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Review

Biochar in cementitious material—A review on physical, chemical, mechanical, and durability properties

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Abstract: Ordinary Portland Cement (OPC) is a crucial building component and a valuable strategic resource. The production of cement accounts for 5% to 10% of global carbon dioxide (CO_2) emissions. Over the years, many researchers have been studying ways to reduce the amount of CO_2 in the atmosphere caused by cement production. Due to its properties, biochar is found to be an interesting material to be utilised in the construction industry due to its effectiveness in CO_2 sequestration. Biochar is a solid residue created by the thermal breakdown of biomass at moderate temperatures (350–700 °C) without oxygen or with a small amount of oxygen, sometimes known as bio-carbon. Biochar has a wide range of uses, including those for heating and electricity generation, cleaning flue gases, metallurgy, animal husbandry, agriculture, construction materials, and even medicine. The objective of this paper is to review the potential of biochar as a cementitious material by evaluating its physical, chemical, mechanical, and durability properties. Using biochar as a cementitious material makes it possible to conclude that cement production will be reduced over time by partial replacement, which will also promote and encourage sustainable development in the future.

Keywords: cement; biochar; physical properties; chemical properties; mechanical properties; durability properties

1. Introduction

Ordinary Portland Cement (OPC) is an indispensable building material and a key strategic resource [1]. There are more than 10 distinct types of cement, each having its own composition and intended use [2]. Cement can also serve as a binder for aggregates in concrete manufacturing [3]. Up to 10% of the world's carbon dioxide (CO_2) emissions result from cement production [4]. Over the past century, Portland cement (PC) production has expanded rapidly and now exceeds 4 billion tonnes per year [5]. As a result of its energy-intensive manufacturing process, cement production generates substantial greenhouse gas (GHG) emissions [6]. The cement industry alone is responsible for about a quarter of all industries for the emission of CO_2 which is also estimated to be the highest CO_2 emission [3]. According to environmental and yearly reports of major Western firms (Cemex, Heidelberg Cement, and La-fargeHolcim), 561 to 622 kg of CO_2 are released each tonne of cement manufactured [7]. The combustion of fossil fuels in kilns, the use of electricity to mill raw materials and final products, and the clinkerization of primary raw materials such as limestone, produce these carbon emissions [8]. As it is well acknowledged, CO_2 emissions are a key source of global warming and climate change, which can have negative effects on humans and the environment [9–11]. Moreover, anthropogenic carbon emissions, which are currently between 5% and 7%, could frighteningly reach 27% by 2050 [12,13]. Furthermore, with annual emissions of nearly 500,000 tonnes of sulphur dioxide, nitrogen oxide, and carbon monoxide, the cement sector is the third most polluting industry [6]. The cement industry’s air pollution can penetrate deeply into the respiratory system, leading to respiratory infections and illnesses, lung cancer, and certain cardiovascular problems [14].

Worldwide research has been conducted to develop mitigation plans to reduce CO_2 emissions from cement-producing industries while maintaining cement's performance [15]. Numerous research concentrates on energy efficiency, technological innovation, environmental protection in cement production, and alternative fuels and materials [16–21]. According to Patrizio et al. [22], biomass can also be used for CO_2 mitigation and removal due to its adaptability. Biomass is expected to fulfil 15% to 50% of the world’s energy demand by 2050 [23,24]. Nonetheless, the combustion of this biomass also contributes to global warming [25]. Biomass combustion is a significant source of air pollution, affecting climate, human health, and air quality at the national, regional, and local levels [26]. If this high-organic biomass waste is properly processed or diverted for waste-to-energy options rather than being burned, there is no doubt that biomass contributes to climate change mitigation by reducing greenhouse gas emissions [27]. Thomas et al. [28] indicate that biomass byproducts, when burned under appropriate conditions, contain large quantities of silica, can work as a renewable energy source with high pozzolanic qualities, and can also serve as filler when finely powdered. Pyrolysis is regarded as a viable technology for residual valorisation by turning biomass waste into biochar [29]. Important characteristics of pyrolysis and co-pyrolysis [23] include the management of waste streams, elimination of hazardous wastes, reduction of environmental pollution, and conversion to a closed-loop system. This study reviews recent research findings with a primary focus on the use of biochar in concrete and cement mortar. Moreover, a discussion of the classification and evaluation of the physical, chemical, mechanical, thermal, and durability qualities of biochar in concrete and cement mortar is also included.

