Biochar as a Carbon-Reducing Construction Material: Productions, Feedstock, Composite, and Applications

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Abstract. In the world of rising CO_2, global warming has become a popular topic of discussion. Among the multiple solutions of this issue, the approach of adding biochar into construction material to store carbon dioxide is gaining persistent interest in both environmental and constructional domains. Biochar is a durable carbon sequestering substance, manufactured from agricultural and forestry residues, which possesses an oxidation-resilient carbon structure. In this review, the productions, feedstock, and composite and applications of biochar will be synthesized. The differences and properties of biochar produced by three different production methods (Pyrolysis, gasification, and hydrothermal carbonization) will be explained; The comparison of four novel kernel shell feedstocks (Apricot shell, date shell, palm shell, and peach shell) of biochar, and the improvements (anti-permeability, strength, and durability) yielded by them will be illustrated; the filler type and aggregate type of biochar will be accounted; and the composite composed of biochar with cement-based material and the composite composed of biochar with asphalt will be interpreted. Moreover, this review will briefly discuss the challenges and limitations of biochar.

Keywords: Biochar; carbon sequestration; construction materials; decarbonization; performance.

1. Introduction

Concrete is the most popular construction material in the world, being largely produced and used. It has high strength, can withstand high pressure, and is durable. Its components are widespread, making it cheap. However, its production process cement hardening releases huge amounts of CO_2, and contributes to global warming in large proportion, around 7-8% globally [1, 2]. In addition, the production of concrete requires resources such as sand, but the exploitation of these resources is irreversible and unsustainable.

To reduce the environmental damage caused by concrete, biochar can be added in the production process, lowering the need for original production materials and the emission of CO_2. Biochar is a product with 50–93% carbon composition [3], produced by processing agricultural and forestry residues, which has aromatic carbon structure stabilizing the carbon's inside. Due to its stability, it becomes a high density, durable carbon sequestrating heterogeneous material. Biochar can not only decrease the negative environmental impact of concrete but also improves the overall performance of concrete. By adding biochar, the hardening process is refined, and the strength, durability, and mechanical performance of concrete are enhanced.

In this essay, production methods, feedstock of new biochar, composite of biochar with constructional materials, and application in construction material of biochar will be explained. The prospects, challenges & limitations will also be included.

2. Production

The common production processes of biochar are pyrolysis, gasification, and hydrothermal carbonization (HTC). The biochar produced in each process is different in physical and chemical properties due to temperature, rate, feedstock, duration, pressure, and other factors. Thus, these three differently produced biochar have different effects on construction material.

Each method produces concrete with enhancement on different aspects. By pyrolysis, the concrete produced possesses best structural performance and strength, can be used for long time, with

high stability of storing carbon [4]. Gasification and hydrothermal carbonization both produce biochar with high hydrophilia that can foster the hydration process and accelerate carbonization, making the process faster and more complete, but hydrothermal carbonization is unique in converting humid biomass into biochar [4].

2.1. Pyrolysis

Pyrolysis is a typical method of producing biochar, relatively cheap and simple in contrast to other two, with high productivity. It has a temperature usually around 250-500℃ and no or less oxygen [5]. During process, agricultural and forestry residues will be decomposed into pyrolytic tar, flammable gas, and biochar. The aromatic structure can be improved with rising temperature, making the biochar produced stable. The biochar produced by pyrolysis has high stability, and specific surface area. The best condition to produce biochar suitable to add in construction material requires wood feedstock, and temperature over 500℃ [6]. The biochar generated in this condition gains higher specific surface area, and stability.

2.2. Gasification

Gasification is a more complex method aimed at producing synthesis gas mainly, with a higher temperature compared to pyrolysis. The environment of this reaction has air, oxygen, and steam, causing the productivity of biochar to be lower than the productivity of biochar in pyrolysis. Yet the biochar produced by gasification has more pores, higher specific surface area, higher alkalinity, lower volatility, and lesser functional group with oxygen (carboxyl, hydroxyl, ester, ether). In addition, the ash minerals are abundant in this biochar.

Its high alkalinity, pores, and low volatility can promote concrete hydration, and the minerals can fill in the concrete to enhance its density and early-state performance. The gasification biochar's aromatic structure is not reliable as pyrolysis biochar due to oxidation, so it needs further adjustments to improve its performance in stability and strength aspects.

2.3. Hydrothermal carbonization

This reaction proceeds in aqueous phase, controlled to be only influenced by autogenous pressure, and its temperature is lower than other two production methods.

The feedstock of this reaction is humid biomass rather than dried biomass that the other two require. The main products of this reaction are hydrochar and aqueous products (Ethanoic acid, etc.).

It is a viable production method for humid biomass, and it can foster concrete hydration due to its oxygen-containing functional groups. With those functional groups, it becomes hydrophilic, so absorbing water when it is mixed with cement, ameliorating concrete hydration reaction. Whereas more water is demanded because of overabundance of oxygen-containing functional groups.

3. Feedstock

By adding some specific types of biochar with specific quantity of them into concrete, the compressive strength, anti-permeability, and other aspects of concrete can be enhanced.

