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Application of biochar in concrete – A review

Sachini Supunsala Senadheera^{a,b}, Souradeep Gupta^c, Harn Wei Kua^{d,**}, Deyi Hou^e,
Sumin Kim^f, Daniel C.W. Tsang^{g,h}, Yong Sik Ok^{a,b,*}

^a Korea Biochar Research Center, APRU Sustainable Waste Management & Division of Environmental Science and Ecological Engineering, Korea University, Seoul, 02841, Republic of Korea

^b International ESG Association (IESGA), Seoul, 06621, Republic of Korea

^c Centre for Sustainable Technologies, Indian Institute of Science, Bangalore, 560012, India

^d Department of the Built Environment, College of Design and Engineering, National University of Singapore, 4, Architecture Drive, S117566, Singapore

^e School of Environment, Tsinghua University, Beijing, 100084, China

^f Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea

^g Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

^h Research Centre for Resources Engineering towards Carbon Neutrality, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

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ABSTRACT

The continuous rise in global temperatures is an evidence of climate change. CO₂ emissions have caused major problems owing to its contribution to climate change. In particular, the construction industry has a considerable carbon footprint. Therefore, investigations into climate change mitigation are indeed a priority. All steps in the construction process, from raw materials preparation to cement production, contribute to CO₂ emissions. This can be mitigated to a certain extent by incorporating bio-based constituents into construction materials. However, bio-based materials may negatively affect cement reaction and structural performance, despite their positive environmental impacts. Biochar, a carbon-rich product of biomass pyrolysis, is considered a potential substitute for cement replacement that can enhance structural properties if used in appropriate amounts. Although biochar has conventionally been used as a soil amendment in the agricultural industry, researchers have recently investigated its applicability in concrete. Importantly, the results thus far have reported its contribution to the enhancement of the mechanical, thermal, and physical properties of cement. This review provides a comprehensive overview of the physicochemical properties of biochar added cementitious materials, including the fresh and hardened properties of biochar-cement mixtures considering both environmental and economic aspects.

1. Introduction

The increasing human population and activities have caused many negative environmental consequences. Climate action is one of the Sustainable Development Goals (SDGs) emphasized by the United Nations. Carbon sequestration has been highlighted by every nation and needs to be addressed in the next few decades. Carbon dioxide (CO₂) is the major constituent of greenhouse gases (GHGs), and its emissions mainly result from human activities [1]. It is a key factor contributing to global climate change, and therefore, requires urgent and effective actions. As revealed by the 2014 Intergovernmental Panel on Climate

Change (IPCC) report, carbon capture and storage (CCS) have been introduced as a promising solution for the reduction of natural and anthropogenic CO₂ emissions [2]. In 2018, IPCC highlighted biochar as a readily available and scalable form of negative-emission technology [3].

Although industries related to mineral-based construction materials have advanced their production processes, reducing CO₂ emissions remains challenging [4]. Unless these challenges are addressed using multi-pronged approaches, problems will prevail owing to high GHG emissions. Therefore, it is important to move toward alternative construction materials with low carbon footprints which can significantly

* Corresponding author. Korea Biochar Research Center, APRU Sustainable Waste Management & Division of Environmental Science and Ecological Engineering, Korea University, Seoul, 02841, Republic of Korea.

** Corresponding author.

E-mail addresses: bdgkuahw@nus.edu.sg (H.W. Kua), yongsikok@korea.ac.kr (Y.S. Ok).

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mitigate climate change. Recent developments include the novel approaches of using biochar, a carbon-rich product of the thermochemical conversion of organic materials in the absence or limited presence of oxygen [5–7] as a potential material for the capture and storage of CO₂. Biochar is considered among the six most promising approaches for carbon sequestration because it can adsorb more than twice its own weight in CO₂ [8]. The physicochemical properties such as its elemental composition, stability, surface area, and surface functional groups, are affected by the pyrolysis temperature [9–12]. Various types of biochar have been utilized in a wide array of fields, including as soil amendments in agriculture [13], building materials [14–16], adsorbents for water pollutants [17–20], adsorbents for air purification [21,22], catalysts in biofuel production [23–25], as well as for biogas upgradation [26–28] and modern applications including electrical energy storage devices, such as supercapacitors and batteries [29]. According to statistics, the production of Portland cement, which is considered a main material for construction, contributes to 8% of the global CO₂ emissions. Furthermore, the emissions are expected to increase with the increasing of global population [30]. Therefore, it is necessary to consider alternative materials with low carbon footprints for construction [31]. Studies have revealed the use of supplementary materials for cement, including industrial and recycled construction wastes [32–35]. As the cement industry plays a major role in the production of GHGs, efforts are being made to reduce its impact on the environment using sustainable materials and practices. For example, the utilization of biochar in the construction and building industries has been identified as a promising approach to decrease carbon dioxide emissions and contribute towards achieving carbon neutrality [31,36]. It is noticeable that global cement manufacturing companies are making decarbonization efforts in relation to UN SDGs, ESG (Environmental, Social, and Governance) and sustainability. For example, ACC Limited, a major cement manufacturer in India, announced in 2021 its commitment to reduce carbon emissions by setting a target to decrease the CO₂ intensity in cement operations from 511 kg in 2018 to 409 kg CO₂ per ton of cementitious material by 2030 (mongabay.com).

Buildings designed with biochar containing materials may act as carbon sinks for years, whereas steel or concrete do not contribute to carbon capture [4]. Furthermore, the use of biochar is one of the most cost-effective approaches for CO₂ sequestration [37]. However, comparatively less information is available on the CO₂ sequestration potential of biochar [38]. Kafková et al. [39] revealed that 2.72 tonnes CO₂eq. could be sequestered using one ton of biochar. Biochar has been proven to improve the quality of materials, such as asphalt used for road construction. The use of biochar as a concrete admixture is an emerging trend in the construction industry [40,41]. Wang et al. [8] suggested that accelerated carbonation, also known as CO₂ curing, can generate hydration products that can subsequently transform into stable carbonates. The introduction of biochar can accelerate the carbonation process because of its enhanced pore structure, which aids in the diffusion of CO₂ [8].

Pyrolysis conditions and feedstock types are key factors that determine the suitability of biochar for application in concrete [42,43]. The pyrolysis temperature is directly proportional to the carbon content but inversely affects the biochar yield [14]. Properties such as water holding capacity, pore size and distribution, surface area, and cation exchange capacity depend on the type of the feedstock biomass [44]. Biochar is an appropriate construction material because of its high chemical stability and low thermal. Furthermore, the porous nature of biochar has been shown to contribute to its low thermal conductivity [41]. However, the release of acidic functional groups and formation of basic oxides during pyrolysis leads to an increase in alkalinity in cementitious materials, resulting in durability problems [44,45], and the use of biomass feedstock with a high mineral content results in low porosity owing to the blockage of micropores caused by the high ash content [46].

The above-mentioned issues are discussed in detail in this review, highlighting the performance of biochar as a construction material,

including the fresh and hardened properties of the cement-biochar composites, and discussing its future prospects in relation to mitigating major environmental issues.

2. Properties of biochar for application in construction

Biochar produced by biomass generally comprises cellulose, hemicellulose, lignin, and other organic compounds in varying proportions depending on biomass feedstock used [7,47]. These constituents exhibit porous structures [14]. Due to the high carbon content and porous nature of biochar, it exhibits high water demand, which can result in reduced workability [14]. However, this can be controlled by identifying the influence of the type of feedstock and the pyrolysis conditions (for example, temperature, pressure, and pyrolysis rate) on the distribution of pores in the microstructure (morphology) of biochar [48–52].

The chemical structure of biochar varies depending on the feedstock material and pyrolysis conditions. Generally, biochar is elementally composed of carbon, hydrogen, oxygen, small amounts of nitrogen and sulfur, and other micro elements such as calcium, zinc, potassium, magnesium etc. [53]. At relatively lower pyrolysis temperatures (300–450 °C) [54,55], the structure of biochar becomes more amorphous whereas the porous nature of biochar becomes more prominent at high pyrolysis temperatures (above 1000 °C) [56], with disordered and irregular arrangements [57]. Therefore, materials such as graphene with regular two-dimensional structure will not be formed [58].

2.1. Physical properties

The release of volatile matter during pyrolysis creates pores of different sizes. Previous studies have suggested that the pyrolysis temperature could have different effects on the surface structure of biochar [10,14]. Similarly, a study by Shaaban et al. [59] revealed the pore creation resulting from the release of volatile matter during pyrolysis can affect the surface area of biochar. However, the pore structure, number of pores, order, compact structure, and porosity of biochar change with increasing pyrolysis temperature [60].

A study revealed that straw biochars (e.g., rice, wheat) had more aligned honeycomb-like pore structures, whereas the surface of lignosulfonate biochar produced at temperatures of 400–600 °C had more cracks and holes. Regardless of the structural changes, studies have revealed that an increase in temperature increases the surface area and porosity of biochar [61]. A study by Ghani et al. [62] reported that biochars prepared from sawdust exhibited elongated and fibrillar structures, whereas softwood based biochars exhibited ridges and honeycomb pores.

It was found that the addition of mixed sawdust-derived biochar particle size less than 200 µm improved the properties of concrete specimens under normal and elevated temperatures [64]. The authors observed that biochar prepared at 500 °C had a wide range of particle sizes from 5 µm to 200 µm in contrast to the cement particles, the sizes of which ranged from 4 to 50 µm. However, a notable percentage of biochar particles were identified as finer than the cement particles, as the results showed that approximately 45% of the biochar granules were finer than 10 µm. In general, grinding is widely considered an important process that enables the size of biochar particles to be more compatible with that of cement particles. However, as shown in Fig. 1, grinding can alter the cellular structure of the biochar pores.

