

Artigo Técnico

Utilization of biofuels co-products for reduction carbon footprint of materials for civil construction - An overview.

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Abstract

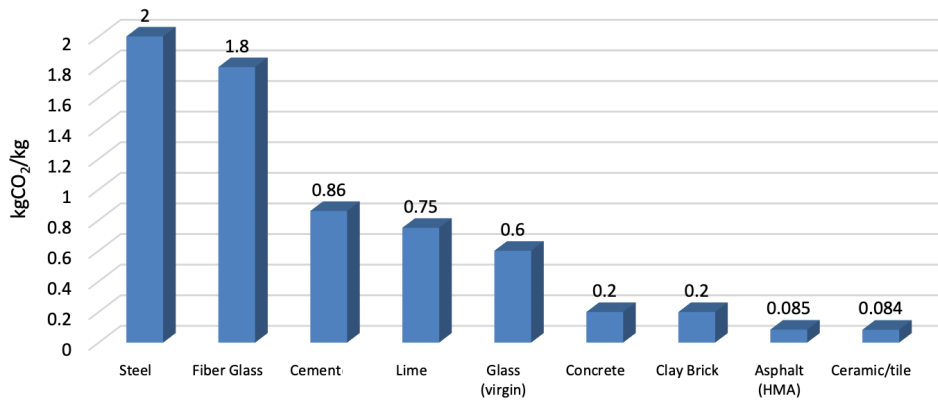
The production of construction materials stands as a pivotal industrial sector in Brazil and worldwide, wielding significant economic influence. However, it also significantly contributes to greenhouse gas emissions and natural resource depletion. Thus, developing new bio-based construction materials emerges as a strategy to mitigate the carbon footprint and environmental impacts of this sector. This study aims to provide an overview of implementing two crucial biomass derivatives, biomass ashes, and biochar, in various construction materials such as supplementary cementitious materials (SCM), lightweight aggregates, concrete formulations, mortars, insulation materials, etc. The assessment encompasses not only the mechanical, physico-chemical, and durability properties of these novel materials but also the importance of analyzing their generation and characteristics that could influence the development of new and more eco-friendly building materials. This includes considerations of the synthesis process (combustion and pyrolysis) and the key properties of ash and biochar.

1 Introdução

The construction industry ranks among the most significant sectors in terms of energy consumption and reliance on fossil fuels, leading to substantial CO₂ emissions during the production of various construction materials. According to the International Energy Agency (IEA), the construction sector accounts for 36% of global energy consumption among industrial sectors, contributing to 39% of related CO₂ emissions. Within this CO₂ fraction, approximately 11% is attributed to the production of materials for buildings and constructions (IEA, 2019; Ali *et al.*, 2020).

The intensity of carbon emissions and energy consumption throughout the production process of construction materials are closely correlated, highlighting the imperative for developing circular processes or innovative materials capable of mitigating CO₂ emissions within this production chain (Shuvo & Sharmin, 2022; Barcelo *et al.*, 2014). **Figure 1** depicts the average CO₂ emission rate per unit (kg) of different building and construction materials.

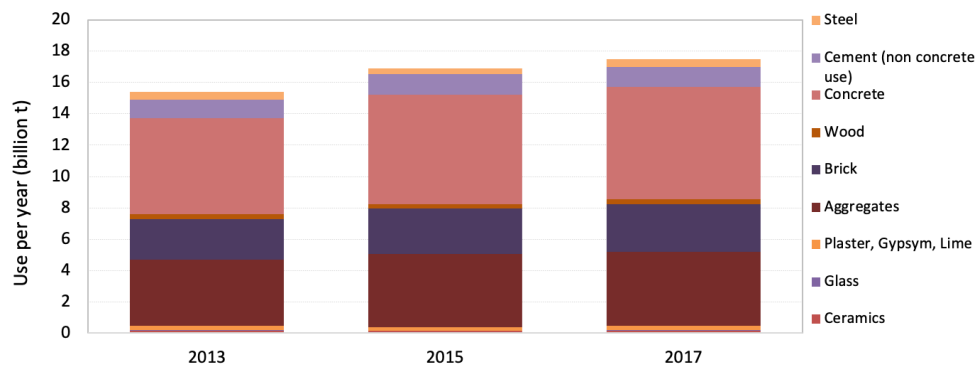
Figure 1 – Emissions of CO₂ of some building materials.



Source: Prepared by the author

The data indicates that steel, glass materials, and cement exhibit the highest carbon intensity in their production processes, coupled with significant energy consumption. However, these figures solely depict the absolute emissions impact of these construction materials. To gain a comprehensive understanding of the true implications of their current utilization, it is imperative to assess their global consumption on a worldwide scale. **Figure 2** illustrates the global consumption (in billion tons) of construction materials during the years 2013-2017.

Figure 2 – Global uses of construction materials of 2013 – 2017.



Source: Adapted from Huang et al. 2020

Consumption data from 2017 reveals that the most utilized construction materials globally include concrete, aggregates, bricks, and cement (non-concrete use). Notably, the consumer market is predominantly led by China, accounting for a substantial 55% share of global construction material consumption during this period, trailed by India (11%), Europe (8%), and Latin America (7%) (Huang et al., 2020). These findings underscore the imperative of exploring solutions and innovations aimed at reducing energy consumption and dependence on fossil fuels in the production of these materials (Ali *et al.* 2020). This may involve the adoption of circulation strategies or the integration of biomaterial sources to either partially or entirely substitute conventional materials.

