# Biochar integration in precast concrete: a critical appraisal of sustainability and performance enhanced

# Biochar Integration in Precast Concrete: A Critical Appraisal of Sustainability and Performance Enhancement

Muath Abu Askar[1,2*], Ahmed Abdalqader[2], Mohammed Sonebi[1], Giuseppina Amato[1]
[1]School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland
[2]Tracey Concrete Ltd, Enniskillen BT74 7LF, Northern Ireland
email: m.abuaskar@qub.ac.uk, ahmed@traceyconcrete.com, m.sonebi@qub.ac.uk, g.amato@qub.ac.uk.

ABSTRACT: Precast concrete is often used in construction because of its highly valued endurance and adaptability. However, because of its energy-intensive manufacturing process and associated greenhouse gas emissions, ordinary Portland cement, the main binder in concrete, causes considerable environmental harm. A carbonaceous byproduct of biomass pyrolysis, biochar has become a very attractive environmentally friendly substitute for cement. The possibility of using biochar as partial cement replacement in precast concrete applications was evaluated in this study. This study begins by reviewing biochar production methods and their feasibility and describing the inherent properties of biochar that make it appropriate for incorporation into concrete, such as its large surface area, porosity, and water adsorption ability. The mechanical performance and durability of precast concrete with biochar incorporation are then thoroughly examined based on the results of current studies. In Northern Ireland, it is estimated that 200 kt of biochar could be produced per year if all housed livestock manure and underutilised silage were used to produce digestate via anaerobic digestion. The global biochar market size was valued at $184.90 million in 2022 & is projected to grow from $204.69 million in 2023 to $450.58 million by 2030. In conclusion, this study underscores the potential of biochar in mitigating the environmental impact of precast concrete production without compromising its performance. Nonetheless, further research is warranted to optimise biochar utilisation in precast concrete and to establish standards for its widespread implementation within the construction industry.

KEY WORDS: Biochar; Precast concrete; Cement Replacement; Carbon sequestration; Construction Industry.

## 1 Introduction

Concrete is in high demand for building materials worldwide owing to its exceptional advantages over other materials used in the construction industry [1]. Currently, more than 2.8 billion tons of concrete is consumed annually [2]. Given the substantial amounts used, the cement industry is responsible for 7% of global $CO_2$ emissions [3]. Increasing levels of these substances have raised concerns and prompted the need for more eco-friendly alternatives.

On the other hand, population growth, urbanisation, and living standards have resulted in a massive generation of waste worldwide. Approximately one-third of the comestible parts of food produced for human intake are lost or wasted globally, which is about 1.3 billion ton per year [4]. In addition to food waste, another significant type of waste is generated by the wood processing industry. In Northern Ireland, councils collected 971,936 tons of waste in 2022/23, which was 6.1% lower than the amount collected in 2021/22, with a substantial portion being biodegradable and suitable for conversion to biochar [5]. This not only translates into wasting the resources used in its production (land, water, energy, and inputs), generating unnecessary $CO_2$ emissions, but also poses serious management problems and costs for the state.

Recently, a popular solution for handling large amounts of organic waste has been to utilise oxygen-free thermochemical processes, such as pyrolysis or gasification. These methods allow the extraction of biomass energy potential, resulting in the production of Biochar. The International Biochar Initiative (IBI) defines biochar as "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" [6].

Compared with other carbon removal techniques, biochar has shown great potential in numerous areas, including technological viability, scalability, carbon removal costs, carbon stability and permanence, verification, and monitoring, as well as its versatility for various applications [7]. Considering the current state of the carbon sink market, biochar synthesis for carbon capture and storage is both technically possible and potentially financially rewarding. The process of carbon sequestration via biochar synthesis is straightforward. During photosynthesis, plants absorb carbon dioxide from the atmosphere and store it within their structure for as long as they live. However, when plants die, carbon is released back into the atmosphere through natural decay, thereby completing the carbon cycle. Biochar production interrupts this cycle by transforming carbon into a form that is resistant to decomposition, thereby preventing the release of greenhouse gases back into the atmosphere [8], [9].

The scope of this review is to comprehensively examine the production methods, properties, applications of biochar, environmental impacts, and economic impacts of biochar in concrete composites.

## 2 Biochar Production

Biochar, a carbon-rich substance, is produced through pyrolysis, which involves thermal decomposition of biomass in the absence of oxygen. To create biochar, it is essential to closely regulate the temperature, heating rate, and residence time to efficiently convert the biomass into stable carbon.