2. Biochar

Biochar is a solid residue created by the thermal breakdown of biomass at moderate temperatures (350–700 ℃) without oxygen or with a small amount of oxygen, sometimes known as bio-carbon [30]. Biochar is produced by the pyrolysis of biomass and it has the capability to mitigate climate change through carbon sequestration [31,32]. The biochar yield is influenced by the pyrolysis circumstances, such as temperature, heating rate, duration, and pyrolysis type, as well as the physical and chemical composition of the biomass [33]. The basic categories of thermochemical processes are pyrolysis, hydrothermal liquefaction, gasification, and combustion/incineration, and these processes convert biomass into bio-oil, charcoal, gas, and other value-added products through the use of heat and oxygen [34]. Pyrolysis is the thermal breakdown of biomass by heat in the absence of oxygen, which produces fuel gas, bio-oil, and charcoal as solid and liquid products [35]. As a method for utilizing biomass for energy, pyrolysis is widely regarded as the most promising [36]. The residence time, heating rate, temperature, and pressure during biochar formation significantly impact the yield, characteristics (amorphous or porous), and quality of the final product such as the shape, size, and chemical composition [37]. The main characteristics directly linked to biochar stability are its elemental and chemical compositions, as well as its carbon structure, and varying biochar properties result in varying biochar stability [38]. These attributes varied due to the different biomass types being pyrolyzed under varying process settings [38,39]. The parent material and preparation temperature are the two key determinants of the attributes of biochar, and as a result, an increase in pyrolysis temperature will increase the surface area of the biochar [40]. Biochar is also reported to densify the microstructure of mortars by suffusing the pores and sealing the microcracks [41]. Kant Bhatia et al. [42] stated that sewage sludge waste, animal waste, algal waste, and other types of biomass can all be used to manufacture biochar. Biochar has a wide range of uses, including those for heating and electricity generation, cleaning flue gases, metallurgy, animal husbandry, agriculture, construction materials, and even medicine [43]. It is reported that by enhancing the penetration function, biochar can improve wet stability and composites’ resistance to moisture [44]. Biochar is found to be an interesting material to be utilized in the construction industry due to its properties and efficaciousness in carbon dioxide sequestration [45]. When made from basic materials like plants, biochar can be generated with little to no additional greenhouse gas emissions, making it a carbon-neutral process [46].

3. Properties of biochar

3.1. Physical properties of biochar

A physical property is a quality that may be observed without modifying the substance’s makeup [47]. The physical properties of biochar promote its use as an environmental control device [48]. As a result of the disintegration of the fibrous biomass structure, physical qualities, such as mechanical stability, are reportedly altered [43]. This section examines the elements that affect biochar’s physical properties. A summary of the preparation and characterization of biochar is presented in Table 1.

Table 1. Preparation and characterization of biochar.

Biochar source	Pyrolysis condition	Particle sizes (μm)	Characterisation analysis	Ref.
Waste peanut shell	Pyrolysis at 500 °C and ramp rate of 10 °C/min.	1–80	BET, SEM, XRD	[50]
Food waste, rice waste (boiled), and wood waste	Pyrolysis at 500 °C and ramp rate of 10 °C/min.	5–20	BET, PIDS, SEM,	[69]
Kenaf stems	Pyrolysis with different temperatures (400, 500, 600 °C) and ramp rate of 5 °C/min.	0.25, 0.4 mm	SEM	[66]
Rice husk	Pyrolysis at 500 °C and ramp rate of 8 °C/min.	<100	BET, SEM, PIDS, XRD	[54]
Bamboo	Pyrolysis at 650–750 °C and ramp rate of 15 °C/min.	50−100	SEM, XRD, XRF	[58]
Wheat straw	Pyrolysis at 650 °C and ramp rate of 18 °C/min.	10−100	FTIR, SEM, and XRD	[70]
Rice husks and sugarcane bagasse	Pyrolysis at 700 °C and ramp rate of 10 °C/min.	<0.1	BET, SEM, XRD	[71]
Waste olive stone	Pyrolysis at 500 °C and ramp rate of 10 °C/min.	50−300	BET, SEM, XRD	[72]
Olive stone, rice husk, chips of forest residues	Pyrolysis at 500 °C and ramp rate of 20 °C/min.	0.2−100	BET, PIDS, SEM, XRD, XRF	[73]
Corncobs, Cassava rhizomes, stem	Pyrolysis at 500–600 °C for 30 min.	-	BET, SEM	[57]