The process of "defossilization" in industrial production entails transitioning from energy and carbon matrices reliant on fossil fuels to those derived from clean energy sources and biological or circular carbon sources, such as CO₂ utilization. Within this paradigm shift, numerous strategies have been developed or are in development to mitigate or even neutralize emissions from the production of construction and paving materials. Many of these technologies are founded on the utilization of fractions or by-products derived from the energy conversion of lignocellulosic biomass or waste materials. Examples include processes such as combustion to produce steam or electricity, as well as fast or slow pyrolysis to yield bio-oil or biochar.

Considering the significance of biomass utilization in the global energy landscape, particularly in countries like Brazil, fostering discussion and disseminating technological advancements could aid the industrial construction sector in achieving greenhouse gas emission reduction targets. Thus, this article highlights recent developments pertaining to the incorporation of biomass energy processing by-products in construction material production, alongside an examination of key economic parameters.

2 Biomass ash applications

Based on data extracted from the national energy balance report of the "Empresa de Pesquisa Energética - EPE" for the year 2023, the utilization of sugarcane bagasse and other renewable energy sources, such as firewood and biomass, accounts for approximately 5.5% of the internal supply of electrical energy. This observation holds significance as the generation of electrical energy from biomass involves a combustion process (thermal process), resulting in the production of pressurized steam designated for a power

cycle. It is noteworthy that in numerous instances, several industries employing biomass boilers to generate steam for their internal operations are not captured within the scope of electrical energy generation data.

The biomass combustion process occurs through the reaction between fuel and air at elevated temperatures within a furnace, which can vary across different types such as grate (stationary, vibrating, alternative, and mobile) or fluidized bed (bubbling or circulating) furnaces. The choice of furnace type depends on the combustion capacity and the physical-chemical properties of the biomass. During the combustion process, combustion gases, including CO₂, N₂, and excess O₂, are produced as effluents, along with contaminants and incomplete combustion by-products such as CO, SO_x, NO_x, HCl, dioxins, and furans.

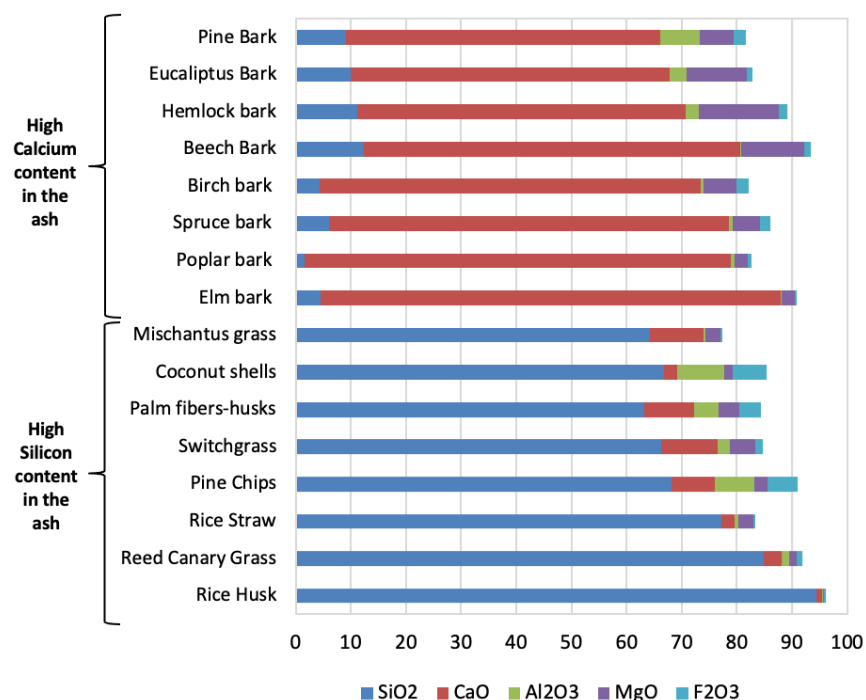
The ash residue, representing the non-combustible fraction of biomass, primarily comprises inorganic compounds. Two types of ash are generated in the biomass combustion process: bottom ash and fly ash. Bottom ash consists of the dense and coarse fraction of ash produced in the grate or primary combustion chamber. Typically, it may contain slag, unburned fuel residues, and mineral impurities. Fly ash comprises particles of low particle size and density that are entrained with the combustion gases and collected in a particle collection system.

Although derived from the same raw material, fly and bottom ash may exhibit distinct characteristics contingent upon the dynamics of the combustion process employed during biomass incineration. Properties such as granulometry, concentration of specific inorganic mineral ores, and the presence of unburned carbon are among the factors that differentiate these two types of ash and influence their suitability as pozzolanic or supplementary cementitious materials.

2.1 Fly Ash

The composition of collected fly ash can vary significantly, influenced directly by the biomass source. Numerous biomass types contain elevated concentrations of elements conducive to pozzolanic activation, notably Silicon (Si), Aluminum (Al), Iron (Fe), Calcium (Ca), and Magnesium (Mg). **Figure 3** presents a compilation of biomass and biogenic wastes with notable content of these elements in their ash composition (Garcia-Maraver, 2016).

Figure 3 – Contents of SiO₂, CaO, MgO, Al₂O₃ e Fe₂O₃ in some biomass ashes.