3.1. Kernel shell biochar advantages

Biochar made from shells of kernels (peach shells, apricot shells, date shells, and palm shells) can, under specific dosage, improve the anti-permeability, compressive strength, and strength and durability via high density achieved by low porosity [7].

Comparison of kernel shell biochar

According to the table 1, which demonstrates the comparison of different shells with different dosage ratio with cement-based construction material mortar, the peach shell biochar with low dosage ratio can maximize the comprehensive performance of mortar. Apricot shell, date shell, and palm shell with optimal dosage ratio show similar features, of lower workability & density, lower compressive

strength, higher anti-permeability, slightly lower electrical flux, higher porosity, lesser hydration products, and little improvement on drying shrinkage, compared with no biochar addition mortar. The peach shell with higher dosage ratio is nearly the same as other shells, but the peach shell with low dosage ratio is better at all aspects. The workability & density of peach shell mortar is slightly lower, yielding little negative influence on strength, and the compressive strength, anti-permeability are significantly higher. The drying shrinkage of it is improved, and the electrical flux, porosity is largely lower, improving its strength and durability. In addition, it can yield greater amounts of hydration products, which helps to enhance mechanical strength.

Table 1. Four shell biochar comparing [7].

Type of biochar	Dosage ratio	Workability & density	Compressive strength	Drying shrinkage	Anti-permeability	Electrical Flux	Microstructure
Apricot shell	Optimal	Significantly lower	Lower	Improved	Higher	Slightly lower	Higher porosity, low density
Date shell	Optimal	Significantly lower	Lower	Improved	Higher	Slightly lower	Higher porosity, low density
Palm shell	Optimal	Significantly lower	Lower	Improved	Higher	Slightly lower	Higher porosity, low density, little hydration products
Peach shell	Low	Slightly lower	Higher	Significantly improved	Significantly higher	Significantly lower	Dense, lowest porosity, hydration products with most abundance.
Peach shell	High	Significantly lower	Lower	Slightly improved	Slightly higher	Slightly lower	High porosity, low density, little hydration products

4. Application and composite

4.1. Types of biochar

Biochar can be added in construction material as filler or aggregate, and the cost, stability, improvement on strength, decarbonization performance and other factors of them are different.

4.1.1 Filler

As minute filler, the cost of biochar is low, only small proportion of biochar is required. The total cost of constructional material decreases due to biochar replacement.

Biochar filler improves the compactness of material, its functional groups help the combination of it with hydration products, and the hydrophilia of it fosters the hydration process. In addition, the pores in it can adjust the moisture of ambience and insulates heat. With appropriate addition of it, the strength and durability of construction material can be enhanced. 2wt% substitutive biochar improves the cementitious materials' compressive strength around 18.95%, the splitting tensile strength around 19.64%, and the flexural strength around 12% [8]. Furthermore, the absorptivity of water declines. The carbon storage of filler biochar is durable, but the amount of carbon stored is scanty compared with aggregate biochar.

It can be filled in mortar, concrete, asphalt, and other materials to provide improvements.

4.1.2 Aggregate

As massive aggregate, the cost of biochar is high, large quantity of biochar is required. But the costly constructional material is substituted, so total cost falls.

Biochar aggregate has similar functions to biochar filler, but some properties are distinct. Material with biochar aggregate is lighter in weight, typically with low strength, not suitable to withstand huge pressure. It is not applicable to be bearing wall, but it can function as insulation board or sidewalk floor. The improvement of it on strength of construction material is instable, with strict requirements. The interface adhesion strength of biochar is low, so making it difficult to combine with concrete, the

strength of concrete with biochar aggregate will be weak. Moreover, the size and irregular shape of biochar aggregate, the necessity to control amount of water filled and proportion of it accurately, and the lack of consistency with hydration product of it cause the strength of concrete to fluctuate. By improving the interface adhesion, controlling water and aggregate ratio, biochar aggregate improves the strength of concrete by approximately 30% [9]. Biochar aggregate stores carbon at a larger quantity, with greater decarbonation capacity than biochar filler.

In comparison, biochar fillers have advantage on strength enhancement and stability. Biochar aggregate needs future modification on its interface adhesion with constructional material.

In environmental perspective, biochar aggregate stores more carbon dioxide, contributing more to carbon-neutrality.

4.2. Composite of biochar and cement

4.2.1 Biochar as filler in cement-based composite

Biochar filler is a promising filler to be added in cement, which can influence the mechanical performance, hydration, and rheology of cement [4]. According to Gupta and Kua's research on biochar-cement composite, large size biochar filler (2-100μm) has more influence on cement's viscosity and flowability than small size biochar filler (0.1-2μm) [10]. In addition, their research claims that small size biochar filler is more effective in improving concrete's early state strength and waterproofness. Small size biochar filler can fill the space between particles in cement, increasing the density so early state strength. The pores in it can absorb large quantity of water and release the water while cement hydration processes, curing the interior of cement. This curing can prevent shrinkage so increasing the durability of composite. Moreover, biochar can improve material's strength better by dry curing. Yet the porosity of biochar indicates that it can't be added in huge number. If too much biochar is added in composite, the density and mechanical strength of composite will decrease. Hence, a balance is required between composite's strength and curing.