3.1.1. Density, porosity, and surface area

Density, porosity, and surface area are crucial factors in determining biochar’s physical qualities. Finding a new method to test the physical properties of biochar was the subject of research [49]. Brewer et al. [49] investigated some new ways of evaluating biochar density and porosity. For the density measurement, the author utilised two methods: biochar skeleton density, which yielded a range of 1.34 to 1.96 g/cm^3, and biochar envelope density, which yielded a range of 0.25 to 0.60 g/cm^3. According to a study by Gupta et al. [50], the increase in compactness and high hydration leads to the density of biochar increasing. According to a different source, however, the decrease in density could be the result of low tensile strength and the inclusion of biochar [51]. According to a more detailed investigation of the density of biochar-like wood by Werdin et al. [52], the density is determined by the fibre wall thickness and fibre lumen diameter. The author stated that biochar with a lower wood density had a greater water-holding capacity (WHC).

The pores in biochar range in size from nanometers to tens of micrometres and the biochar’s internal structure can be evaluated using its pore distribution, which is based on the notion that a model with equivalent interactions and regular-shaped pores could represent the complex pore structure in real solids [53]. Due to the release of volatiles and organic matter during the pyrolysis process, the scanning electron microscopy (SEM) of the biochar surface reveals pore structures [54–57] that can absorb water and act as a self-curing agent for mortar and concrete [58].

Biochar porosity increases dramatically as production temperature rises, resulting in an increase in a specific surface area [59]. The increase in milling and mass of wet-milling solvents such as hexane, ethanol, and heptane are the most significant factors influencing the rise in the surface area of biochar particles [60]. Compared to biochar pyrolyzed at lower temperatures, biochar pyrolyzed at high temperatures tends to have wider pores due to the practically full release of volatiles and organic materials during the pyrolysis process [61]. Wani et al. [62] showed that the surface area increases with temperature due to the high temperature-induced breakage of internal bonds, which leads to carbonization. According to Gao et al. [63], biochar has a relatively low surface area, which inhibits its application in the storage of significant amounts of energy and ultimately influences the carbon-based electrode and pore size distribution.

3.1.2. Microstructure

Scanning electron microscope (SEM) provides a comprehensive depiction of the surface morphology of biochar [64]. The SEM pictures of powdered biochar indicate irregularly shaped particles with some sharp edges, which can occur during the grinding of biochar. The milling process can also disintegrate the macropores on the surface of biochar but does not eliminate the mesopores and micropores [65]. For instance, Khiari et al. [66] analysed the SEM images of raw kenaf stems at different magnifications to be converted to biofuel and biochar as displayed in Figure 1. Following the grinding and sieving, long and fine fragments with needle-like shapes were observed. Figure 1 in the set shows that the kenaf stems have macropores, also known as primary punctuation, which are naturally present in the main wall to facilitate cell-to-cell contact. Several other research shows that biochars from peanut shells, date palms, coconut debris, and wood waste, exhibit irregular shapes and sharp edges [50,67,68]. The irregular shapes and sharp edges can be seen clearly in Figure 2, which displays the SEM image of biochar for peanut shells, date palms, coconut waste, and wood waste. In addition, Gupta et al. [67] demonstrated that the milling procedure destroys the surface macropores of biochar.