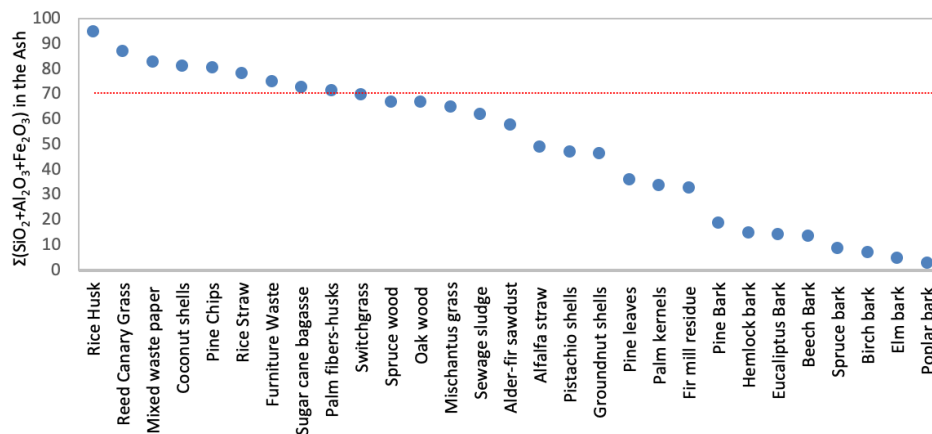
Source: Prepared by the author

Pozzolanic materials refer to substances that, upon combination with lime (calcium oxide) and water, undergo a chemical reaction leading to the formation of cementitious compounds. This reaction is similar to the process that occurs during the hardening of Portland cement. Some data indicate that when the sum of the total active oxides of SiO₂+Al₂O₃+Fe₂O₃ in the ash is greater than 70%, there is a good possibility that this is an excellent pozzolanic material (Sun et al., 2023). According to this information, Figure 4 shows biomass with a high propensity to generate ash with good pozzolanic activity. It is possible to observe that derivatives of rice biomass (husk and straw), coconut shells, palm fibers, sugar bagasse, and switchgrass can generate ash with promising properties to generate good supplementary cementitious materials.

It is worth highlighting that not only the chemical composition of the ash is important to evaluate its potential for use as an eco-substitute for construction materials, but also other physical, chemical, and mechanical properties. These properties include density, porosity, specific surface area, particle size distribution, water absorption, and friability, in addition to identifying the mineralogical phases. These parameters are crucial in influencing the formulation of new materials as well as their usability (Cabrera, 2014).

Sun *et al.* (2023) conducted a comprehensive evaluation of ash additions from various biomass sources, including rice husk, palm oil biomass, sugarcane bagasse, corn cob, and elephant grass, at different replacement levels in the formulation of different concrete mixtures, such as high-strength concrete, self-compacting concrete, lightweight aggregate concrete, ordinary concrete, and ultra-high-performance concrete, as well as cement mortar. The study aimed to assess differences in mechanical properties and durability across these mixtures. Results indicated that while corncob ash impacted negatively concrete properties due to its high alkaline element content, notably potassium (K_2O), rice husk ash significantly enhanced both the mechanical properties and durability of concrete. However, its high SiO_2 content and specific surface area led to reduced workability. Overall, minor fractions of biomass ash did not cause significant effects on concrete and cement mortar properties.

Figure 4 – Sum of SiO_2 , Al_2O_3 and Fe_2O_3 contents in the ash of biomass with content of silicon, aluminum and iron.



Source: Prepared by the author

Tosti *et al.* (2018) examined the disparities among three types of fly ash derived from different biomass combustion processes and subsequently incorporated into cement mortar as secondary cementitious materials. The three ashes originated from the combustion of clean wood in a fluidized bed (FA1), combustion in a pulverized fuel furnace (FA2), and the combustion of paper sludge mixed with demolition wood in a fluidized bed (FA3). While the replacement of up to 40% of FA1 and FA3 in Portland cement exhibited a

certain reduction in compressive strength, it still demonstrated some level of applicability, whereas the performance of FA2 was inferior. Furthermore, all samples underwent leaching tests to evaluate their resistance, and they all met the standard criteria for reuse.

Fly ash, apart from serving as a supplementary cementitious material, has also been utilized in the synthesis of lightweight aggregates, either through pre-synthesis or by grinding it to appropriate particle sizes. Several studies suggest that incorporating fly ash in the production of lightweight aggregates can yield a significant reduction in density, accompanied by enhanced mechanical strength and durability. This presents advantages such as decreased transportation costs for concrete and mitigating environmental impacts associated with lightweight aggregate production (Kayali, 2008). Punlert *et al.* (2017) formulated a lightweight aggregate by blending clay with ash derived from combustion in the cellulose and paper sector. Their findings indicated excellent performance when using a 80:20 ratio of clay to ash and sintering temperature of 1250 °C. Substituting coarse aggregates with this lightweight aggregate at 100% in concrete production resulted in a 25% reduction in weight, among other beneficial properties.

2.1 Bottom Ash

The volume of research dedicated to formulating construction materials and civil infrastructure utilizing biomass fly ash far surpasses that focused on bottom ash. While fly ash generally exhibits finer and more uniform characteristics compared to bottom ash, recent significant research indicates its practical feasibility (Cabrera *et al.*, 2014).

Most biomass combustion processes yield bottom ash with a predominant composition of SiO₂ and CaO, alongside trace elements such as iron, aluminum, and magnesium, the proportions of which vary considerably depending on the biomass type and combustion system employed. Cabrera *et al.* (2020) conducted an extensive evaluation of the utilization of bottom biomass ash across various applications, including the formulation of innovative sustainable cement-based materials like cement mortar and concrete. **Table 1** presents key conclusions drawn from their research.

Table 1 – Some impacts and effects of adding biomass heavy ash to mortars, concretes and CTGM.