Gupta et al. [65] identified the porous structure and presence of ridge-shaped structures in biochar as the core reasons for the improved bonding with cement mixtures. During concrete preparation, the grounded biochar in the cement adsorbs part of the mixing water resulting in a decrease in free water in the pores of the matrix [64,65]. In addition, Gupta et al. [65] hypothesized that, at high temperatures the pores could act as pressure release valves by releasing water vapor. A study by Sirico et al. [66] concluded that adding 10% of waste wood-based biochar had no significant effect on the densities of concrete

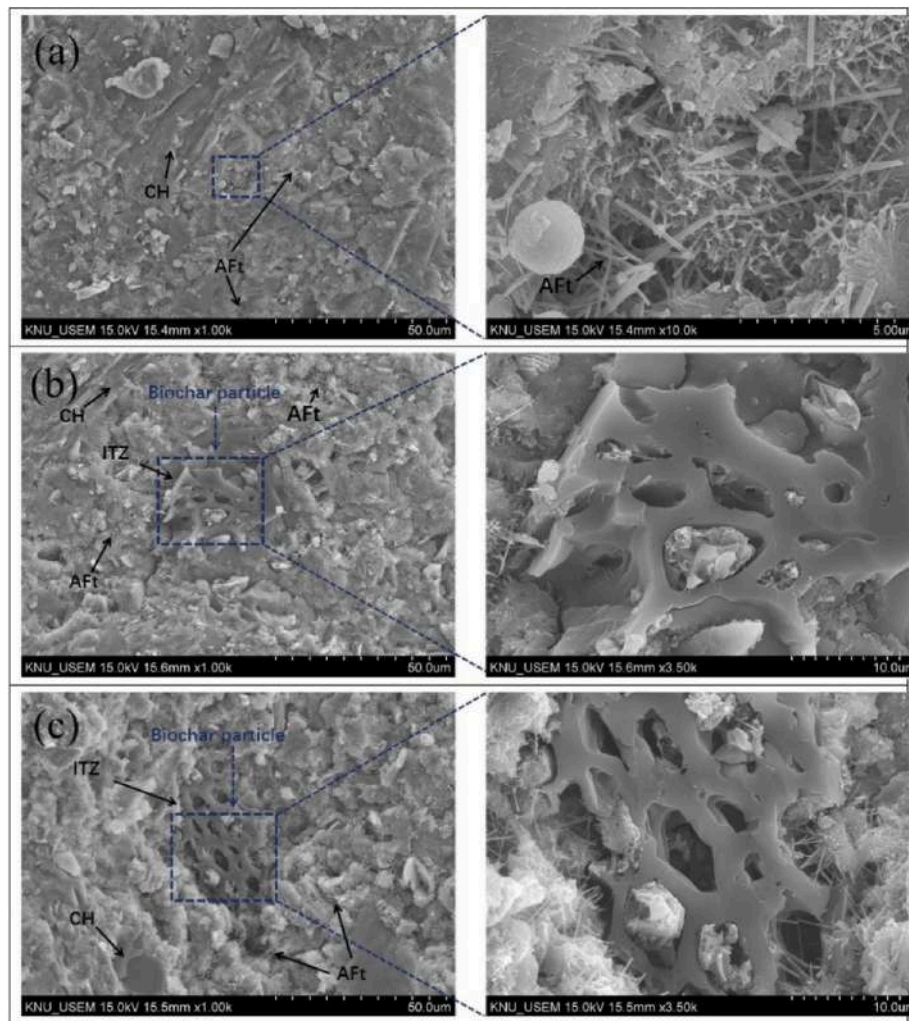


Fig. 1. Scanning electron microscopy (SEM) images of (a) control paste, (b) 2% rice husk biochar, and (c) 5% rice husk biochar [63].

specimens, but caused a maximum of 5% reduction in strength. However, Praneeth et al. [67] showed that with 40% biochar addition, the density of mortar decreased by approximately 20%.

Thermal bridging within the concrete was broken by the pores in biochar, causing enhancement of the thermal insulation and humidity control properties [68]. In addition to the microstructure, chemical stability also plays an important role when biochar is applied as a constituent of concrete in building construction. Studies have revealed that reactive oxygen groups and the stability of fixed carbon in the chemical structure affect the stability of biochar. The oxygen to carbon ratio (O:C ratio) is used as a parameter to designate a threshold for the relative stability of biochar. A study by Cross et al. [69] found that the complete removal of active oxygen-containing functional groups from the chemical structure at elevated temperatures contributed to higher stability. In addition, microspores were found to act as sites for water adsorption [70–72]. Pore size, pore volume, and pore surface area (physical properties) variations by different feedstock and pyrolysis conditions are summarized in Table 1.

2.2. Chemical properties

The key elemental constituents of biochar are carbon, hydrogen, and nitrogen (C, H, N) which make up more than 95% of the weight as well as small amounts of heavy metals and inorganic minerals such as Ca and Mg as shown in the Table 2. However, the contents may vary depending on the pyrolysis conditions and feedstock [16]. A study by

Muthukrishnan et al. [75] using rice husk biochar (RHB) identified, its high organic content as a key factor for the unfavorable effects upon its addition to mortar. Properties such as the hardness and toughness of biochar are related to the carbon content and therefore, a higher amount of biochar leads to a decrease in the toughness of the mortar mixtures [31]. Biochar with a higher density has a lower carbon content and can be added in higher dosages to cement mortar mixtures [64].

The proportions of cellulose, hemicellulose and lignin in the biomass feedstock are the deciding factors for the stabilization of carbon content in biochar [62]. The decomposition of cellulose occurs at higher temperatures than that of hemicellulose. A sawdust pyrolysis study conducted at 500 °C reported the decomposition of cellulose and hemicellulose at temperatures of 280–400 °C and 220–280 °C, respectively. They also noted that the elimination of the sources of sugars and labile groups is fundamental to the chemical stability of biochar [76]. Parihar et al. [77] showed that the pyrolysis of softwood and hardwood biomass at 500 °C resulted in the structure not containing phenol, alcohol, or methylene groups, which would otherwise influence the stability of cementitious mixtures [16].

The availability of inorganic elements such as calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), phosphorous (P), aluminum (Al), sulfur (S), silicon (Si), and chloride (Cl) depends on the biomass type. For example, it was revealed that there was less ash, K, Na, S, Cl, and Si but more Ca in woody biomass than in grass biomass [78]. Kim et al. [79] reported similar results for witchgrass, poultry litter, pine-wood, and willow. The inorganic mineral salts of K, Na, Mg, Ca, S, P, and

Table 1
Variations in physical properties (pore size, volume, and surface area) based on feedstock and pyrolysis conditions.

Feedstock	Pyrolysis conditions		Physical properties			Reference
	Pyrolysis temperature (°C)	Residence time (min)	BET surface area (m ² /g)	Average pore diameter (nm)	Total pore volume of pores (x 10 ⁻³ cm ³ /g)	
Rubberwood saw dust	300	60	1.8	7.4	3.2	[59]
	400	60	1.4	9.6	3.4	
	500	60	2.2	11	6.1	
	600	60	2.7	11.8	8	
	700	60	2.3	15.8	8.9	
	300	180	1.9	7	3.4	
	400	180	2.1	12.4	6.6	
	500	180	2	12.7	6.4	
	600	180	1.9	13	6.3	
	700	180	5.5	7	9.7	
Rice straw	300	20	2.1	18.1	9.5	[60]
	400	20	4.9	11.6	14.6	
	600	20	13.5	4.6	15.8	
	800	20	303.7	2.1	161	
Pine saw dust	300	180	1.3	9.9	3.4	[73]
	600	180	371.2	1.6	151.8	
Chicken manure derived biochar	300	180	4.0	20.5	20.6	
	600	180	86.6	4.3	94.2	
Maize straw	300	180	3.7	13.2	12.5	
	600	180	353.5	1.8	165.9	
Sewage sludge	400	120	33.4	9.4	783	[74]
	600	120	37.1	8.3	935	

Si were found to be in their oxide forms owing to the elevated pyrolysis temperature, along with an increase in the ash content [80]. Restuccia and Ferro [81] revealed that the hydration process could be accelerated through a potassium salt reaction with biochar containing a high amount of potassium, which would enable the evolution of mechanical properties. To avoid the environmental impacts and drawbacks related to cementitious composites with high heavy metal contents, the selection of a feedstock with a low heavy metal content is a key factor [82].

3. Influence of biochar on the fresh properties of cementitious composites

3.1. Rheology and workability

Workability can be defined in relation to rheology, which refers to the systematic study of flow. It is associated with rheological properties such as yield stress and viscosity [84]. Stability, mobility and compactability are the major rheological parameters defined based on forces or stresses. These rheological properties of biochar-cement, including static yield stress, dynamic yield stress and plastic viscosity, depend upon the particle size, dosage and porosity of biochar. For example, highly workable mixes susceptible to bleeding and/or segregation can be identified by monitoring their flow rates [85]. Because absorbed water does not chemically bond with the biochar particles, the addition of biochar causes the hydration process in the early stage of concrete curing to be favored [14]. Moreover, the water retention capacity of biochar results in improved material properties and concrete durability. Gupta et al. [41] found that although water was absorbed by biochar at an early stage, during the curing of concrete, the absorbed water was desorbed to the surrounding paste, this is known as the reservoir effect. This process leads to reduced permeability and improved hydration owing to internal curing. The addition of biochar enhanced the porosity of the cementitious mixture, which played a vital role in regulating the water content and the water distribution within the cement mixture. This finding is consistent with those of Sirico et al. [66]. Moreover, a study conducted to assess the hydration process of magnesia cement and magnesia-Portland binary cement incorporated with biochar revealed

that the carbonation process was further facilitated by CO₂ diffusion [8]. It has been reported that the replacement of more than 5% of the mass of cement with biochar can reduce the workability of mortar mixtures [14]. However, a study by Yang and Wang [63] reported a loss of workability even with a 2% biochar replacement.

