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The Outlook for using of Lignocellulosic Polymers and their Biochar for a Net-Zero-Carbon Construction Material

Juan Li[1]* and Bohumil Kasal[1,2]

[1]*Fraunhofer Wilhelm-Klauditz-Institut WKI, Riedenkamp 3, 38108 Braunschweig, Germany*

[2]*Organic and Wood-based Materials, Department of Civil and Environmental Engineering, TU Braunschweig, Hopfengarten 20, 38102 Braunschweig, Germany*

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***Corresponding author:** Juan Li, Fraunhofer Wilhelm-Klauditz-Institut WKI, Riedenkamp 3, 38108 Braunschweig, Germany

Abstract

Lignocellulosic polymers such as wood, flax, hemp, bamboo and other plants are the most abundant natural polymers and wood has been used as a versatile construction material for thousands of years. To achieve a more environmentally friendly construction material, the innovative usage of low carbon footprint or waste materials has been promising for a net-zero-carbon construction material. Various kinds of supplementary cementitious materials (SCMs) as Portland cement substitutes, and lignocellulosic polymers as bio-aggregate or reinforcement, can be used in concrete. Biochar is produced from the pyrolysis of plant materials such as agricultural and forest residues and has been used as a soil conditioner, a feed supplement in livestock farming or for water decontamination [1,2]. This mini-review focuses on using lignocellulosic polymers and their biochar to achieve a net-zero-carbon construction material. The biochar retains the microstructure and chemical components partially based on the production process. The similarities and dissimilarities between lignocellulosic polymers and biochar will provide a perspective for studying their potential and mechanism as a carbon-neutral construction material.

Keywords: Lignocellulosic polymers; biochar; net-zero-carbon construction material; LC3 cement; carbon storage; carbon capture; durability; cement hydration and microstructure; interface

Abbreviations: SCMs: Supplementary Cementitious Materials; NFRC: Natural Fiber Reinforced Concrete; LC3: Limestone Calcined Clay Cement; ITZ: Interfacial Transition Zone

Review

Bio-aggregates and concrete

Bio-aggregates in concrete for carbon storage

Natural fiber reinforced concrete (NFRC) has been extensively studied in Portland cement-based concrete materials, as reviewed in [3-5]. Research has showed that plant-based bio-fibers (or fiber bundles) could increase the tensile strength, flexural strength, tensile ductility, and flexural toughness, reducing the drying shrinkage and density of concrete [6]. Bio-fibers were also comparable to synthetic fibers in improving the toughness and impact resistance [4]. By bridging the cracks, fibers provide post-cracking ductility, leading to significant improvement of toughness [5]. However, little attention has been paid to the durability and ageing of such systems and resent research showed the susceptibility of these systems to alkaline environment [7,8].

Bio-aggregates and supplementary cementitious materials (SCMs)

The degradation of natural fibers is due to the susceptibility of hemicelluloses and lignin to chemical deterioration and the alkaline environment of Portland cement. Using SCMs in the concrete mix could decrease the alkalinity of the matrix and effectively prevent the chemical attack on lignocellulosic fibers in the matrix [9-12].

Bio-aggregates and Limestone Calcined Clay Cement (LC3)

Using supplementary cementitious materials (SCMs) is a promising possibility to reduce the carbon footprint of mortars or concrete by partially replacing the clinker [1,2]. LC^3 cements have a relatively low alkalinity due to the lower overall calcium content [13,14]. The combination of LC^3 with natural fibers can be a promising composition to achieve a net-zero carbon concrete, but studies in this respect are still limited. Again, issues such ageing and/or fiber deterioration need to be addressed especially in long-term structural applications.

Biochar and concrete

Biochar-incorporated concrete for carbon storage.

Biochar is a carbon-sequestering material and can be produced from waste biomass through pyrolysis [15]. According to the Intergovernmental Panel on Climate Change 23 report, biochar is a safe and promising solution for efficient carbon storage, with 1-ton biochar storing 2.0-2.6 tons of CO_2 [16]. The European Biochar Market size is predicted to increase from 101.40 kilotons in 2023 to 295.82 kilotons in 2028 [17]. Biochar is a carbon-negative material and the application of biochar in construction materials can generate new chances to achieve low-carbon or even carbon-negative concrete. Important point here is that for production of biochar, plants, wood waste material and wood species with low quality or not suitable for other utilization are used.

Due to the abundant micropores/mesopores and the water adsorption/retention capacity, biochar can serve as a water reservoir for internal curing and provide nucleation sites, which could promote the cement hydration process and facilitate the precipitation of hydration products onto biochar [15]. However, only up to 5wt% of biochar has been used in the cement system to achieve a comparable mechanical strength, because the introduction of excessive porosity and the weak interfacial transition zone (ITZ) could inevitably cause a degradation in strength [18].