Several thermochemical conversion technologies, including pyrolysis, gasification, flash carbonisation, and hydrothermal carbonisation, have been used to produce biochar [7], [8]. The selection of conversion technology is influenced by several factors, such as the feedstock, the desired secondary products, and biochar characteristics. The primary methods for achieving these objectives are discussed in subsequent sections.

### 2.1 Pyrolysis

Pyrolysis is the most common technology used to produce biochar and depends on a thermal process that involves the decomposition of biomass at a certain temperature in an oxygen-free atmosphere [9]. Pyrolysis can be classified as slow, intermediate, or fast. Slow pyrolysis, also known as conventional carbonisation, entails heating biomass at a relatively low temperature of approximately 400 °C for an extended period based on the biomass source in an oxygen-free environment. This method has been employed for many years to produce charcoal and typically leads to a high yield of biochar (35%) from biomass, as well as tar (25%), non-condensable gases (25%), and minor losses (15%) [10].

Intermediate pyrolysis entails a processing temperature range of 400–650 °C, but with slower to moderate heating rates, resulting in biochar yields of approximately 20–40%. The process is continuous and can last up to 30 minutes. Common reactor designs include externally and internally heated rotary kilns as well as screw-based kilns, many of which are commercially available. In some cases, intermediate pyrolysis is called slow pyrolysis in the literature [11], [12], [13], [14].

On the other hand, fast pyrolysis produces biochar at a high heating rate between 500-1000 ºC in the absence of oxygen too, and a short residence time of less than 2 s. Generally, this type of pyrolysis provides high biofuel yields (75%) from biomass, together with non-condensable gases (13%) and biochar (12%) [15].

The production of biochar requires precise control of temperature, heating rate, and residence time to achieve optimal conversion of biomass into stable carbon.

### 2.2 Gasification

Gasification is a process that generates biochar as a byproduct, while its primary purpose is to produce syngas. This thermochemical process typically occurs between 700 and 1000 °C in a slightly oxidising atmosphere using air, steam, or oxygen. Although the products of gasification and pyrolysis are similar, the former favours syngas generation. According to the literature, the average yields of biochar, oil, and syngas are 5%, 10%, and 85%, respectively. However, this technology is inefficient for biochar production because of the low amount of char produced. Gasification is well-suited for generating energy and chemicals from syngas [16], [17].

### 2.3 Flash carbonisation

Flash carbonisation involves igniting and controlling a flash fire in a packed bed of biomass at elevated pressures. This mechanism results in the upward movement of fire and downward movement of air, which primarily causes the conversion of lignocellulosic material into gaseous and solid fractions. This technique typically requires less than 30 minutes residence time, while maintaining a temperature range of 330–650 °C[8], [18]. The literature suggests that biochar yields from flash carbonization (28-32%) are equivalent to those from slow and intermediate pyrolysis; however, some producers claim higher biochar yields. The main disadvantage of flash carbonisation is the requirement for a high pressure [19]. Nevertheless, this is another possible approach for the effective manufacture of biochar.

## 3 BIOCHAR PROPERTIES

Biochar has garnered attention for its potential to be incorporated into concrete, offering a sustainable solution for reducing carbon emissions in the construction industry. Its inherent qualities, such as a large surface area, porosity, and water adsorption ability, make it an excellent candidate for enhancing the properties of concrete while contributing to carbon sequestration.

### 3.1 Large surface area

Biochar has a substantial surface area, which is a consequence of its pyrolysis process. This large surface area is advantageous for various concrete applications. Initially, it allows for enhanced interaction between the biochar particles and cement matrix, which may improve the mechanical characteristics of the concrete. Moreover, the large surface area of biochar enables the adsorption of carbon dioxide from the atmosphere, thereby contributing to the mitigation of greenhouse gas emissions associated with the production and use of concrete [8], [20]

### 3.2 Porosity

The porosity of biochar is another inherent property that makes it suitable for incorporation into concrete. Biochar's porous structure can enhance the internal curing of concrete by retaining moisture necessary for the hydration process of cement. This moisture retention capability can lead to a more uniform hydration process, potentially improving the durability and strength of the concrete over time. The porosity of biochar also contributes to its ability to sequester carbon dioxide, as the pores provide spaces where $CO_2$ can be trapped and stored, further enhancing the environmental benefits of biochar-amended concrete [8], [20].