Moreover, to obtain the desired workability the amount of biochar replacement to be used varies depending on the loss on ignition level of the specific biochar [14]. Based on the findings, it can be said that the loss of workability is mostly due to the elevated porosity of the biochar, which can absorb water during the mixing process.

The results of studies conducted by Gupta et al. [84] reported the time-dependent evolution of static yield stress of biochar-cement with two particle size ranges of biochar, prepared from coconut shell and wood waste – coarser biochar with median size range of 45–50 μm, and finer biochar with median size range of 10–18 μm. The authors found that the build-up of static yield stress in coarse biochar cement was 1.83–2.74 times of that with finer biochar at similar dosage (2% by mass of cement) and water-binder ratio (0.50). The difference was attributed to higher water absorption by macro-pores in coarser biochar particles, leading to reduction in water film thickness (WFT). WFT plays an important role in lubricating the surfaces of solid particles and reducing the yield stress of cementitious mixtures.

The same study reported the addition of 1 and 3 wt% of biochar resulted in an increase in yield stress at all measured time intervals (after 7 min and 43 min from the time of addition of mixing water). Over time, the yield stress increases as a result of a bridging network formed between particles due to cement hydration [86]. The study also found that the addition of 3 wt% biochar led to a 14–15% increase in shear stress at a shear rate of 100s⁻¹, compared to the control mix. Furthermore, at a significantly low shear rate of 5.35s⁻¹, the shear stress increased by 36% and 71% after 7 min and 43 min from the time of addition of mixing water, respectively. This increase in shear stress is attributed to the finer particle size and higher surface area of biochar, which enhances the contact between particle friction. However, the plastic viscosity of the control, 1 and 3 wt% added biochar did not significantly change with time due to minimal hydration during the first hour of mixing [84].

Table 2
Variations in chemical properties based on feedstock and pyrolysis conditions.

Feedstock	Pyrolysis conditions		Elemental composition									Chemical composition						Reference	
	Residence time (h)	Temperature (°C)	C	H	N	S (X 10 ⁻³)	Ca (X10 ⁻³)	Mg (X10 ⁻³)	Si (X10 ⁻³)	Al (X10 ⁻⁶)	Fe (X10 ⁻⁶)	SiO ₂	CO ₂	Al ₂ O ₃	SO ₃	MgO	CaO		Na ₂ O
Rice Husk	2	500	41.01	2.12	0.68	ND	130	110	19240	ND	0.06 (X10 ⁶)	15.77	82.57	0.03	0.05	0.08	0.04	0.19	[75]
Mixed Wood	1	500	79.86	2.65	0.76	0.02 (X10 ³)	0.13 (X10 ³)	0.58 (X10 ³)	0.15 (X10 ³)	0.06 (X10 ⁶)	0.16 (X10 ⁶)								[45]
Switchgrass		450	66.54	3.43	1.28	1.25	10.44	9.64	22.84	411	457								[79]
		600	71.52	2.53	1.13	1.33	14.61	11.8	29.38	533	797								
		800	71.62	1.16	0.86	1.91	17.51	15.02	37.18	427	633								
Pine wood		450	71.8	3.94	0.23	0.15	2.32	0.73	1.16	77.2	202								
		600	84.66	2.81	0.23	0.21	4.16	1.28	1.62	155	167								
		800	89.7	1.24	0.26	0.27	4.91	1.95	1.94	212	164								
Hardwood	2	300	48.64	6.8	0		0.36	0.04											[80]
		500	71.13	1.08	0		1.1	0.16											
		750	88.47	1.14	0.05		1.14	0.17											
	4	300	52.72	5.74	0		0.27	0.03											
		500	85.77	3.19	0.11		0.88	0.11											
		750	95.14	1.06	0.18		1.03	0.12											
	6	300	60.58	5.4	0		0.38	0.04											
		500	78.86	2.98	0.07		0.92	0.13											
		750	97	1.07	0.09		1.4	0.22											
Softwood	2	300	47.17	0.43	1.59		6.75	1.26											
		500	45.77	2.55	1.76		12.58	2.43											
		750	45.5	5.61	1.19		16.64	3.53											
	4	300	45.29	4.69	1.61		7.89	1.54											
		500	45.71	1.92	0.86		13.96	2.58											
		750	46.16	0.82	0		16.84	3.99											
	6	300	42.13	4.61	0.26		8.63	1.72											
		500	43.61	2.07	0		13.84	2.6											
		750	47.34	0.79	0.27		15.99	3.9											
Hazelnut shells	800	97.9		0.02 (X10 ³)	0.44 (X10 ³)	-	0.11 (X10 ³)	0.25 (X10 ⁶)							[83]				
Coffee powder	800	82.9		0.03 (X10 ³)	0.47 (X10 ³)	1.35 (X10 ³)	0.3 (X10 ³)	-											

3.2. Setting time

The setting time for cement composites includes the initial and final setting times. The initial setting time is when the cement mixture begins to lose its plasticity, which occurs from the point when it turns into a paste with the addition of water. The final setting time is the time at which the material gains a certain strength after completely losing its plasticity [87]. According to national standards, the initial and final setting times of Portland cement should not be less than 45 min (as it requires time to complete processes including casting) or greater than 6.5 h (to enable the hardening process).

Studies have revealed that the introduction of fine biochar particles increases the filler effect and water retention capacity as the spaces between the cement particles and sand are filled by the biochar which contributes to a lower setting time [87,88]. Gupta et al. [89] demonstrated a reduction in both the initial and final setting times (Fig. 2) using mortar-containing biochar (CO₂ adsorbed and non-CO₂ adsorbed). The resulting setting times were confirmed to be within standard limits.

The occurrence of carbonation is assumed to be the reason for the initial and final setting times being higher for CO₂ adsorbed biochar than for non-CO₂ adsorbed biochar. Meanwhile, the setting times decrease with the addition of biochar compared to the control without biochar.

3.3. Hydration kinetics

Several studies have revealed the effects of micro fillers on the rate of hydration. The degree of cement hydration and reaction kinetics have enhanced by the action of these micro fillers [87,88,90]. The primarily act as sites for heterogeneous nucleation leading to the formation of additional hydration products. Similar behavior was observed for biochar by Gupta et al. [89].

The early age strength of cement-based materials is influenced by the rate of hydration. There are two methods by which inert fillers can influence the hydration kinetics of cement. First, the replacement of clinker with fillers increases the space for the precipitation of hydration products. Second, the fillers themselves act as sites for the nucleation of hydration products [91]. The addition of biochar has a substantial impact on the hydration kinetics depending on its particle size, feed-stock, and preparation conditions. Gupta et al. [92] compared the hydration kinetics of cement pastes containing 2 wt% biochar prepared from sawdust, dairy manure, and cotton stalk. Sawdust biochar (MWBC) was prepared at 500 °C, dairy manure biochar (DM) was prepared at 600 °C, and biochar from cotton stalk was pyrolyzed at 210 °C (CS210),

250 °C (CS250), and 290 °C (CS290). It was found that the addition of MWBC led to a slight acceleration of cement hydration by 55 min compared to that of the control, and increased the peak heat associated with tricalcium silicate hydration. This is attributed to the nucleation effect of biochar as it offers surface area for the precipitation of hydration products. Due to finer size than cement particles, biochar granules can pack into the spaces between the cement particles and other solid grains. The negative charges on the biochar particle surfaces attract the positively charged clinker grains, where they form nucleation clusters, resulting in enhanced cement hydration [45]. However, the DM led to a substantial reduction in the peak heat with retardation of hydration. This was attributed to its high ash content (84.30% compared to 12% in MWBC) and the presence of phosphorus. Phosphorus can undergo dissolution forming an insoluble layer of calcium phosphate on the clinker grains. This acts as a barrier to moisture, limiting its interaction with the anhydrite clinker, which leads to a reduction in the hydration kinetics [93]. The addition of cotton stalk biochar, particularly CS210 and CS250, led to a slight retardation in and a prolonged induction period of hydration. Meanwhile, the addition of CS250 resulted in a 10% reduction in the hydration heat of the biochar-cement paste compared with that of the control. This is related to the presence of organic derivatives in the CS biochar, including levoglucosan, hydroxyacetone, and furan, which are formed by the dehydration of cellulose between 200 °C and 280 °C [94]. Depending on their amount in the pore solution, these acidic derivatives can inhibit cement hydration by lowering the pH or forming films around the clinker grains.