Application of BBA	Main Conclusions
Cement mortars	The prevalent presence of SiO_2 and CaO in most bottom ash samples renders them with favorable pozzolanic activity. Nevertheless, certain findings suggest that incorporating bottom biomass ash (BBA) into mortar formulations leads to a decrease in density and diminished mechanical strength, attributed to an increase in porosity induced by its addition. The results are inconclusive regarding whether this effect stems the presence of unburned organic matter in the bottom ash.
Concrete	Overall, the incorporation of biomass bottom ash into concrete formulations typically results in a deterioration of mechanical properties. Concrete mixes with lower water-to-binder ratios are particularly affected, as the dense ash tends to absorb water, thereby directly impacting both mechanical behavior and workability.
Cement-treated granular materials - CTGM (or cement soil)	Biomass bottom ash, characterized by elevated levels of CaO and $\text{Al}+\text{Si}+\text{Fe}$ in its composition, enhances the mechanical properties of treated soil when combined with cement. Moreover, the substantial CaO content has been demonstrated to enhance the bearing capacity of soils.

Source: Prepared by the author

A recent study utilized woody bottom biomass ash sourced from a large-scale fluidized bed boiler (22 MW), characterized by a high silica content in its chemical composition and mineralogical phases (SiO_2). The $\text{SiO}_2+\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3$ composition amounted to 91%. This ash was employed as a substitute for sand in mortar mixtures. The findings indicate that at lower and moderate substitution rates, there were improvements in mechanical strength and open porosity properties. Despite observing some alterations in hydration degree and kinetics, the utilization of this biomass bottom ash appears feasible as a sand material in the formulation of mortars and cementitious materials (Schlupp et al., 2023).

Another important construction material with high embodied energy consumption are bricks, the production of which uses tens of GWh including electrical and thermal energy, mainly due to the consumption of natural gas. In this scenario, research is also studied the utilization of lignocellulosic biomass ashes as source to production new and sustainable formulations of bricks (Labaeid *et al.* 2012). Although there are several kinds of bricks (like Common Burnt Clay Bricks, concrete bricks, Sand Lime Bricks, Engineering Bricks, acid proof bricks, Flay Ash Clay Bricks and other variations) the traditional bricks

production involves the preparation and molding of raw materials (such as clay, shale, etc.), followed by a high-temperature firing process wherein sintering and mechanical stabilization of the brick occur.

Research has demonstrated the technical feasibility of incorporating bottom biomass ash (derived from pine-olive pruning, wood, olive pomace, and olive stone) at a replacement rate of 20% of clay in brick manufacturing processes. It was observed that the addition of biomass enhances the thermal insulation properties of the bricks. However, an excess of bottom wood ash resulted in a reduction in compressive strength of approximately 18-31% compared to traditional clay bricks. From an environmental perspective, the utilization of biomass bottom ash, particularly from wood, emerges as a promising alternative for promoting circular economy principles and mitigating the environmental impacts associated with residual ash disposal in landfills (Eliche-Quesada et al., 2017).

In addition to fly ash, several studies have indicated the potential use of biomass bottom ash in the manufacturing of lightweight aggregates for the production of lightweight concrete. These studies have explored the combustion of common biomass sources such as wood and have examined ash derived from the incineration process of urban solid waste. Investigations have focused on varying replacement and mixing rates with expanded clay, alongside thermal sintering processes (Cuenca-Moyano et al., 2023; Woo et al., 2021; Giro-Paloma et al., 2017).

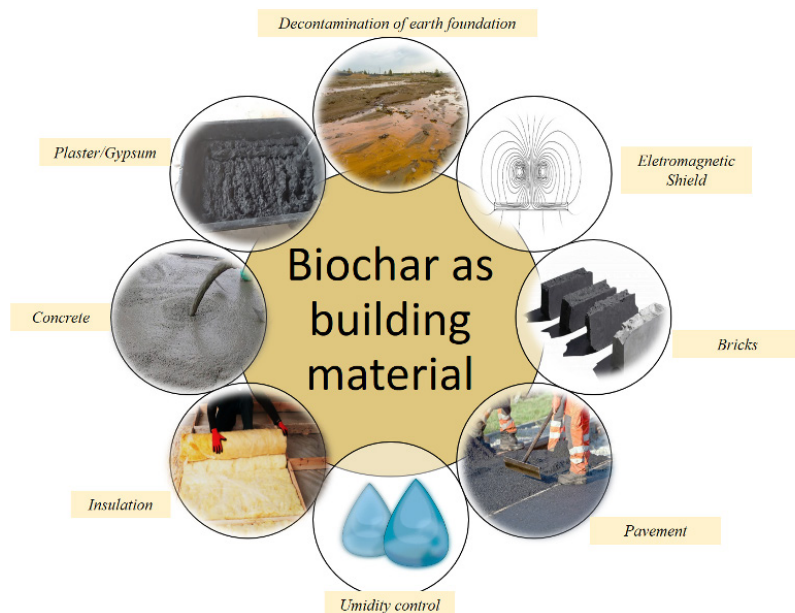
3 Biochar applications

Biochar is a solid carbonaceous produced through thermochemical processing at high temperatures and in the absence of oxygen of the several kind of materials like organic waste such as crop residues, forestry waste, urban solid waste fractions, animal manure, and sewage sludge. The primary method for generating biochar is through the pyrolysis process, wherein biomass is fractionated into biochar, gas, and bio-oil. Slow pyrolysis, conducted at temperatures ranging from 300 to 500°C with extended residence times, yields the highest quantity of biochar. Intermediate and fast pyrolysis processes also produce biochar, albeit with lower yields. Additionally, traditional methods like gasification and innovative techniques such as hydrothermal carbonization and flash carbonization, involving intense conditions of temperature, pressure, and biomass input, have emerged as potential biochar production methods, each imparting specific energy and biochar characteristics. Owing to its stable carbonaceous structure, biochar has garnered significant attention for various applications, serving as a versatile tool for circular

bioeconomy strategies. These applications include soil amendment, energy storage, catalyst and absorbent production, composting, among others (Yaashikaa et al., 2020).