### 3.3 Water Adsorption Ability

Biochar's high water adsorption capacity is a critical quality for its application in concrete. This refers to the ability of biochar to hold or retain water molecules on its surface. This property can improve the workability of the concrete mix, making it easier to handle and place during construction. Additionally, the water adsorption ability of biochar can contribute to the internal curing of concrete by providing a reservoir of water that can be gradually released to support cement hydration. This can result in concrete with better mechanical properties and reduced shrinkage, thereby enhancing its overall performance and longevity [8], [20].

## 4 EFFECT OF BIOCHAR IN CONCRETE STRENGTH AND DURABILITY

The incorporation of biochar into concrete has garnered significant attention owing to its potential to enhance the concrete properties and provide environmental benefits. Numerous studies have explored the impact of biochar on concrete, including its effects on mechanical strength, permeability, and durability. For example, Gupta et al. [21] explored the effects of biochar on concrete exposed to high temperatures. Their study demonstrated that the incorporation of biochar increased the compressive strength and diminished the permeability, particularly at elevated temperatures. This implies that biochar can bolster the heat resistance and resilience of concrete under high-temperature settings. Their study revealed that the addition of 5% biochar to cement led to a 10% increase in compressive strength and a 15% drop in permeability at elevated temperatures.

In contrast to previous studies, Akhtar and Sarmah [22] investigated the impact of biochar on the compressive strength of concrete composites. The researchers carried out a comprehensive analysis, including manufacturing, characterisation, and mechanical property evaluation, to determine the effects of adding biochar to concrete mixes. The findings revealed that the incorporation of biochar significantly influenced the compressive strength of the concrete specimens. Specifically, the samples containing biochar showed a decrease in compressive strength compared with the control group without biochar. This reduction in strength was attributed to the porous nature of biochar, which compromised the overall structural integrity of the composite. This study highlights the importance of carefully selecting the proportion of biochar to ensure the desired compressive strength of biochar-concrete composites.

The strength of biochar concrete tends to exhibit a pattern where it initially increases with the biochar incorporation ratio up to a certain point and then may begin to decline. This phenomenon is often ascribed to the balance between the positive and negative effects of biochar on concrete properties. Initially, the addition of biochar can serve as a filler, enhancing the packing density of the concrete mixture, which can bolster its strength. However, if the biochar content is excessive, it can obstruct the formation of the cementitious matrix, thereby diminishing the strength of the concrete.

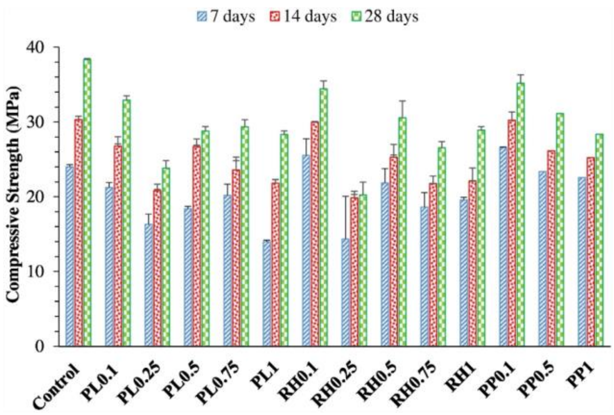


Figure 1. Compressive strength of biochar-concrete composites after 7, 14 and 28 days of curing [22]

The high porosity of biochar may also lead to weaker interfaces between biochar and cement paste. Biochar has the ability to act as an internal curing agent in concrete. This means it can retain moisture within the concrete mixture, preventing it from evaporating too quickly during the curing process. The internal curing effect can result in improved hydration of cement particles, leading to a denser and more robust cementitious structure. This, in turn, can contribute to higher compressive and tensile strengths. Biochar can fill voids within the concrete mixture, improving the packing of solid particles and reducing the porosity. This filling effect can enhance the mechanical properties of concrete. It also contributes to the reduction in water demand, which can lead to a lower water-to-cement ratio, further improving the overall strength and durability of the concrete [20].

The reviewed studies indicate that biochar has a beneficial effect on the strength and durability of concrete. Specifically, it improves the mechanical strength, reduces permeability, and facilitates carbon sequestration. However, to ensure consistent and reliable results, further studies are necessary to optimise the dosage, particle size, and production method of biochar. In addition, long-term performance and environmental impact assessments are crucial for fully understanding the sustainability and practical applicability of biochar-concrete composites in construction applications. This will enable the adoption of biochar as a viable and eco-friendly solution for the construction industry.