Dixit et al. [95] investigated the impact of biochar particle size on the hydration kinetics of cement paste prepared at a water-cement (W/C) ratio of 0.265. Three categories of biochar particles based on their size – coarse, medium and fine, were used as described previously. The biochar of each particle size were added to the cement paste in amounts of 2, 5 and 8% of the mass of the cement. The authors observed acceleration of cement hydration and a higher peak heat evolution (associated with C₃S hydration) at 5 h in the paste containing 5% fine biochar (F5) compared to those of the control (without biochar) Fig. 3a. Meanwhile, the cumulative heat of hydration, which represents the total hydration that occurs, increased by 30% due to the addition of coarse (>250 μm) biochar (Fig. 3b). The addition of 8% fine biochar (F8) resulted in the acceleration of the hydration by 10 h compared to that of the control (R1), although the cumulative heat evolution exhibited were similar (Fig. 3c–d). It should be noted that the peak heat appeared at a later time in the case of F8 (at 22 h) compared to that of F5 (8 h) because of the higher dosage of superplasticizer required to maintain workability

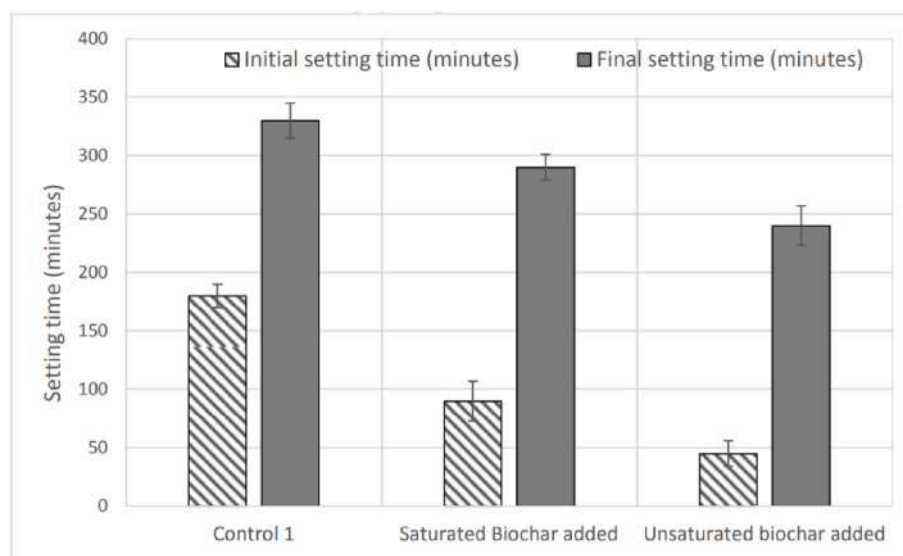


Fig. 2. Initial and final setting times based on the addition of CO₂ adsorbed and non-CO₂ adsorbed biochar [89].

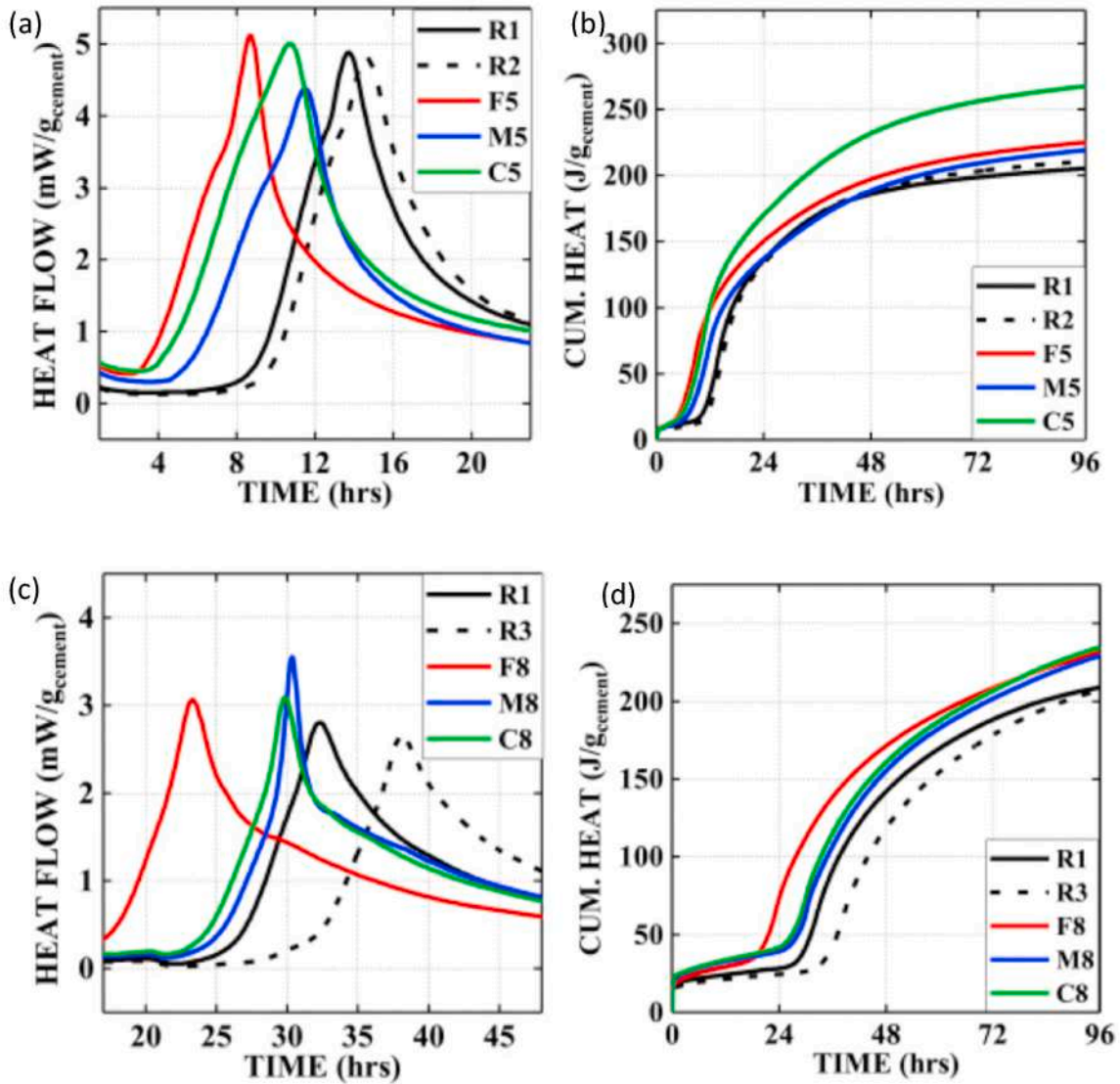


Fig. 3. Hydration heat evolution and cumulative heat profile per gram of cement with (a,b) 5% of coarse, medium and fine biochars, and (c,d) 8% coarse medium and fine biochar [95].

which retarded early hydration. The findings indicated the nucleation of cement hydration on the biochar surface and in the pores, which was also evident from the SEM images (Fig. 4).

To prepare low-carbon concrete, the binary blending of admixtures is often performed to reduce the consumption of Portland cement. In doing so, it must be ensured that the hydration kinetics are not compromised, which would otherwise affect the early development of strength and durability. Gupta et al. [92] studied the effect of a blended admixture comprising of 10% silica fume (SF) and 5% biochar by weight of cement (total cement replacement of 15% by weight) on the hydration kinetics of Portland cement paste at water-binder ratio of 0.50. Biochar was prepared from waste coconut shells (CBC) and wood waste (SWBC) from landscaping. A commercially procured biochar (TBC) was used for comparison. The median particle sizes of the CBC, TBC, SWBC and SF were 8, 4, 5 and 7 μm respectively, while that of cement was approximately 20 μm . Irrespective of the biochar type, the blend of biochar and SF led to an increase in the rate of heat evolution compared to that of control (without biochar), as measured by isothermal calorimetry, suggesting accelerated hydration of tricalcium silicate (C_3S). The cumulative heat evolution after 7 days of hydration was 20–22% higher than in the control, indicating that the blending of biochar and SF caused

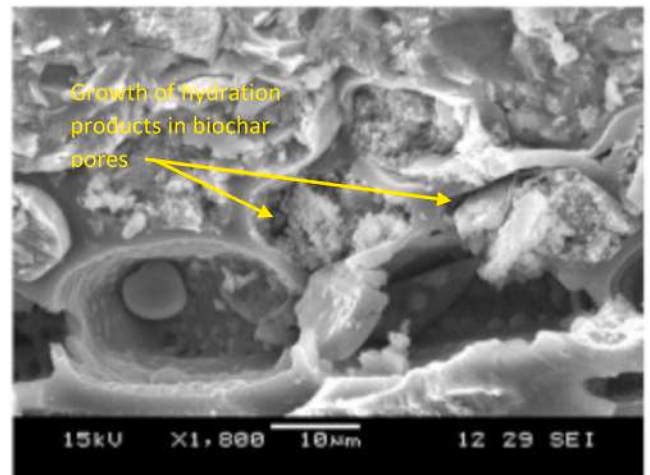


Fig. 4. Growth of hydration products in pores of biochar [95].

faster hydration. Pastes with only SF (15% by weight of cement) and biochar-SF composites both demonstrated similar rates of hydration, thus suggesting that biochar prepared with locally sourced wastes can be utilized to reduce the consumption of SF without compromising hydration. Many countries require SF to be imported, which increases transportation costs and emissions. Thus, the use of biochar to reduce the demand for SF offers a sustainable option for designing high-performance structural concrete. Gupta and Kashani [96] investigated the influence of a biochar (3% by weight of cement) and fly ash (FA 20% by weight of cement) blend on the hydration kinetics of cement paste at a water-binder ratio of 0.50. The median particle size of the biochar was 12.50 μm , lower than those of cement (19 μm) and FA (22 μm), respectively. Based on isothermal calorimetry, the combination of biochar and FA reduced the heat evolution associated with the accelerated phase of hydration compared to that of the control (plain cement paste), although a higher heat evolution compared to that of the FA-cement (no biochar) paste was observed. The reduction in heat evolution in comparison with plain cement paste is attributed to the dilution effect caused by the replacement of 23% of the cement with biochar and FA. This is beneficial for mitigating thermal cracking particularly when concreting in large quantities simultaneously in warm climatic regions (e.g., tropical regions and the Middle-East). The increase in early heat evolution compared to the FA-cement paste was due to the filler effect and nucleation of cement hydration on the biochar particles. The blending of biochar and FA resulted in a higher cumulative heat evolution in the first 24 h of hydration compared to the paste with only FA, but no discernible difference was observed after 7 days of hydration. The findings indicated that the nucleation effect of biochar particles was more prominent during the early stages of hydration than at later stages.

3.4. Fresh density and air content

The fresh and hardened properties of cement composites are affected by the density of biochar. In general, ordinary Portland cement has a higher density than biochar [97]. The density and porosity of materials are inversely proportional. When the pyrolysis temperature increased, the porosity increases, thereby lowering the density [98]. Therefore, it can be presumed that the voids present in the biochar are responsible for the reduction in density.

