compared to SSC. This makes biochar a viable tool in mitigating CO_2 emissions when integrated into concrete, which is considered a significant emitter of CO_2.

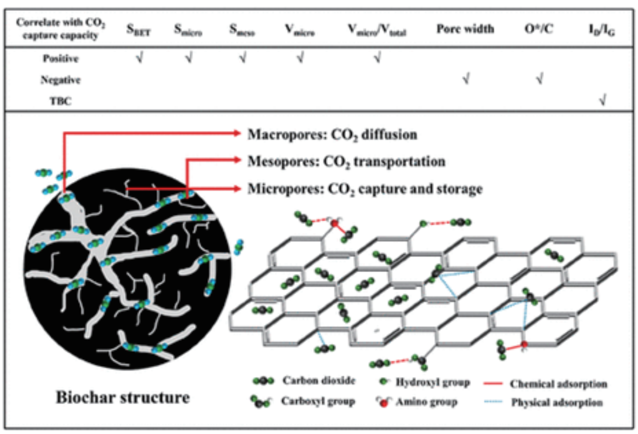


Fig. 11 Potential mechanism of CO_2 physisorption by a porous material [112].

Concrete production, particularly the manufacture of Portland cement, is responsible for a sustainable portion of global CO_2 emissions. The estimated eCO_2 of conventional concrete is about 354 kg CO_2-e/m³, with Portland cement contributing up to 76.4% of the emissions [115]. By partially replacing cement with biochar, concrete's CO_2 emissions can be reduced while simultaneously facilitating long-term carbon sequestration. Biochar has the potential to capture up to one gigaton of greenhouse gases annually, potentially reducing global emissions by nearly 10% if applied for carbon neutrality. This significant environmental benefit is largely attributed to the global availability of biomass for biochar production, biomass's carbon-neutral nature, and biochar's capacity for long-term CO_2 storage [112]. Biochar can also enhance the CO_2 uptake during accelerated carbonation curing (ACC) processes, where concrete is exposed to CO_2 under controlled conditions to promote faster carbonation. For instance, a study conducted by Mishra, et al. [16] explored the viability of biochar as a CO_2 adsorbent in concrete; the addition of 1% biochar resulted in a 42% increase in CO_2 uptake. When combined with 10% class C fly ash, the CO_2 capture capacity of the mix further increased by 92%. Similarly, a study by Li and Shi [116] examined the use of concrete washout water (CW) for pre-treating biochar to enhance its CO_2 adsorption capacity.

The CW-treated biochar demonstrated a CO_2 uptake of 22.85 wt% after 14 days of weathering. When incorporated at 30% by weight into Portland limestone cement, the modified biochar contributed to making the cement paste carbon-negative. Furthermore, a study by Chen, et al. [96] found that the incorporation of 5% biochar into cement mortar resulted in a significant increase in CO_2 uptake, ranging from 13.1% to 32.2% after 28 days of accelerated carbonation curing (ACC) when compared to the control samples without biochar. This observed enhancement underscores the synergistic effect between biochar and cement mortar in promoting carbon sequestration during the CO_2 curing process. Notably, the study also revealed that biochar pyrolysed at 500°C exhibited the highest carbon sequestration performance, with a 31.6% increase relative to biochar processed at 300°C and 700°C. Kua and Tan [72] compared the CO_2 adsorption performance of internally and externally carbonated mortars incorporating dry and pre-soaked biochar. Internally carbonated dry biochar showed the highest carbonation efficiency, exceeding the target of 0.03%/hour, while also enhancing compressive strength, although pressoaked biochar improved CO_2 uptake, its strength was comparatively lower. These findings suggest that dry internal carbonated biochar offers an optimal balance between CO_2 sequestration and structural performance. In addition to these studies, a novel biochar-enabled core-shell aggregate (BCSA) was developed by Zou, et al. [117] to address the challenges of using high volumes of biochar in concrete, such as high water absorption and low strength. BCSA-concrete achieved a CO_2 sequestration of 247.1 CO_2/m³, demonstrating greater carbon storage potential compared to carbonation curing, while maintaining structural integrity. Incorporating biochar into concrete reduces carbon footprints by acting as a carbon sink and replacing cement, a major CO_2 emitter. Made from biomass waste through pyrolysis, biochar can be sustainably produced using renewable energy [30]. Life cycle assessments show that biochar-augmented concrete significantly lowers emissions compared to traditional concrete, promoting climate mitigation and sustainable construction practices.

4. Conclusion and Suggestions for Future Research

This paper provides a state-of-the-art review of the properties, production, and sustainability of biochar-enhanced concrete composites. It offers key insights into how biochar can improve concrete performance, promoting a more sustainable construction approach. The review aims to guide future developments in sustainable construction by focusing on enhancing the strength, durability, and environmental benefits of concrete. The conclusion can be summarised as follows:

The properties of biochar, shaped by its feedstock and pyrolysis temperature, play a crucial role in determining its impact on concrete strength, with higher pyrolysis temperatures producing more porous biochar.

Concrete workability is reduced due to biochar's water absorption; higher biochar content increases this effect, though adjustments like using superplasticisers can mitigate the reduction.

Biochar improves the durability of concrete by reducing water absorption, enhancing chloride resistance, and decreasing permeability, although excessive biochar content may have some negative effects.

While initial findings suggest significant improvements in strength and durability, the long-term performance remains inadequately explored. Essential factors such as carbonation, leaching, and degradation require in-depth investigation to assess the stability and reliability of biochar-based concrete over time. Further studies are necessary to refine biochar properties, explore its synergistic effects with other sustainable additives, and fully evaluate its potential in reducing the environmental impact of concrete.

The incorporation of biochar into concrete shows potential for enhancing carbon capture; however, the optimal concentration that balances carbon sequestration with mechanical strength remains underexplored. Further investigation is needed to determine the ideal dosage for different applications

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