## 5 Environmental Impact of Biochar in Concrete

The utilization of biochar in concrete has both positive and negative environmental consequences, which must be carefully managed. On one hand, it helps in the sequestration of carbon dioxide and combat climate change, but on the other hand, its production and use must be managed with caution. To decrease greenhouse gas emissions, it is crucial to use renewable energy during the production of biochar. A comprehensive life cycle assessment of biochar is necessary to ensure that its environmental benefits surpass any drawbacks.

It is essential to source the feedstock used in biochar production from sustainable sources in order to avoid contributing to deforestation or habitat destruction. By prioritizing environmental responsibility in the selection and handling of raw materials, the biochar industry can positively impact sustainable practices and contribute to a greener future. The integration of biochar into concrete requires rigorous quality control and testing to ensure the structural integrity and durability of the final product. A range of tests, including compressive strength, water absorption, and durability assessments, should be conducted to evaluate the performance of biochar concrete thoroughly. This ensures that the desired properties of concrete are maintained even with the incorporation of biochar [23], [24], [25].

## 6 Economical IMPACT of biochar in concrete industry

The economic feasibility of using biochar in concrete is a crucial aspect to be considered when evaluating its potential adoption in the construction industry. Although biochar offers several environmental benefits, it is essential to assess its economic viability to ensure its practical application. Biochar production primarily involves thermochemical conversion of biomass in an oxygen-limited environment, a process known as pyrolysis. The cost of biochar production is influenced by several factors, including the type of biomass feedstock, technology used, and scale of production. The production costs of biochar in the UK context may range from GBP -148 to 389 per ton, depending on the assumptions regarding the feedstock and production methods. The variability in cost was significant, indicating that the economic feasibility of biochar can greatly depend on local conditions and specific operational efficiencies [26].

### 6.1 *Market Dynamics and Potential*

The global market for biochar is on a growth trajectory, and its valuation is expected to increase from $204.69 million in 2023 to $450.58 million by 2030. This growth is driven by rising awareness of the environmental benefits of biochar and its potential applications in various sectors, including agriculture and construction. For the construction industry, particularly in the production of precast concrete, the integration of biochar not only helps reduce the carbon footprint but also potentially reduces the overall cost of materials by substituting a portion of Ordinary Portland Cement (OPC) with biochar.

### 6.2 *Financial Viability and Cost-Benefit Analysis*

Integrating biochar into precast concrete could lead to direct and indirect financial benefits. Directly, the use of biochar can reduce the amount of OPC required, thereby reducing material costs. Indirectly, biochar incorporation enhances the sustainability profile of construction materials, which can be leveraged for marketing and in compliance with increasingly stringent environmental regulations. However, a comprehensive cost-benefit analysis needs to be conducted to evaluate the overall economic impact. This analysis should consider the initial investment in biochar production or procurement, operational changes in concrete manufacturing, and the potential long-term savings from reduced material costs and environmental compliance.

### 6.3 *Challenges and Strategic Considerations*

Despite the promising economic and environmental prospects, several challenges must be addressed to fully realise the potential of biochar in precast concrete. These include:

- Regulatory and Standards Development: There need for clear regulatory guidelines and industry standards specific to the use of biochar in construction to ensure quality and safety.
- Supply Chain and Logistics: Establishing a reliable supply chain for biochar is crucial, especially in regions without substantial biomass resources.
- Technology and Innovation: Continued research and development are required to optimise biochar production for use in concrete and to enhance the material properties of biochar-enhanced concrete.

## 7 CONCLUSION

In summary, the incorporation of biochar into concrete is promising with respect to its mechanical properties and durability. However, additional research is necessary to optimise biochar production processes and fully understand its potential benefits. Future studies should focus on the long-term performance of biochar-enhanced concrete under diverse environmental conditions and applications. Additionally, further investigation should explore the economic viability and scalability of biochar-enhanced concrete in extensive construction projects, as well as its potential to minimise the carbon footprint of the industry. To maximise the benefits of biochar-enhanced concrete in reducing the carbon footprint of the construction sector, it is crucial to examine the environmental advantages of employing this method on a large scale and to evaluate its lasting effects on the environment.

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