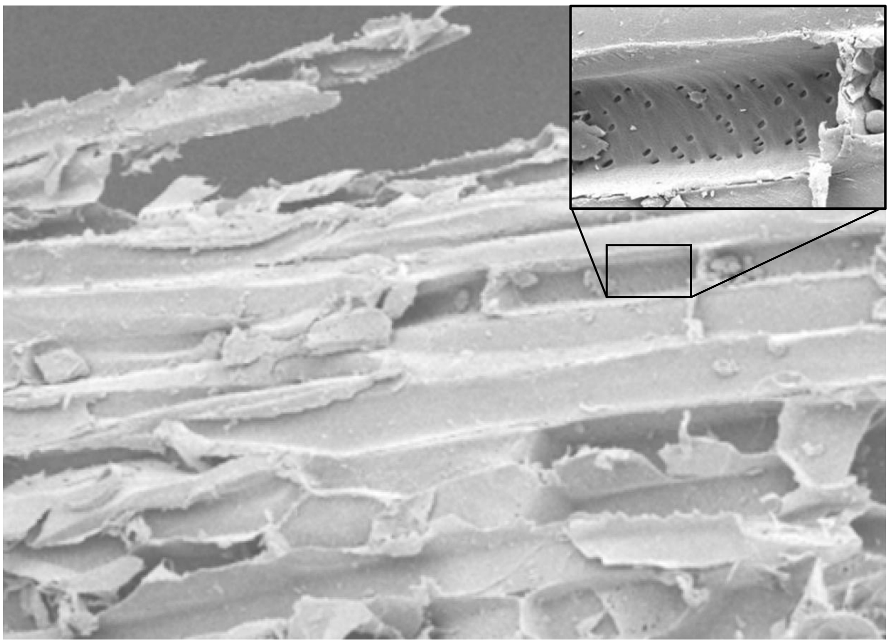

Figure 1. SEM of raw Kenaf stems with 500× magnification and in set 5000× magnification showing the macropores [66].

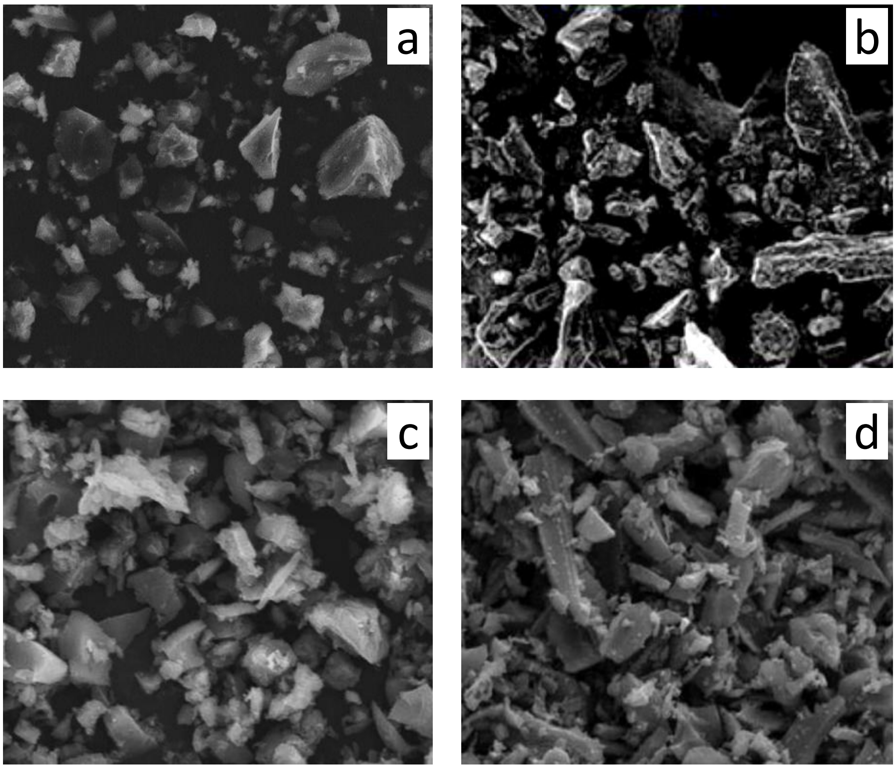

Figure 2. SEM of biochar (a) waste peanut shell, (b) date palms, (c) coconut waste (d) wood waste [50,67,68].