A study by Khushnood et al. [99] revealed that the flexural strength of a biochar-cement composite could be enhanced by using high density

hazelnut shell biochar. Gupta et al. [89] observed a slight reduction in the fresh density of the cement-mortar paste upon the addition of CO_2 adsorbed and non- CO_2 adsorbed biochar at 2 wt% of cement (Fig. 5). Under both conditions, the fresh density decreased slightly. According to their results, the CO_2 adsorbed biochar-mortar paste had a lower density than the non- CO_2 adsorbed biochar-mortar paste. However, the densities of the control specimens were higher than those of the biochar-supplemented specimens.

4. Influence of biochar on the hardened properties of cementitious composites

4.1. Mechanical strength and elastic modulus

The increase in the elastic moduli and hardness of cement-based composites was due to the formation of covalent bonds between the carbon atoms during pyrolysis. This process is favored with increasing pyrolysis temperature [100]. Several studies have reported a decrease in the elastic moduli of cement-based composites with an increase in the amount of biochar added [101,102]. However, this property of biochar could be useful for constructing flexible building materials in earthquake-prone areas [103].

4.1.1. Compressive strength

Choi et al. [14] investigated the effects of biochar on the mechanical properties of mortar. The authors replaced 5–20% by weight of the cement in mortar with biochar made of switchgrass and hardwood. The study revealed that replacing 5% of the cement with biochar increased the compressive strength by approximately 10% after 28 days (Fig. 6). However, it was also noted that due to the high-water retention capacity of biochar, the water demand of the reference mortar was lower than that of the biochar containing mortar. Additionally, it contributed to the internal curing of the mortar during the hardening phase.

Another study by Gupta et al. [89] also reported a 40% increment in the 7-day strength of concrete samples upon the replacement of only 2% of the mass of cement by mixed wood biochar. In addition, Gupta et al. [65] reported increases in 7-day compressive strength by 18, 13, and 10% upon the replacement of 0.50, 1, and 2% of the mass of cement, respectively, with biochar made from mixed wood sawdust pyrolyzed at 500 $^\circ\text{C}$. The study also reported strength increases of 16, 10, and 9% for 0.5, 1, and 2% biochar replacement respectively at 28 days. However, the strength improvement after 28 days was less than that after 7 days.

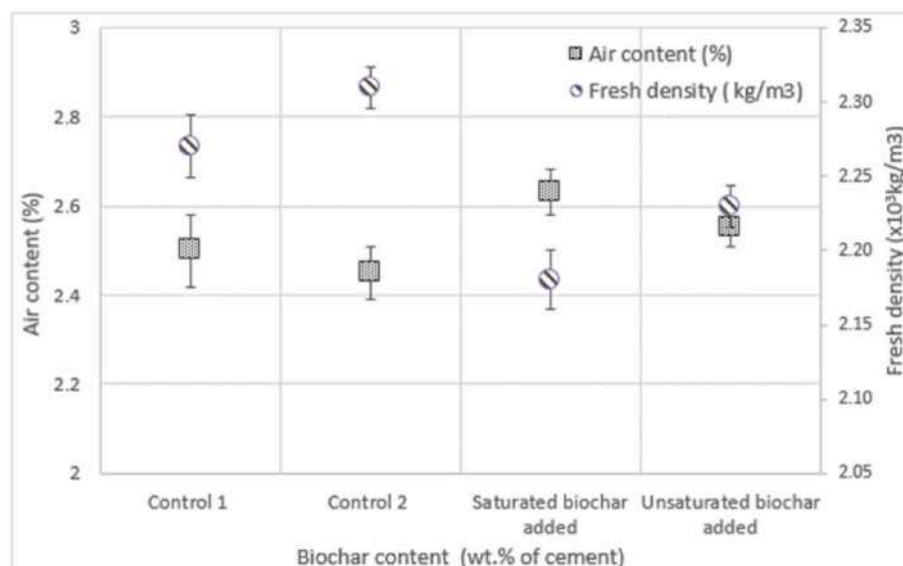


Fig. 5. Fresh density and air content of mortar paste with saturated and unsaturated biochar [89].

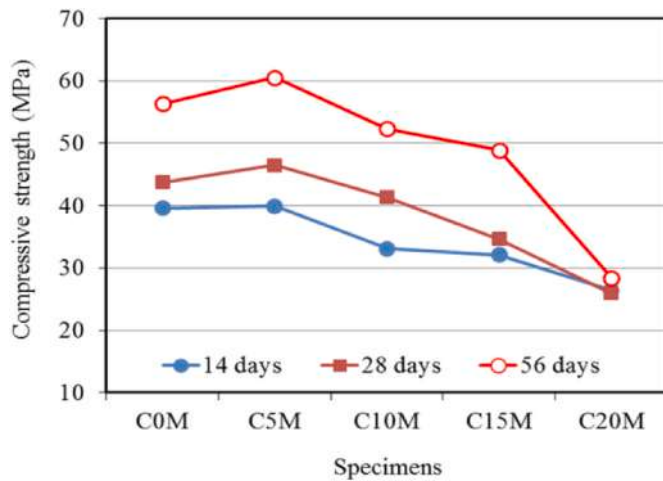


Fig. 6. Compressive strength [14].

Sirico et al. [66] investigated the effects of wood-waste-derived biochar on the composites under dry and wet curing conditions (Fig. 7) and observed an increase in compressive strength for all the curing times upon 5% replacement with biochar.

Park et al. [68]; investigated the effect of oilseed rape biochar and mixed softwood biochar on the compressive strength of mortar, by varying their mixing ratio between 2 and 8 wt%, and obtained the highest strength using 4 wt% (by weight% of binder) of biochar, regardless of the type of biochar. Similar results were reported by Kim et al. [104] for biochars made from n-octadecane-incorporated rice husks, spruce trees, and Miscanthus straw: the addition of 4% biochar increased the strengths of specimens, while 6% biochar degraded the strengths. Therefore, the authors concluded that replacing 4% of the mass of cement with biochar can enhance strength as well as thermal conductivity. However, as shown in Fig. 8, an increase in biochar content resulted in a decrease in thermal conductivity.

Samples with biochar made from spruce tree (ST), rice husk (RH), and Miscanthus straw (MS) are compared with samples containing artificial stone (AS), lightweight artificial stone (LAS), and PCM artificial stone (PAS) specimens, xGnP is a representative carbon material used for comparison with biochar. By contrast, a study by Yang and Wang [63] revealed an increase in compressive strength by 31.7%, 40.3%, and 40.5% from 7 to 28 d for RHB replacements of 0, 2, and 5% of the mass of cement, respectively. However, in all cases, the compressive strength improvement was low compared to that of the control specimen Fig. 9.

Chindaprasirt and Rukzon [105] conducted a study wherein they replaced 10–20% of the mass of cement with rice husk ash (RHA), and

reported a 2–3% increase in 7-day and 120-day compressive strengths. Additionally, they noticed a 20% reduction in strength when the amount of mass replaced was increased to 40%. Another study by Zeidabadi et al. [106] involving RHB revealed that a 5% replacement of cement with RHB enhanced the compressive strength by approximately by 12% compared to that of the control, which was attributed to the early age filler effect of the biochar particles.

However, the above studies revealed that increasing the biochar replacement rate causes the carbon percentage of the concrete to increase, which in turn increases the water demand, causing a reduction in the compressive strength.

4.1.2. Flexural strength

A study by Restuccia and Ferro [83] showed that 0.8% replacement of cement with hazelnut-derived biochar improved the flexural strength by 30% for both 7day tests and 28day tests. Moreover, an increase in the fracture energy was observed due to the tortuosity of the crack path caused by the biochar in the cement matrix.

Khushnood et al. [99] observed resistance to crack propagation in cementitious composites when 1% biochar (peanut shell and hazelnut shell) by mass was introduced, which caused an improvement in their flexural strength and toughness. Ahmad et al. [107] reported similar findings, they found that an addition of 0.08 wt% bamboo-derived biochar by weight of cement enhanced the toughness and flexural strength of cement composites. Praneeth et al. [67] reported that the addition of 20% poultry litter-based biochar to replace 10–40% sand (fine aggregates) increased the flexural strength by 26% compared with that of the control mortar (Fig. 10). Compressive and flexural strength of construction material containing biochar feedstock are summarized in Table 3.

4.2. Degree of hydration

The moisture exchange between porous admixtures and cement paste contributes to moisture regulation and internal curing action. Typically, biochar comprises a wide range of pore sizes, including micropores (<2 nm), mesopores (2–50 nm), and macro-pores (>50 nm to several microns) according to the IUPAC classification [109]. These pores absorb part of the mixed water during concrete preparation and retain it at an effectively lower W/C ratio around the biochar particles. Furthermore, external pores, which are the pore spaces between biochar particles, and residual macropores, which range in size from 1 to 100 μm and are inherited from the vascular structure of plants, also contribute significantly to water absorption and retention [70]. As the concrete hardens, the internal relative humidity decreases, and moisture from the biochar pores can be released under the humidity gradient [43]. This mechanism serves two functions: the initial capillary porosity in the

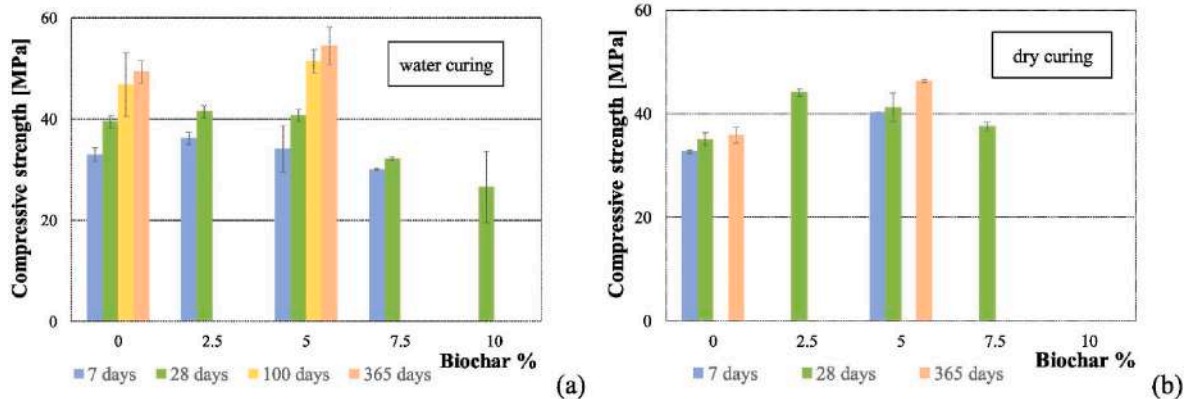


Fig. 7. Average compressive strength (and corresponding standard deviation) for different curing times and conditions (water (a) and dry (b)) with increasing biochar (wood waste) additions [66].