Synergistic effect of biochar and CO_2 curing in concrete for carbon capture

CO_2 curing of biochar or biochar-incorporated concrete has shown a synergistic effect of carbon capture and strength enhancement. Wang et al (2020) [18] used CO_2 to cure the 5 wt% biochar-incorporated concrete and found that the accelerated carbonation could mitigate these adverse effects, in which the abundant cement hydrates improved the bonding strength and the carbonates densified the microstructure. Li and Shi (2023) [19] pretreated biochar with concrete washout water and air-borne CO_2 and successfully used up to 30 wt% biochar in Portland limestone cement. The 30 wt% biochar-incorporated concrete achieved the 7 days and 28 days compressive strengths of 22.1 MPa and 27.6 MPa, respectively, which were more than double compared to those without pretreatments as reported in Chen et al (2022) [15]. The synergistic carbon capture of concrete washout water and biochar precipitated calcium carbonate onto biochar, which enhanced the material strength of biochar and also improved the interfacial zone via compatibility between calcium carbonate and cement hydration products.

Biochar and supplementary cementitious materials (SCMs) for net zero-carbon concrete

The combination of SCMs and biochar is promising to produce net-zero carbon concrete as a technically feasible and financially profitable construction material. Chen et al (2022) showed that 30wt% of biochar as aggregates and 9wt% metakaolin as a binder were the most promising mixture, which could sequester 59 kg CO_2 tonne^{-1}, and potentially generate an overall profit of 35.4 USD m^{-3}. Wang 2023 used up to 2 wt% biochar in an LC^3 mixture and got similar conclusions as in Portland cement mixtures that biochar could facilitate cement hydration. Still, the porosity and the weak interfacial transition zone could weaken the mechanical properties [20,21].

Carbonation by CO_2 curing

CO_2 source for cement carbonation. The major resources of a high-concentration CO_2 gas are concentrated pure CO_2 (almost 100%) with intensive production and storage costs, and the flue gas (20-30% CO_2) with no post-production treatment [22]. A continuous or cyclic supply of 20% CO_2 gas achieved an enhanced CO_2 absorption of up to 6% of cement weight and a carbon sequestration of about 13 kg/m [22,23].

Discussion

Similarities and dissimilarities between bio-aggregate and biochar in cement

Similarities between bio-aggregate and biochar in cement (Figure 1). (1) they could both serve as water reservoirs for the internal curing of cement due to their water absorption and retention properties; (2) they could both provide additional nucleation sites for cement hydration products. The precipitation cement hydrates onto biochar could enhance the pore structure and biochar material strength, but the precipitation of carbonate in bio-fibers is deemed as the most prominent degradation mechanism of lignocellulosic materials in cement; (3) their compatibility with cement and the formed interfacial transition zone (ITZ) are critical to the concrete strength; (4) they can both come from waste material and storage carbon, which could lower the carbon footprint of concrete.

Dissimilarities between bio-aggregate and biochar in cement. As a residue material after pyrolysis, biochar is a brittle and low-strength material, which can cause the initiation of material failure in concrete. In comparison, fibers have a high strength-density ratio and could enhance the material strength and ductility of concrete. However, fibers can be degraded in the alkaline cement environment by alkaline hydrolysis [7,8] and mineralization, which can make them brittle and lose material strength [19,24].

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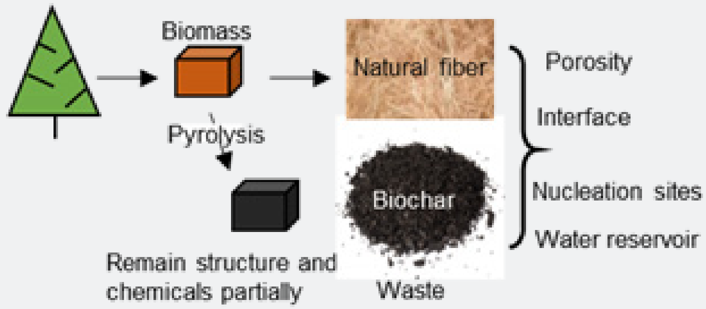

Figure 1: Schematic of bio-aggregate and biochar production options and their effects in concrete.

Research gaps

The following research gaps were identified:

a. The studies of natural fiber reinforced concrete mainly focus on the strength and durability, but the effect of natural fibers on the properties of fluid cement paste, such as rheological behavior and the cement hydration including the viscosity, setting time, etc. are not well understood and reported in the literature

b. The mechanisms of interactions between biochar and LC^3 cement are not yet understood, including the influence on the cement hydration process, microstructure and strength development, and the interfacial properties between biochar and cement.

c. The mechanism and kinetics of CO_2 adsorption in biochar are not understood. This includes the microstructure of carbonated biochar, and the interfacial properties between biochar and the precipitated calcium carbonate.

d. The efficacy of CO_2 curing using flue gas for bio-aggregate/biochar concrete, including the amount of CO2 absorption, the effect of CO_2 curing on the compressive strength of concrete, and the pH value of the concrete have not been sufficiently studied.

e. The durability of bio-aggregate/biochar-incorporated concrete needs more attention.

Conclusion

The use of low- or negative-carbon material, such as lignocellulosic polymers and their biochar as bio-aggregates and limestone calcined clay cement (LC^3) as a low-carbon cement alternative, provides an innovative concept for a net-zero-carbon construction material. The carbonation technology could further develop the carbon-capture potential and reduce the carbon footprint.

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