According to IPCC (International Panel Carbon Control) guidelines, biochar is one of the five technologies recognized for carbon sequestration, with 1 ton of biochar saving around 2.2 tons of CO₂ (Pecha et al. 2022). Biochar has emerged as a significant material in the construction and pavement sectors, primarily owing to its capacity for carbon sequestration. Its utilization substantially contributes to mitigating the greenhouse effect associated with the production and use of construction materials, while also enhancing their quality. These properties position biochar as a powerful tool for fostering the development of low-carbon cities (Chen et al., 2023). Figure 5 illustrates various applications of biochar in this sector.

Figure 5 – Biochar applications as building material.



Source: Prepared by the author

3.1 Biochar as supplementary cementitious material (SCM)

Each biochar generation process, whether through pyrolysis, gasification, or hydrothermal conditions, yields biochar with specific characteristics and properties. However, biochar produced via the traditional fast pyrolytic process generally exhibits favorable properties for serving as supplementary cementitious materials. These properties include a high specific surface area and increased water sorption capacity, enabling significant cementitious replacement values. Numerous studies have been published investigating

the formulation of cement and aggregate substitution in construction materials. These studies encompass analyses of rheology, thermal and mechanical properties, cement hydration mechanisms, and environmental considerations (Mensah et al., 2021).

Numerous published studies have indicated that the addition of biochar to cement paste or composites significantly influences the performance of these materials. Parameters such as workability, hydration, as well as transfer and mechanical properties, have been shown to improve with the incorporation of biochar as a supplementary cementitious material. Maljaee *et al.* (2022) underscore in their study that the mechanical properties and moisture transfer in cementitious materials containing added biochar are strongly dependent on and directly influenced by the physicochemical characteristics of the biochar, the type of feedstock utilized, its granulometry, and the conditions during the formulation of the cementitious material.

Several significant research studies have examined the effects of incorporating biochar into cementitious materials. **Tables 2, 3, and 4** provide a summary of the primary causes and observed effects on the physical, mechanical, and durability properties of cementitious materials resulting from the addition of biochar sourced from various origins and processing methods (Gupta et al., 2018; Akinyemi et al., 2020).

Table 2 – General effects of biochar addition on the physical properties of cementitious composites.

Propertie	Effects and results observed
Workability	The incorporation of waste biochar typically results in a decrease in the workability of mortar mixes. This reduction can be attributed to the high-water absorption capacity of biochar, wherein the mixture restricts the availability of water necessary for workability. Consequently, achieving optimal workability necessitates a greater demand for water in the mixture.
Setting Times	The incorporation of biochar into cement-based materials has been found to decrease setting times primarily through two mechanisms. Firstly, biochar particles act as additional nucleation sites for cement hydration, accelerating the hydration process and enhancing the formation rate of hydration products such as calcium hydroxide (Ca(OH) ₂) and calcium silicate hydrate (C-S-H). This accelerated formation of hydration products results in a reduction in setting time. Additionally, the presence of biochar leads to a reduction in free water content, further contributing to the decrease in setting time.
Air Content	The incorporation of biochar into mortar mixes has been observed to increase the air content, primarily attributed to the porous structure of biochar.

Source: Prepared by the author

Table 3 - General effects of biochar addition on the mechanical properties of cementitious composites.

Properties	Effects and results observed
Compressive strength	Compressive strength exhibited varied responses in accordance with technical data available in the literature. However, it is generally indicated that incorporating low levels of biochar in lieu of Portland cement in mortar mixes may result in a slight improvement in compressive strength.
Tensile strength	In a manner analogous to compressive strength, modest enhancements in compressive strength are observed with minor rates of substitution of biochar derived from wood waste (up to approximately 2%). However, augmenting this proportion results in a deterioration of this parameter. The introduction of elevated levels of this type of biochar correlates with a decline in tensile strength, attributed to a reduction in the quantity of hydrated calcium silicate formed relative to lower cement content. Conversely, the incorporation of rice husk biochar confers a benefit to tensile strength when utilized for up to 10% cement replacement. In this instance, the potential refinement of the interfacial transition zone is ascribed as a contributing factor.
Flexural strength	The enhancement of flexural strength in concrete upon the addition of biochar is contingent upon factors such as the biochar's source and the curing methodology employed. In instances where the inclusion of biochar results in a reduction of pore content within concrete, an amelioration of flow resistance is observed. Additionally, research indicates that the wet curing process yields more favorable outcomes and is recommended for cementitious composites containing biochar. In contrast, air curing may yield marginal improvements in flux resistance.

Source: Prepared by the author

Table 4 – General effects of biochar addition on the durability properties of cementitious composites.