Biochar filler refines the CO_2 diffusion and controls the water content inside cement-based composite, and Wang and others believe the combination of biochar and CO_2 curing can enhance the composite's performance. The effect will be more significant for Mg-based cement, because it will dilate after hydration, filling the pores of biochar, so the negative effect of pores is cancelled. So, the composite of Mg-based cement and biochar filler can be an important constructional material in future. But the combination between cement and pre-saturated biochar is weak. Hence, this combination damages the compressive strength of composite [10]. Despite the improvement in performance, further resolution to the lack of compressive strength is required.

Biochar has abundant pores and high specific surface area, so the biochar cement-based material has the capacity to absorb and store moisture, and the ability to insulate and regulate temperature. The heat stability at 450°C of light cement-mortar containing cenosphere with 40 wt% rice husk biochar as filler is proved to be higher due to low permeability (9-25%) and higher strength retention (15-20%) [11]. In addition, the cement-based composite containing biochar with 10-30wt% ganister sand shows 66 Mpa huge compressive strength of 28 days, and density lower than 2102 kgm^{-3}. Yet there can be further improvements in price and density. The cost of cenosphere and ganister sand is high compared to biochar, so before this composite enters building or other sectors, the reduction of ganister sand and cenosphere is required. The density needs to decline, because according to American Concrete Institute the density of lightweight concrete should be 1920 kgm^{-3} or less [12].

Biochar filler can also be used to purify wastewater and modulate temperature. pervious concrete containing 5% biochar can absorb 117 kgm^{-3} water, and the increase of quantity of water absorption cools the surface temperature of pervious concrete by 6°C [13].

Biochar as filler can improves mechanical performance, hydration process, durability, heat stability and other attributes of cement-based material with it. Besides reinforcing overall performance, new ability, for instance, temperature regulation and wastewater purification can be provided.

4.2.2 Biochar as aggregate in cement-based composite

As aggregate, biochar can be added in cement to make lightweight concrete. There is research of wood, hollow cenospheres, and fibers biochar as aggregate to be added in constructional material, which aims to explore composite achieving lightweight and high performance. In one investigation, via replacing sand by 20% lightweight small size biochar aggregate (26μm) in concrete, the flexural strength rises by 26%, and the density declines by 10% [14]. A composite which is light and possesses high performance is created. The flexural strength can be further improved by using nano biochar aggregate (10-15μm) made from hazelnut shells and coffee powder [15]. The rupture modulus rises by 22% and the fracture energy of samples increases by 61% [15]. The flexural strength and toughness of composite increase. In environmental aspects, the addition of 30%wt biochar as aggregate into concrete allows concrete to be carbon negative [16].

Biochar as aggregate can improve the composite's overall performance. In environmental and economic aspects, the benefits of biochar as aggregate are momentous as well.

4.3. Composite of biochar and asphalt

Asphalt composite is a typical construction material used in road building. It is composed of asphalt and other aggregate materials such as carbon-based material. Although carbon-based material can enhance the performance of asphalt, the cost is high, and the effectiveness is low, not optimum. Some scholars regard biochar as a better substitute that can improve asphalt's fatigue performance, durability, and temperature sensitivity [4]. Biochar enhances asphalt's rutting resistance and temperature sensitivity more effectively than carbon-based materials. Moreover, rotational viscosity and low-temperature crack resistance, that are necessary to an asphalt binder modifier, can be achieved by biochar with particle size less than 75 μm [17].

One issue of Asphalt composite is ageing, which can induce fatigue, cracking, and raving. Ageing can also increase the viscosity and decrease the stiffness of asphalt composite. Due to the negative influences of ageing, more people are focusing on the enhancements of ageing resistance and sensitivity of asphalt composite. Pyrolysis biochar, which mainly prevents the oxidation-ageing, as a substitute of carbon-based material can protect asphalt from ultraviolet radiation, which is the cause of photo-oxidative ageing, so the asphalt's high temperature stability is improved [18, 19]. In addition, bio-oil, the by-product of pyrolysis, can slow the ageing of asphalt [20]. Bio-oil with pyrolysis biochar can act simultaneously to extend the durability of asphalt.

Hydrochar is another biochar that can improve the high temperature resistance of asphalt. With appropriate dosage and other parameters, hydrochar can strength the high temperature performance of asphalt significantly. However, hydrochar will lower the workability of asphalt at low temperature, which requires more investigation on hydrochar properties.

5. Conclusion

Biochar is a new carbon-storing material that can be produced by pyrolysis, hydrothermal carbonization, and gasification. Each method produces biochar with different applications and capacity. It can be used as filler or aggregate into different construction materials to create composites with various applications, decarbonizing and improving the comprehensive performance of construction materials. There are limitations and challenges of it, such as the interface adhesion issue of biochar aggregate, the lack of compressive strength and the overlarge density of biochar filler, and the reduction of workability of asphalt caused by hydrochar, but after further modifications, biochar can function more perfectly in protecting environment and improving construction material strength and other abilities.

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