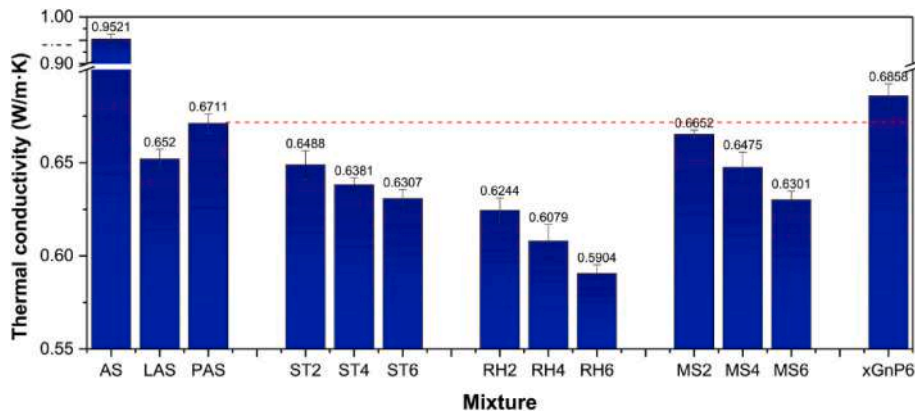


Fig. 8. Results of thermal conductivity test [104].

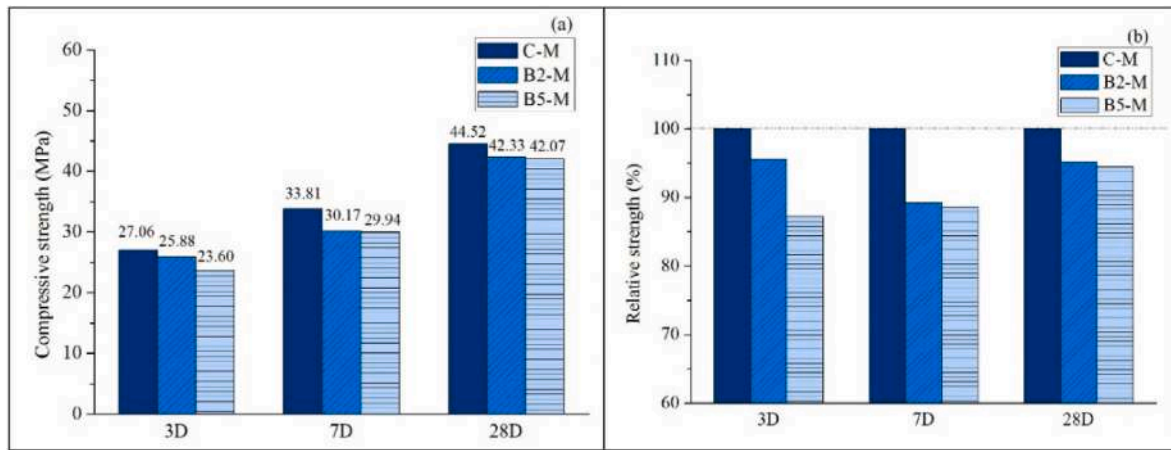


Fig. 9. Compressive strength and relative strength comparison [63].

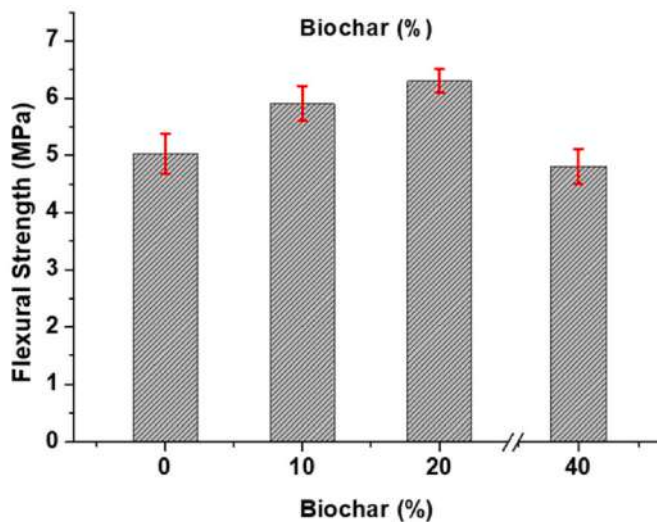


Fig. 10. Flexural strengths of cement-sand-biochar mortar as a function of biochar percentage at 28 days curing [67].

cement paste is reduced due to a decrease in the effective W/C ratio, and the released water can trigger the hydration of unhydrated clinker in the vicinity of the biochar particles via the internal curing effect. This improves hydration and the development of mechanical and durability properties. For instance Gupta and Kashani [96], investigated the degree

of hydration of cement paste with the addition of 1% and 3% of biochar, prepared from waste peanut shells. The prepared biochar had a total porosity of 34% (based on mercury intrusion porosimetry) and a pore surface area of 2.78 m²/g (based on nitrogen adsorption). The authors found that the degree of hydration of cement paste improved by 6–12% owing to the addition of 1% and 3% biochar 3 days and 7 days after mixing. This was further confirmed by X-ray diffraction (XRD) analysis, the spectra of the pastes with biochar showed a noticeable increase in the peak intensity corresponding to calcium hydroxide compared to that in the spectrum for the control. In the study, the pastes were subject to sealed curing. Similar results were reported by Dixit et al. [95] who investigated the effect of the biochar particle size on the degree of hydration of cement pastes designed at a W/C ratio of 0.265, which is representative of ultra-high performance mortar. Biochar was prepared from mixed wood sawdust pyrolyzed at 500 °C. The cooled biochar was crushed and sieved to obtain three different particle sizes – 1) Coarse (C; 250–500 μm), 2) Medium (M; 125–250 μm), and 3) Fine (F; <125 μm). Thus, prepared biochar was then used to replace 2% and 5% of the mass of cement. The degree of hydration, measured based on thermogravimetric analysis and Bhaty’s method, improved by 10–15% upon the addition of the biochar particles, irrespective of their sizes. For instance, while the control paste (without biochar) exhibited degrees of hydration of 40% and 43% at 7-day and 28-day age respectively (similar to those reported in the literature), the paste with 5% fine biochar exhibited degrees of hydration of 54% and 58% respectively. Gupta [110] found that the incorporation of 2.5% biochar by weight of cement led to a 3% increase in calcium hydroxide (CH) content in 7-day aged cement paste prepared at a W/C ratio of 0.40. This translates to a 6% increase in the

Table 3
Compressive and flexural strengths of construction material containing biochar feedstock.

Construction material	Feedstock	Pyrolysis conditions	Compressive strength (MPa)			Flexural strength (MPa)			Reference
			7-day curing	14-day curing	28-day curing	7-day curing	14-day curing	28-day curing	
Ordinary Portland Cement	Poultry litter	450C at a residence time of 20min	21	27	33			5	[108]
	Pulp and paper mill	500C	27	31	36			4	
	Rice husk	500C at a residence time of 20min	26	30	35			5	
Cement mortar	Mixed wood	500C at a residence time of 45–60min	40		58	11		13	[64]
	Food waste	500C at a residence time of 45–60min	36		54	10		13	
	Rice waste	500C at a residence time of 45–60min	36		45	9		11	
	Mixed saw dust	300–500C	67	70	73			13	[43]
	Rice husk	500C	55		65				[75]

degree of hydration, attributed to the internal curing and nucleation effects of biochar particles. However, the generation of CH in biochar–cement mixtures is also dependent on the type of feedstock used [111]. For example Yang and Wang [63], found that using 2% and 5% biochar, prepared at 450–550 °C from rice husk, resulted in a reduction in CH content based on thermogravimetry analysis. This can be attributed to the presence of amorphous silica in rice husk, which can convert CH into calcium silicate hydrate.

4.3. Autogenous and drying shrinkage

The deformation of cement composites resulting from moisture exchange between the external environment and composites is generally defined as drying shrinkage. Furthermore, the autogenous shrinkage caused by self-desiccation is indicated by sealed shrinkage [75]. According to Choi et al. [14], both plastic shrinkage and drying shrinkage can be reduced with the addition of biochar, as it reduces water evaporation from the concrete. However, Sirico et al. [66] reported that adding 5% biochar to concrete specimens did not result in significant changes in shrinkage compared to those of plain concrete specimens when strain measurements were taken up to 60 d after casting (Fig. 11).