Properties	Effects and results observed
Water absorption	Even at low contents (< 5%), biochar demonstrates an ability to diminish the porosity within mortar mixtures. This reduction in porosity restricts water absorption, thereby limiting the depth of water penetration.
Shrinkage properties	The impact of biochar on shrinkage properties remains ambiguous and heavily dependent on the biochar's raw material and production conditions. Some findings suggest that when biochar replaces cement, it may increase drying shrinkage during early stages. However, at later ages, even at low levels of cement replacement (2%), a decrease in shrinkage can be observed.
Resistance to elevated temperature	When compared to concretes produced solely with Portland Cement, the incorporation of biochar into the concrete mix was observed to enhance resistance to temperature rise. Concretes formulated with a fraction of biochar replacing cement exhibited reduced mass losses at elevated temperatures (550°C). The porous structure of biochar contributes to a decrease in the thermal conductivity of the mixture and impedes the accumulation of pressure within the composites.

Source: Prepared by the author

3.2 Biochar for insulation material and electromagnetic shield

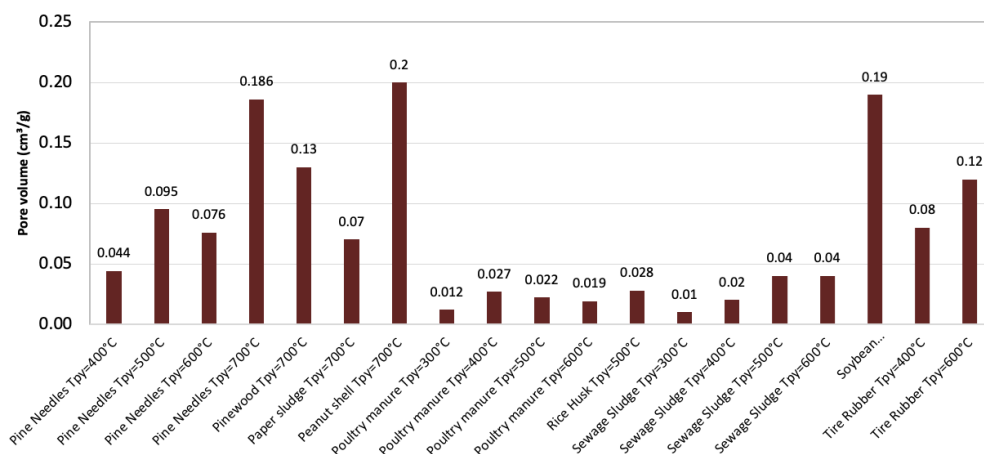
Due to its porosity and fines generation characteristics, biochar has great potential to replace fine aggregates in concrete formulations. Furthermore, its porous structure assure low thermal conductivity for biochar based concretes contributing for thermal insulation of the buildings. The extent of porosity in biochar is strongly influenced by the biomass feedstock, pyrolysis process, and pyrolysis temperature. Moderate pyrolysis temperatures are known to yield higher levels of porosity in biochar (Li *et al*, 2023).

The incorporation of biochar into cementitious materials promotes increased porosity within the new material, facilitating multidimensional heat distribution and mitigating unidirectional heat flow, thus enhancing thermal insulation properties. Several studies have demonstrated that the addition of biochar results in a reduction of thermal conductivity in biochar-cement composites by approximately 25% and in biochar-clay composites by up to 67% (Osman, 2024).

Another notable benefit attributed to the incorporation of biochar into cementitious composites is its potential for acoustic insulation and sound absorption. The interconnected network of pores within the biochar structure creates a pathway for sound waves to pass through, dissipating them through refraction effects and converting them into heat within the pores (Cuthbertson, 2019). Additionally, studies suggest that the enhanced acoustic insulation achieved through the addition of biochar within the frequency range of 20-2000 Hz exhibits a significant sound absorption coefficient, indicating promising potential for commercial utilization in the construction of panels for soundproof environments (Osman et al., 2024; Raja et al., 2023).

The findings indicate that incorporating biochar into cementitious composites, including clay composites, tends to decrease the density of the mixture, particularly in concretes formulated with biochar. This addition leads to significant enhancements in thermal and acoustic insulation properties. The principal attribute of biochar contributing to these property enhancements is its elevated level of porosity. Figure 6 depicts various types of biochar derived from diverse feedstocks and pyrolysis temperatures (Ahmad et al., 2014).

Figure 6 – Pore volume of biochar derived from various biomass sources.



Note: Tpy: pyrolysis temperature

Source: Prepared by the author

In addition to its role in providing thermal and acoustic insulation within building materials, biochar exhibits advanced applications as a construction material for protected environments. Its physicochemical properties, characterized by an amorphous carbohydrate structure and electrical conductivity, render biochar suitable for use as a lightweight construction material endowed with electromagnetic shield characteristics. This represents a significant application in construction, particularly in the contemporary era dominated by technology-driven lifestyles where exposure to electromagnetic fields is nearly unavoidable. Effective strategies to mitigate exposure involve reducing exposure time, distance, and employing shielding measures. Electromagnetic Interference (EMI) shielding materials operate through absorption and reflection mechanisms reliant on properties such as electrical conductivity and magnetic permeability. Certain carbon-based materials, including biochar, demonstrate electromagnetic shielding effects through both mechanisms, which can be further enhanced with the incorporation of metal oxide nanoparticles (Natalio et al., 2020).