3.2. Chemical properties of biochar

3.2.1. Elemental composition

Since hydrogen is most commonly associated with organic matter in biomass, the C/H ratio has been utilised as a measure of carbonization. If this ratio increases, it shows that biochar contains more alkyl groups. A greater C/O ratio in biochar may imply that more oxygenated functional groups are present, such as hydroxyl, carboxylate, and carbonyl, which may explain why biochar has high Cation Exchange Capacity (CEC) values, indicating that biochar has a more negatively charged surface [74]. The heating rates also had a significant effect on the elemental distribution, with an increase in heating rates causing a decrease in carbon content and an increase in oxygen content, resulting in a decrease in the C/O ratio, while the C/H ratio for biochar was generally reported to be above 5.0, indicating that it was highly aromatic [75]. There are experiments conducted on empty fruit bunch [76] and rice husk biochar (RHB) [76,77] that demonstrate the highest proportion of oxygen (O) in comparison to carbon (C). The increase in O content was attributed to pyrolysis at different temperatures, whereas the decrease in C content was a result of lowering carbonization levels and a large percentage difference between O and H [76]. However, Crombie et al.'s [78] studies on RHB revealed a decline in the proportion of O relative to C. Observing that the percentage of carbon increases with an increase in temperature, one might conclude that the pyrolysis temperature can be adjusted to optimise other benefits, such as structural, chemical, and energy generation. This is possible without impairing the biochar's capacity to store carbon. Due to the action of pyrolysis [56,67,79–81] and the influence of the size and type of biomass [56,79], the C content of wood waste biochars and herbaceous biochars such as bamboo increases while the O content decreases. It is evident from Figure 3 that the majority of biochar contains a greater proportion of carbon and oxygen than other components.

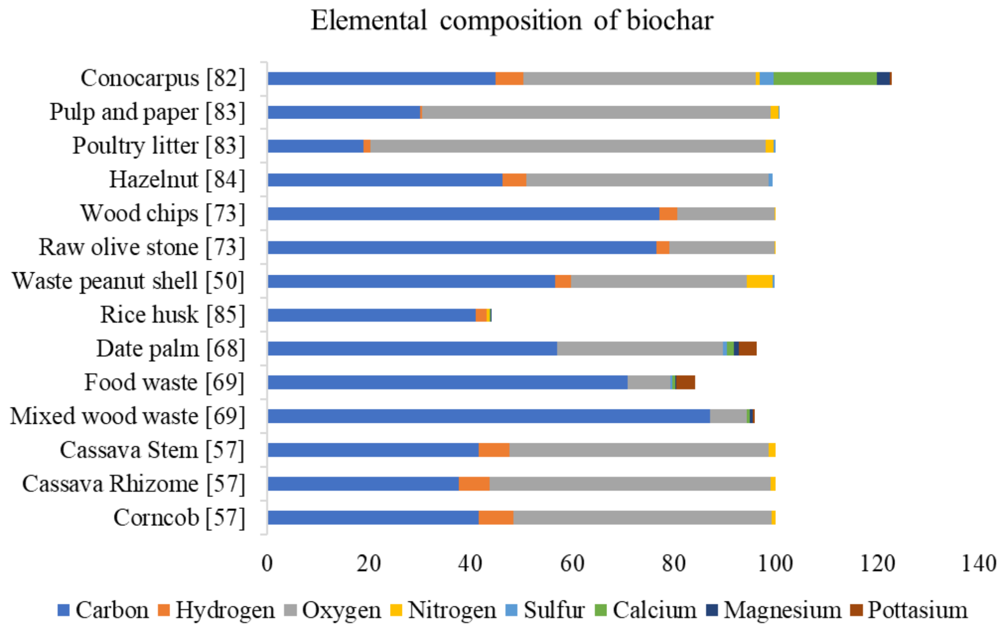

Figure 3. Elemental composition of different types of biochar.

3.2.2. Pozzolanic reactivity

According to ASTM 618-03 [86], pozzolan is a siliceous or siliceous and aluminous material that chemically reacts with $Ca(OH)_2$ at room temperature to form compounds having cementitious characteristics [87]. According to ASTM C618-19, the total amount of SiO_2, Fe_2O_3, and Al_2O_3 in class N pozzolan [88] must be at least 70%. Rice husk biochar (RHB) can be utilised as a pozzolan in cementitious material since the sum of the 3 oxides is greater than 70%, which exceeds the criterion for class N pozzolan [77]. This is in contrast to the investigation conducted by [85], which reveals only a total of 15.85% for the chemical composition of RHB, proving that it does not match the class N pozzolan criteria. The total percentages of SiO_2, Fe_2O_3, and Al_2O_3 in biochar derived from wood waste are less than 70% and do not meet the criterion [89,90]. Several other pozzolan reactivities were investigated and are mentioned in Table 2.