Muthukrishnan et al. [75] studied drying and autogenous shrinkage using Rice Husk Ash (RHA) and Rice Husk Biochar (RHB), and reported high autogenous shrinkage compared with other cement mortar composites. This implies that the hydration process continues owing to the drawing of capillary water. The results of the study indicated that higher shrinkage was observed in the LabRHA20 (RHA produced under controlled laboratory conditions) than in the TRHA20 (thermally

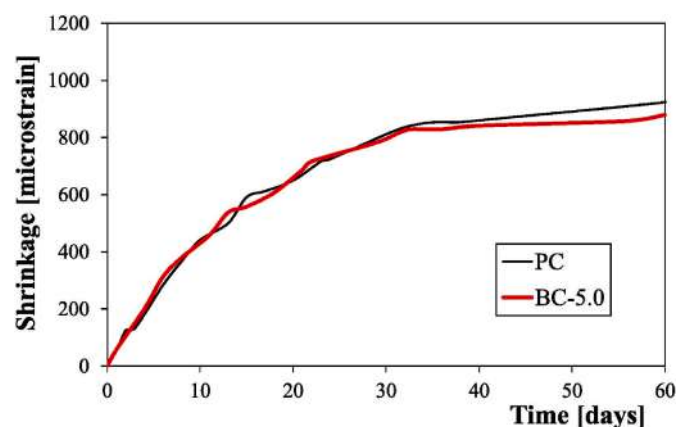


Fig. 11. Development of shrinkage strain with time for plain and 5% biochar-added concrete [66].

treated RHA) after the first 7-day period. During the 7-day monitoring period, both LabRHA20 and TRHA behaved as fillers because the pozzolanic reaction was slower. However, after the initial 7-day period, high amounts of CH were generated, which accelerated the pozzolanic reaction and caused the LabRHA to exhibit higher shrinkage. However, notably, mixtures of the RHA and RHB exhibited a net expansion, suggesting that their addition could avert the early-age shrinking-induced cracking of mortar (Fig. 12).

4.4. Permeability

The water-retention capacity of cement is enhanced by the addition of biochar owing to its pores, which can absorb water. Water permeability (BS EN 12390–8), water sorptivity (ASTM C1585), and water-accessible porosity (ASTM C642) tests were performed. Capillary absorption is categorized into primary and secondary absorption, depending on the rate and mechanism of water uptake. Water uptake by small capillary pores and micropores within the first 24 h is defined as primary (or initial) absorption, whereas absorption after 1 d is defined as secondary absorption.

A study by Gupta et al. [71] revealed that the incorporation of 1–2 wt % of RHB and mixed SWBC biochar into cement mortar could reduce its water permeability. Furthermore, it was found that the 7-day, 42-day, and 120-day strengths increased by 15–18% and 9% after 120-day exposure. The lower permeability resulted from sodium chloride absorption, which reduced the rate of mass gain owing to the addition of biochar.

A study by Muthukrishnan et al. [75] reported that the addition of 20% RHA (RHA20) increased capillary absorption by approximately 30% compared with that of the control specimen. Furthermore, while the initial absorption showed a similar pattern for both specimens, the secondary absorption was more prominent in RHA20. The combination of RHA and RHB reduced the total absorption compared with that of the control specimen (Fig. 13). Moreover, studies have revealed that the initial absorptivity can be significantly reduced by adding 2 wt% of biochar [64,89].

5. Environmental benefits of biochar-cement composites - carbon sequestration

The carbon in the structure of the biochar is accounted for in the embodied carbon of the material. This is influenced by several factors, including feedstock, pyrolysis conditions and utilization of other co-products including bio-gas and bio-oil. For instance, findings from Roberts et al. [112] suggest that depending on feedstock and preparation conditions, biochar has the potential of reducing net greenhouse gas emissions by about 870 kg CO₂ equivalent (CO₂-eq) per ton dry

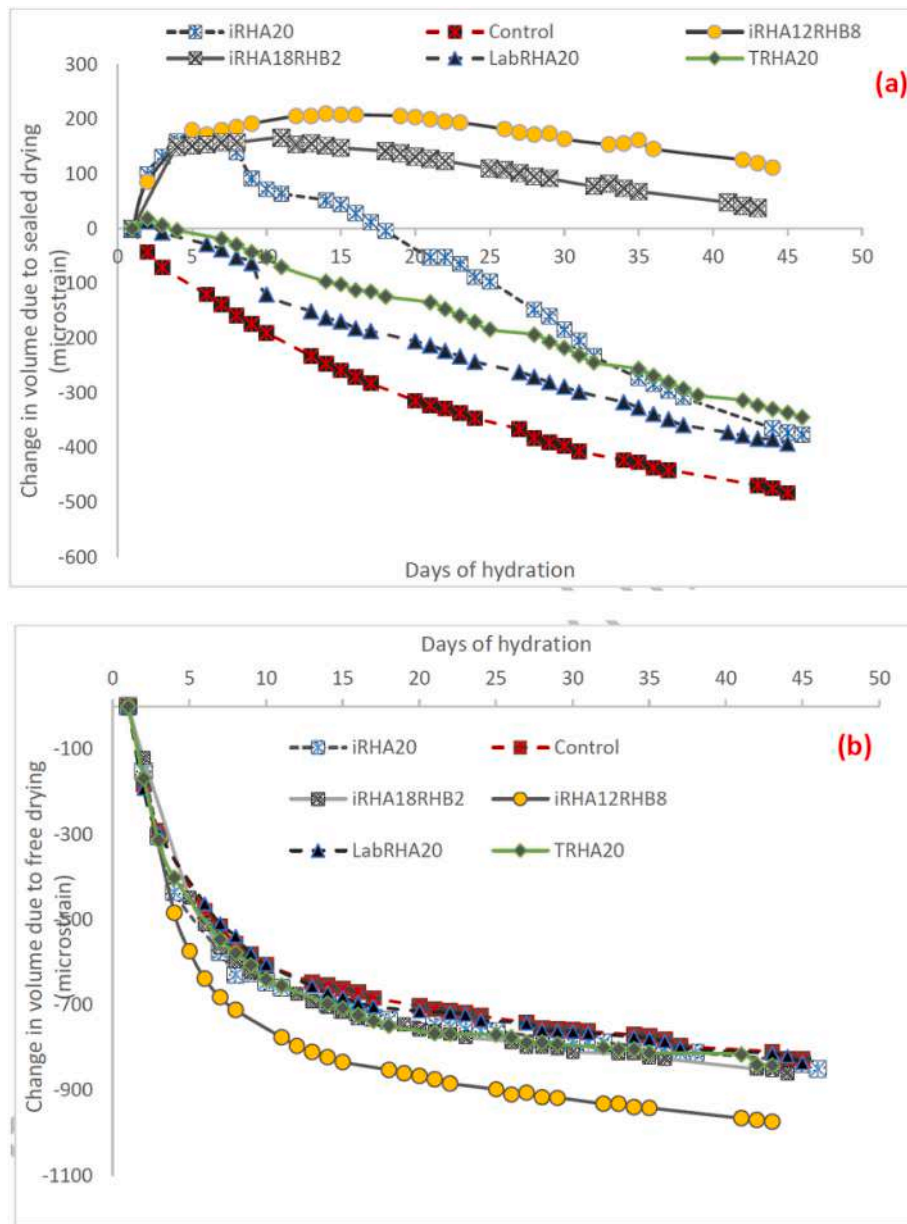


Fig. 12. a) Sealed shrinkage and (b) drying shrinkage of mortar composites with RHA and RHB [75].

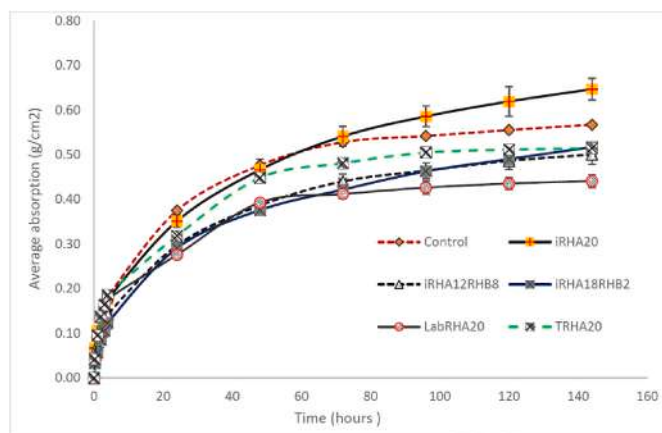
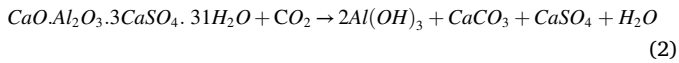


Fig. 13. Capillary absorption of water by RHA-mortar and RHB-mortar composites [75].

feedstock, of which 62–66% are realized from CCS by the biomass feedstock of the biochar [112]. Additional reduction will be possible by allowing biochar to capture CO₂ and utilizing bio-oil and syngas to offset some of the fossil fuel demand [112]. Storing the fixed carbon in biochar-cement will further reduce the embodied carbon of future constructions depending on the dosage of biochar. Additionally, it could be used as a promising solution for waste management, promoting waste recycling and reducing waste disposal. The cement industry can be identified as one of the largest greenhouse gas emitters causing serious environmental impacts. The use of biochar in cement composites is identified as a potential advantage in construction engineering.

The carbon storage in biochar-cement composites depend on the adsorption capacity of the biochar, diffusion of CO₂ through the pores in hydrated cement matrix and the carbonatable products, including calcium hydroxide (CH) and calcium silicate hydrate (C-S-H). Gupta et al. [45,110,113] found that biochar acts as nucleation sites for hydration resulting in generation of additional hydration products, including CH and C-S-H, which can react with CO₂ to form calcium carbonate (Equations (1) and (2)). Furthermore, biochar increases the affinity for

CO₂ capture, attributed to its high surface area and micro-pore volume, resulting in higher CO₂ capture compared to control (without biochar) [110].