For EMI applications, the structural properties of biochar are highly relevant, such as the quantity and dispersion of micropores. In general, pyrolysis processes at higher temperatures, around 700°C, microporosity and surface uniformity tend to increase in the biochar structure, while at lower temperatures amorphous regions are often observed. This greater porosity blocks the programming of electromagnetic waves, dissipating them in the form of heat due to impedance dissimilarity, improving microwave absorption properties. Furthermore, the greater number of micropores makes biochar an even lighter material for the mixing and formulation methods of polymer-based EMI shielding composites (Nikolopoulos *et al.* 2023)

Some studies have investigated the performance of Cement-based and polymer composites as constructive materials for electromagnetic shielding. di Summa *et al.* (2023) examined the impact of adding varying amounts of wood biochar (commercial) and sewage sludge on the magnetic shielding properties, considering the influence of different biochar contents and water levels in the cement paste formulation. They reported shielding effectiveness values exceeding 20 dB with wood biochar, with wet curing demonstrating superior benefits over air curing for EMI properties. Fenta and Ali (2024) investigated the effects of different biochars, each with varying carbon contents, obtained from pine wood, maize cob, sugarcane bagasse, and coffee husk through slow pyrolysis, when blended with HDPP for producing composites with electromagnetic shielding properties. Pine wood biochar exhibited the highest carbon content, pore volume (0.236 cm³/g), pore radius (9.897 Å), and specific surface area (734.5 m²/g). Composites containing 30-40% biochar showed significant enhancements in EM shielding effectiveness, reaching 44.03 dB at 2.1 GHz. Furthermore, the presence of func-

tional groups such as aromatic, aliphatic, alcohols, phenols, and oxygen-containing functional groups contributed to notable improvements in other pertinent properties of the composite, including electrical conductivity, thermal stability, composite crystallinity, and thermal stability.

3.3 Biochar for pavementation

One of the main applications of biochar, whether as a supplementary material or a substitute for aggregates in construction materials, involves its incorporation into asphalt-based materials for paving. This utilization serves dual purposes: firstly, it aids in reducing the carbon footprint within this sector, and secondly, it enhances the properties of the asphalt.

Carbon black and carbon fibers, traditionally employed as carbonaceous additives in asphalt mixtures due to their ready availability, primarily stem from fossil sources. In contrast, biochar has the capability to sequester and retain approximately 850 kg of CO₂ per ton of dry material over decades, rendering it an environmentally friendly source of carbonaceous material for the production of more sustainable modified asphalts (Zhao et al., 2014).

As previously mentioned, the characteristics of biochar crucially depend on the biomass source and pyrolysis process parameters, exerting significant influence on its performance as an asphalt additive. Key properties affecting its efficacy in this regard include:

- Presence of aromatic carbons: Enhances suspension stability with the asphalt binder, thereby improving the physical stability of modified asphalt;
- High specific area: Facilitates increased interaction between the binder and other asphalt constituents;
- Porous and fibrous structure: Acts as a skeletal filler, augmenting binder performance.

These properties have led to observations indicating that incorporating biochar in modified asphalts increases the proportion of viscous elements in the binder, resulting in notable enhancements in hot properties such as penetration, softening point, and viscosity, by approximately 35%. This underscores its applicability in tropical and sub-tropical regions (Ma et al., 2022).

Zhao *et al.* (2014) evaluated the performance of hot mixed asphalt (HMA) utilizing binders modified with biochar, alongside two other reference additives (carbon black powder and microsized carbon fibers), assessing various rheological properties. Results indicated significant improvements in moisture susceptibility and resistance to crack propagation with biochar additions ranging from 5-10%, thus suggesting its potential as an excellent additive for paving engineering (Legan *et al.*, 2022; Li *et al.*, 2023).

However, notwithstanding the evident benefits, it's worth noting that biochar contains species, originating from biomass sources like nitrogen and phosphorus, which may leach as pollutants, particularly when applied in porous asphalt pavements, whether as a filler for asphalt formulation or as a filter layer (Jiawen Liu *et al.*, 2021).

Generally, studies employ biochar additions in the range of 2-20% in modified asphalt, with optimal values often reported below 10%. Despite the promising potential demonstrated in bio-asphalt production, these investigations are relatively recent, with fewer than ten years of publications, necessitating further validation across various aspects including biomass type, pyrolysis parameters, asphalt type, socioeconomic and environmental impacts, and the study of binder-biochar-aggregate interactions in asphalt formulation (Rondón-Quintana *et al.*, 2022).

4. Addressing CO₂ emissions in construction: opportunities and challenges

The utilization of biochar in the construction industry has been the subject of intensive studies by various researchers. According to Aman *et al.* (2022), the addition of biochar as a partial substitute for cement in concrete not only enhances its properties but also contributes to the reduction of CO₂ emissions. Experiments have indicated that the mineral carbonation of concrete composites containing biochar can increase their strength, thanks to the formation of calcium carbonate. Additionally, studies highlight the efficacy of carbon dioxide curing for concrete composites with biochar, demonstrating greater CO₂ capture compared to biochar-free mortar.

Regional governments have shown growing concern about carbon emissions from the construction industry, as pointed out by Chen *et al.* (2023). The construction phase presents considerable annual emissions per square meter, mainly due to the use and transportation of construction materials and equipment operation. The adoption of

sustainable materials and environmentally friendly practices during construction can significantly reduce these emissions.

Legan *et al.* (2022) emphasize the importance of reusing biomass waste in the form of biochar in construction materials to improve their mechanical and chemical properties, as well as reduce the carbon footprint. Studies have shown that the pyrolysis of biomass waste for biochar production is preferable to incineration due to lower greenhouse gas emissions. Biochar is capable of capturing CO₂, contributing to the reduction of carbon emissions in the construction industry.

The addition of biochar to cement has also been studied to mitigate CO₂ emissions associated with Portland cement production, as reported by Maljaee *et al.* (2021). Studies have indicated that biochar can improve the mechanical properties of cement and reduce greenhouse gas emissions during production. Additionally, biochar can be used in low-impact systems to treat stormwater, reducing urban runoff.