Table 2. Metal oxide content of biochar.

Biochar source	SiO_2	Al_2O_3	Fe_2O_3	Total (%)	Pozzolanic
Rice husk [76]	86.26	0.17	0.69	87.05	Yes
Waste peanut shell [50]	0.44	0.18	0	0.62	No
Olive stone [73]	1.25	0.57	2.86	4.68	No
Wood chips [73]	1.13	0.73	0.23	2.09	No
Bamboo [58]	-	-	-	68.53	Yes

3.2.3. pH

The effect of admixtures on the hydration and temperature of cement can be precisely evaluated by pH [91]. The pH and nutritional content of biochar are known to be substantially influenced by pyrolysis temperature, residence time, and feedstock [92]. According to reports, older biochars tend to have a lower pH [93]. Due to the creation of inorganic minerals, such as carbonates and phosphates, and ash during gasification and carbonization [45], biochar is often alkaline. Several investigations support the notion that biochars are predominantly alkaline [55,94]. In a recent study, the pH of biochar derived from legumes and non-legume materials was compared, and it was determined that the alkalinity of biochar derived from legumes was greater than that of biochar derived from non-legume materials [95].

3.3. Mechanical properties of biochar-amended cementitious material

As shown in Table 3, the mechanical properties of biochar have been investigated by numerous researchers. The compressive strength test, flexural strength test, and tensile strength test can determine the mechanical properties of biochar in cementitious material. The results of a study on certain biochar process parameters that significantly affect the improvement of mechanical properties of cementitious composites are reported to be extremely significant because they demonstrate that biochar can be used to create new environmentally friendly building materials even when the process parameters are not optimal [96].

3.3.1. Compressive strength

Concrete specimens with imposed loads are known to produce normal design compressive stress with less impact on the strength as compared to specimens without imposed loads upon heating [97]. When temperatures are above 350 ℃, the compressive strength of unsealed concrete drops quickly [98]. Cement hydrates, namely C–S–H and C–A–H gels, can increase mechanical strength [99]. According to Sirico et al. [45], there is a correlation between the high C–S–H concentration of biochar and the increase in compressive strength, despite the absence of a direct association [73]. The high sorptivity of water, the storage of biochar, and the high mixing proportion of biochar may also contribute to the rise in compressive strength. The water retained during the mixing and storage of samples can evaporate, leaving behind large capillary holes, which diminishes compressive strength; consequently, the addition of biochar could absorb that water, thereby increasing the strength [100]. Fast drying rates are claimed to have a negative effect on the compressive strength of plain cement and mortar containing dry biochar [101]. The results of a study on certain biochar process parameters that significantly affect the improvement of mechanical properties of cementitious composites are reported to be extremely significant because they demonstrate that biochar can be used to create new environmentally friendly building materials even when the process parameters are not optimal [96]. A study on biochar formed from wood chips, for instance, showed a little decrease in compressive strength with increasing biochar dose, with a similar pattern at 7 and 28 d of curing [102]. In a prior study, the author noted that the inclusion of a lower percentage of biochar increases compressive strength because it facilitates cement hydration, whereas the use of a high percentage of biochar as an additive diminishes strength due to biochar's porosity and brittleness [103]. Several studies on biochar indicate that the addition of a smaller amount of biochar increases compressive strength [58,73], and [100]. Nonetheless, according to certain researchers, a high optimal proportion of biochar addition can boost compressive strength [44,71].