A portion of the CO₂ emitted during the production of cement is absorbed by cement composites during the carbonation process. The CO₂ thus absorbed is stored in the form of calcium carbonate [114,115]. Studies have identified biochar as an excellent CO₂ adsorbent due to the high content of surface pores and its affinity to non-polar compounds [89]. Biochar consists of micropores with pore size less than 2 nm diameter are capable of adsorbing gases and solvents [116]. Wei et al. [117] calculated that 300 kg of CO₂ equiv. can be captured per ton of feedstock biomass with the advantage of CO₂ adsorption capability. Additionally, studies have shown that the physical, chemical, and morphological properties of biochar remain unchanged following CO₂ adsorption [62,118]. However, it was confirmed using XRD and thermogravimetry analysis that carbonation by the adsorbed CO₂ leads to reduction in late strength [89]. Furthermore, they revealed that biochar saturated with CO₂ activated the internal carbonation, leading to loose bonds with the mortar paste. The SEM images in Fig. 14a and b clearly show the gap between the biochar particle and the mortar paste interface. The interface gaps enhanced the void spaces, favouring more hydration products, which eventually affected the mechanical strength development of the cement composites. Johannesson and Utgenannt [119] also observed micro cracking and debonding in the mortar due to the volume expansion caused by the transformation of calcium hydroxide and calcium silicate hydrate to calcite.

Carbon sequestration via accelerated carbonation curing (ACC) has been widely investigated to decrease carbon emission associated with Portland cement-based construction materials [120,121]. In this process, prefabricated cement-based materials are exposed to high concentrations of CO₂, typically in the range of 1–20% (1000–200,000 ppm), under controlled humidity and temperature conditions within the first 24–48 h of casting [96,120,122]. This leads to the reaction of CO₂ with calcium calcium-bearing phases, resulting in the formation of calcium carbonate minerals. Through this method, it was deduced that CO₂ from industrial flue gas streams could be captured in a cementitious matrix through ACC, although further investigation is necessary to investigate CO₂ capture from mixed gas streams (such as flue gas). It is to be noted that for a certain concentration of CO₂, carbon sequestration through ACC depends on the transport channels in the material matrix and hydration products, which in turn, are influenced by the density and mix composition of the cement blocks. Owing to its high micro-pore volume and surface area, depending on the preparation conditions, the addition of biochar can increase the affinity for CO₂ uptake in cementitious building materials. Several studies have investigated carbon sequestration in biochar-based normal-density and lightweight mortars [31,67,96,110]. Gupta et al. [113] reported that the addition of 3 wt% of cement resulted in a 3–6% increase in carbonate mineralization compared to that of the control at ages of 7 d and 28 d. Carbon sequestration in biochar-mortar also led to a reduction in water accessible porosity and a 13% increase in compressive strength compared to those of the control after 7 d of carbonation. The study also investigated the effects of the replacement of 23 wt% cement with biochar and FA (20% of FA and 3% biochar) (FA20BC3) on carbon sequestration; the results showed a 5–7% enhancement in carbon sequestration compared to that of the control with only FA (no biochar; FA20) without compromising strength development. In addition, the chemical shrinkage associated with carbonation was drastically reduced in FA20BC3 compared to FA20 after exposure to 2% CO₂ for 28 days, 56 days and 77 days. Similarly Praneeth et al. [123], found that a combination of 20% FA and 2–4% biochar prepared from corn stover resulted

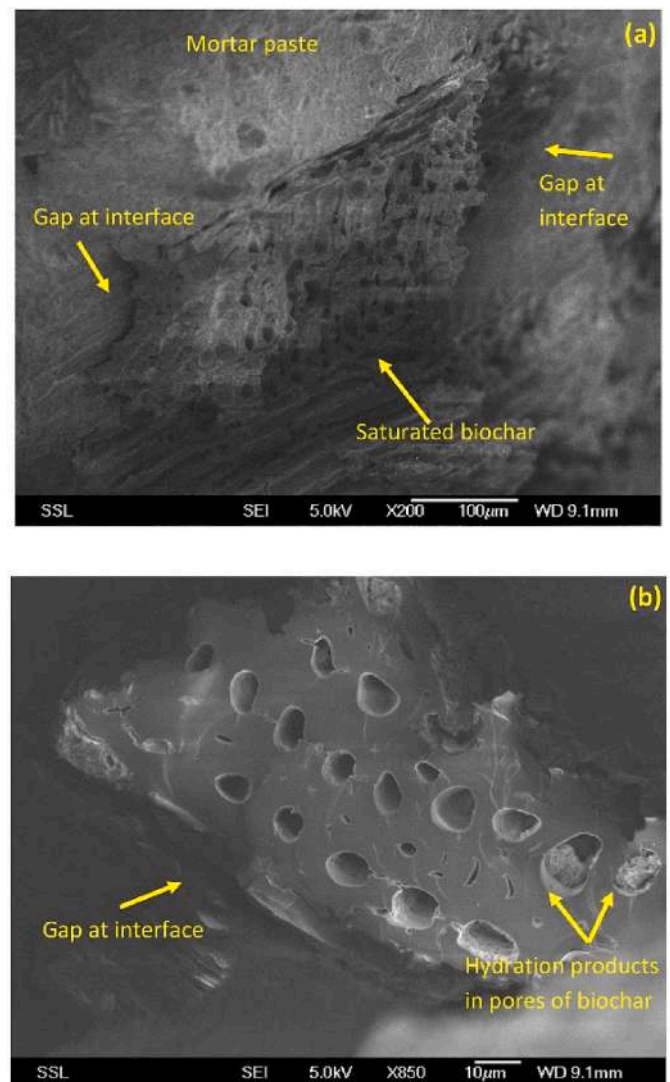


Fig. 14. SEM images of (a) of interface of biochar particles and mortar paste at magnification of 200X (b) deposition of hydration products in the pores of biochar products and gaps at the interface at a magnification of 850X [89].

in higher mass gain after 2 h of carbon dioxide exposure than when the mortar contained only FA (control), which was attributed to an increase in the mineralization of carbonates owing to the addition of biochar. The compressive strength of carbonated biochar-FA mortar was 17.60% higher than that of carbonated mortar containing only FA. The authors attributed this to the higher CO₂ uptake by the porous sites in the biochar, resulting in greater conversion of calcium hydroxide to calcium carbonate. This conversion was associated with an 11.80% increase in molar volume [124], leading to pore filling and strength enhancement.

Gupta [110] investigated a means for the internal carbonation of cement mortar by introducing pre-adsorbed CO₂ into the micropores of biochar prepared from SWBC. The adsorption capacity of biochar was measured to be 1.30 ± 0.21 mmol of CO₂ per gram of dry biochar. The mentioned approach led to improvement in the 7 day compressive strength of the mortar by 23% compared to that of the uncarbonated control (without biochar). This was attributed to two factors: densification owing to the filler effect of the biochar and the precipitation of carbonation products triggered by the adsorption of CO₂ in the biochar pores [110]. These findings demonstrate the potential of using spent biochar in cement-based materials. Wang et al. [31] investigated the effects of ACC at 100% CO₂ for 24 h on the physical properties of biochar cement-based composites and found that ACC resulted in accelerated

hydration and the formation of calcium carbonate, which led to an enhancement in strength by 75% and 66% in biochar-cement blocks aged 2 and 7 day, respectively, compared to those of the reference specimen.

6. Conclusions

The type of biomass feedstock and pyrolysis conditions can have significant influence on biochar properties. Furthermore, process conditions and parameters, such as pyrolysis temperature, rate, and pressure, can affect the structure of the biochar produced. The biochar particles exhibit excellent structural compatibility with the cement matrix, which is further confirmed by SEM analysis. However, many studies have reported that biochar properties, including its chemistry and surface functional groups, vary over time because of factors such as oxidation and aging. When considering long-term behavior, the improvement in compressive strength was more prominent under drying conditions.

Additionally, internal curing in concrete mixtures is favored as it enhances cement hydration under drying conditions. Over time, the water restrained in the biochar pores is released, promoting strength development. Although chloride diffusivity, electrical resistivity, and number of meso-sized air voids increased with increasing biochar content, the strength, hydration heat, degree of hydration, and workability decreased. The porosity of the cement paste affects its permeability and water absorption rather than the porosity of the aggregate: the lower the porosity of the paste, the lower the permeability and water absorptivity. Replacement of more than 5% of the mass of concrete with biochar is not advisable as it negatively affects strength development. Engineered biochar, such as biochar saturated with CO₂, can be used as a constituent of concrete mixtures. This carbon capture and storage concept [125] may be beneficial in the long term; however, it is vital to study the effect of absorbed/adsorbed CO₂ on the structural durability issues caused by carbonation in reinforced concrete. Furthermore, methods to regulate and improve adsorption processes require modifications that can enhance the adsorption capacity. Additionally, few studies have reported that mixing biochar with biofilters enhances its adsorption capability for environmental remediation.

Moreover, it is important to study the environmental, social, economic, and financial benefits of employing biochar in construction. In conclusion, this review suggests biochar as a promising sustainable additive to improve the durability of structural concrete, which can promote waste recycling, reduce carbon footprint, and mitigate climate change.

Author contributions

Sachini Supunsala Senadheera: Data collection, Formal analysis, Investigation, Writing- Original Draft, Writing - Review & Editing.

Souradeep Gupta: Discussion, Writing - Review & Editing.

Harn Wei Kua: Discussion, Writing - Review & Editing.

Deyi Hou: Discussion, Writing - Review & Editing.

Sumin Kim: Discussion, Writing - Review & Editing.

Daniel C.W. Tsang: Discussion, Writing - Review & Editing.

Yong Sik Ok: Conceptualization, Discussion, Theoretical framework, Supervision - Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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