3.3.2. Flexural strength and tensile strength

It is straightforward to assess the flexural and tensile strength of brittle materials [104]. It is feasible to calculate an optimal cement percentage for flexural strength of 1% by weight, which would result in a small increase in flexural strength for mortar resembling ready-mix concrete [102]. Due to the air spaces formed by the inclusion of biochar particles, the development of flexural strength is less impacted by the addition of dry or pre-soaked biochar. However, tensile strength tends to decrease due to the effect of internal curing and densified matrix [101]. Despite considerations impacting flexural and tensile strength, increasing biochar content has been shown to improve the tensile and flexural strength of the composite [105]. Specimens created with biochar exhibited higher yields for flexural strength and fracture energy than those made with normal cement [106]. According to research conducted by Maljaee et al. [73], the optimal cement replacement in terms of flexural strength development was 2% olive stone biochar and rice husk biochar, and replacing 4% of biochar increased in 28 d, indicating that a higher addition of biochar can have a positive effect on flexural strength. The examination of wood biochar revealed a somewhat greater improvement in flexural and tensile strength in samples with a higher wood content [107]. In contrast, the majority of researchers claim that adding a tiny quantity of biochar boosts strength [65]. For instance, the addition of biochar to coconut shell charcoal resulted in a small decrease in flexural strength [108]. The kind of feedstock can also influence flexural strength [109]. On the other hand, the split tensile has a distinct influence on the property, which improves the strength at later stages of growth, and the tensile strength is also higher when a little amount of biochar is added, regardless of the type [83]. However, studies [71,110] have demonstrated a loss in tensile strength, which has been linked to homogeneity concerns in the specimen's tensile plane caused by the incorporation of biochar particles [111]. Under flexural and tensile stress, air voids often become visible in the specimen's tensile plane, which facilitates the spread of cracks and limits the development of flexural or tensile strength [112]. The micro-cracks also tend to enlarge and link with existing cracks, decreasing tensile strength [110].

3.4. Durability properties of biochar

Currently, studies on durability are one of the most important since they have proven enhanced compressive strength, breaking tensile strength, and elastic modulus at different ages [113]. Studies on biochar-infused cement mortar and concrete's durability features, such as sulphate assault, acid attack, chloride attack, and seawater environment, are fairly restricted [114,115]. Nevertheless, a number of scholars [111,116–118] have conducted investigations on thermal conductivity. Thermal conductivity is affected by numerous parameters, including temperature and moisture content [119]. The thermal treatment greatly reduced the biochar's volatile matter content, leading to an increase in its fixed carbon concentration [116]. With the addition of biochar, the thermophysical and mechanical properties of cement composites have been enhanced due to the abundant and intricate micro-pore structure of biochar, which provides a large specific surface area with numerous polar functional groups on the surface, and the biochar particles in the cement composites that create the voids and networks of the porous structure increase the heat resistance of the concrete [116,117]. Tan et al. [120] investigated the thermal effect of incorporating a tiny amount of biochar into pervious concrete to increase its hygrothermal properties. The cementitious material containing biochar has low heat conductivity without sacrificing mechanical characteristics [73]. Biochar ensures the thermal and energy efficiency of buildings, as it has a lower thermal conductivity than biomass for lightweight mortar [121]. Finer biochar particles enhanced the thermal insulation of cementitious materials more effectively [122]. Gupta et al. [114] research on the effect of biochar-incorporated cement mortar on chloride and sulphate conditions revealed that when sulphate ions penetrate the matrix, the expansion intensifies over time, and when chloride ions do the same, they release sulphates and significantly increase the synthesis of expansive ettringite, resulting in matrix fissures.

Table 3. Mechanical properties of biochar.

Biochar used	Extra material	Biochar used as	Percentages added (%)	Days of curing	Test conducted	Optimum percentage (%)	Ref.
Mixed wood, Food waste	Silica fumes	Cement replacement	2, 4, 6, 8, 10	7, 28	Compressive strength	18–20 (including silica fume)	[123]
Wood waste	-	Filler	2.5, 5, 7.5, 10	7, 28, 100, 365	Compressive strength, Split tensile	5	[45]
Peanut	-	Admixture	1, 3	7, 28	Compressive strength	1, 3	[100]
Rice husk	Cenosphere, Silica Fume	Filler	10, 20, 30, 40	1, 7, 28	Compressive strength	10–30	[85]
Waste peanut shell	Fly ash	Cement replacement	1, 3	7	Compressive strength	3	[50]
Bamboo	-	Cement replacement	0.2, 0.4, 1, 2, 3, 4	7, 14, 28, 40	Compressive strength	1, 2, 3	[58]
Olive stone, Wood chips and Rice husk	-	Cement replacement	0.5, 1, 2, 4	7, 28	Compressive strength, Flexural strength	1 (OSB, RHB) 2 (FWB, RHB)	[73]
Rice husk, sugar baggase	-	Cement replacement	5, 10	28	Compressive strength, Split tensile	5	[71]
Waste wood sawdust	-	Filler	5, 1.0, 2.5	7, 28	Compressive strength	1	[103]
Rice husk, coconut shell, bamboo	Red clay	Cement replacement	2.5, 5, 7.5, 10	28	Compressive strength	10	[44]
Mixed wood sawdust	-	Additives	2	7, 28	Compressive strength, Flexural strength, Split tensile	-	[101]
Softwood	-	Cement replacement	0.8, 1	7, 28	Compressive strength, Flexural strength	1	[106]
Coffee powder, hazelnut shells	-	Cement replacement	0.5, 0.8, 1	7, 28	Compressive strength, Flexural strength	0.5 (Coffee powder) 0.8 (Hazelnut shell)	[124]
Poultry litter, rice husk, paper mill sludge	-	Cement replacement	0.1, 0.25, 0.5, 0.75, 1.0	7, 14, 28	Compressive strength, Flexural strength, Split tensile	0.1	[83]

3.5. Biochar as filler and cement replacement in cementitious material

The optimum biochar content in mortar and concrete varies according to the sources of biochar used (Table 3). A maximum of up to 40 wt% may be added when the biochar has pozzolanic properties [71,125]. It was understood from the literature that the properties of mortar and concrete tend to reduce upon reaching the optimum percentage. The dosage of biochar is suggested to be limited to a certain value when added as a partial cement replacement in cementitious material to maintain the workability of the material [126]. For instance, Gupta et al. [55] reported that the addition of 8% of biochar to the cement mortar showed a decrease of 22% in its workability. In another study by Restuccia et al. [127], the maximum biochar content was 2.5% as the biochar additions require a significant increase in water (or superplasticizer) addition to achieve adequate flowability. The aforesaid studies show that the addition of biochar in amounts greater than 2% may give the cementitious material a firmer mix. However, in a study on biochar-red clay composite, a 10% addition of bamboo biochar mixture as partial cement replacement was reported to improve thermal and mechanical performance without workability issues [44]. A concrete mix of pozzolan, such as rice husk biochar combined with silica fume, may be added up to 30 wt% and the cenosphere retains higher water tightness [85]. Regarding the inclusion of biochar as a concrete filler, it was stated that the biochar percentages had a significant impact on workability, and the same consistency of plain concrete can only be achieved by increasing the superplasticizer dosage or reducing the biochar addition percentage [45].

4. Way forward

Numerous scholars have investigated and reviewed various forms of biochar, as seen by the review conducted. However, relatively few biochars, such as bamboo, have been explored that have the potential to operate as carbon sequestration and encourage future sustainable development. Comparatively, this sort of biochar from agriculture should be researched more as a cementitious material due to its lower environmental impact. As a cementitious material, it is also the type of biochar for which less research has been conducted. In addition, there are few investigations on the durability characteristics of biochar as a cementitious material. The resistance to chemical attacks, acid attacks, and varying climatic conditions can be recorded for future reference. Therefore, the durability of biochar as a cementitious material can be studied in the future so that it can endure a variety of situations if utilised to construct buildings. When biochar is infused into mortar or concrete, the quantity of carbon dioxide (CO_2) can also be detected, according to a study that is extremely rare. The level of CO_2 can be measured using the Carbonation Test for concrete. This could aid future generations in modifying their materials in accordance with the amount of CO_2 emitted in order to minimise their environmental impact. The majority of biochar research has focused on soil enhancement in agriculture, as well as mechanical and thermal strength in the building industry. These can be expanded by examining the durability attributes and amount of CO_2 emitted in further detail.

5. Conclusion

It can be concluded that biochar derived from various plant materials has the potential to be utilized as a cementitious material. Utilization of biochar as a cementitious material aids in carbon dioxide sequestration by preventing the release of carbon into the atmosphere. Some of the silica-rich biochars, like the ones derived from rice husk, also have pozzolanic properties. Biochar in general is noted to be an alkaline substance. The quantity of biochar used, the number of curing days, the curing technique, and the type of biochar all have an impact on the strength of biochar-infused concrete or mortar. However, numerous investigations concluded that the use of biochar at lower concentrations (<5 wt%) tends to produce high-strength mortar and concrete. Most of the previous work focuses on the thermal stability of biochar. However, research on chemical and chloride attacks as well as the ageing and weathering study is scarce. Therefore, future work should focus on the aforementioned gaps in knowledge.

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Conflict of interest

The authors declare no conflict of interest.

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