Zhang *et al.* (2022) highlight the importance of using filler materials, such as biochar, as a promising way to reduce CO₂ emissions in the production of construction materials. Studies have shown that the incorporation of biochar into cement systems can reduce CO₂ emissions by more than 13%. Furthermore, biochar as an aggregate in concrete can enhance CO₂ absorption and reduce carbon emissions associated with concrete production.

In summary, the use of biochar in the construction industry presents significant potential to reduce CO₂ emissions and promote environmental sustainability. However, further research is needed to fully understand the impact of biochar on different construction materials and its potential to mitigate climate change.

5. Conclusions, practical actions and future challenges

The construction industry stands at a critical juncture, facing the imperative of mitigating its substantial carbon footprint while concurrently addressing the escalating global demand for infrastructure. The imperative to reduce CO₂ emissions within the production of construction materials is of paramount importance, and the integration of biochar emerges as a promising avenue towards achieving sustainability objectives.

The production of bioenergy from biomass in thermoelectric plants can be considered a major producer of ash with high potential to be introduced as Supplementary Cementi-

tious Material (MCS), being one of the ways to slow down the environmental impacts associated with the generation of construction materials such as pozzolanic materials, lightweight aggregates, bricks formulations etc. Allowing the evolution of circular economy projects leading to co-production of bioenergy and construction materials with a lower environmental impact

Research on the use of biomass ash deserves to be highlighted in Brazil, due to the significant potential for using bioelectricity in its electrical matrix and, in addition, biomass with low alkalinity in ash, such as rice husks, coconut shells, pine shells, is highly prone to generate ash with good pozzolanic and cementitious properties. However, studies on greater durability that take into account the evaluation of the resistance of new ash-based concretes, taking into account variations in climate cycles and temporary events, are still scarce.

The efficacy of biochar in abating CO₂ emissions during the production of materials, particularly in concrete manufacturing, has been extensively documented. Numerous studies have underscored its potential not only in diminishing emissions but also in actively sequestering CO₂ from the atmosphere, thereby fostering a more favorable carbon balance throughout the lifecycle of construction materials.

However, unlocking the full potential of biochar in construction necessitates overcoming a myriad of challenges. Ensuring the widespread availability of biochar while simultaneously maintaining economic feasibility stands as a primary concern. Moreover, careful evaluation of environmental and social considerations is imperative to mitigate any adverse impacts associated with the scale-up of biochar production.

Despite these challenges, the integration of biomass ashes and biochar into construction offers a unique opportunity to mitigate CO₂ emissions and propel environmental sustainability forward. Sustained research endeavors and advancements in technology are indispensable in realizing the complete potential of these biomaterials and facilitating the transition towards more environmentally conscious and low-carbon construction practices on a global scale.

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7 References

Ahmad, M., Rajapaksha, A., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. S., and Ok, Y. S., "Biochar as a Sorbent for Contaminant Management in Soil and Water: A Review," **Chemosphere**, Vol. 99, 2013, pp. 19-33, <https://doi.org/10.1016/j.chemosphere.2013.10.071>.

Ali, K. A., Ahmad, M. I., and Yusup, Y., "Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector," **Sustainability**, Vol. 12, 2020, Article 7427, <https://doi.org/10.3390/su12187427>

Aman, A.M.N.; Selvarajoo, A.; Lau, T.L.; Chen, W.-H. Biochar as Cement Replacement to Enhance Concrete Composite Properties: A Review. **Energies** 2022, 15, 7662. <https://doi.org/10.3390/en15207662>.

Barcelo, L., Kline, J., Walenta, G., and Gartner, E., "Cement and Carbon Emissions," **Materials and Structures**, Vol. 47, 2014, pp. 1055-1065, <https://doi.org/10.1617/s11527-013-0114-5>

Balanço energético Nacional. **Empresa de Pesquisa Energética**. Disponível em: <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2023>. Acesso 02 de Janeiro de 2024

Cabrera, M., Galvin, A. P., Agrela, F., Carvajal, M. D., and Ayuso, J., "Characterization and Technical Feasibility of Using Biomass Bottom Ash for Civil Infrastructures," **Construction and Building Materials**, Vol. 58, 2014, pp. 234-244, <https://doi.org/10.1016/j.conbuildmat.2014.01.087>.

Chen, L., Huang, L., Hua, J. *et al.* Green construction for low-carbon cities: a review. **Environ Chem Lett** 21, 1627–1657 (2023). <https://doi.org/10.1007/s10311-022-01544-4>

Cuthbertson, D., Berardi, U., Briens, C., and Berruti, F., "Biochar from Residual Biomass as a Concrete Filler for Improved Thermal and Acoustic Properties," **Biomass and Bioenergy**, Vol. 120, 2018, pp. 77-83, <https://doi.org/10.1016/j.biombioe.2018.11.007>.

Nikolopoulos, C. D., Baklezos, A. T., Kapetanakis, T. N., Vardiambasis, I. O., Tsubota, T., and Kalderis, D., "Characterization of the Electromagnetic Shielding Effectiveness of Biochar-Based Materials," **IEEE Access**, Vol. 11, 2023, pp. 6413-6420, <https://doi.org/10.1109/ACCESS.2023.3237327>.

Cuenca-Moyano, G. M., Cabrera, M., López-Alonso, M., Martínez-Echevarría, M. J., Agrela, F., and Rosales, J., "Characterization and Technical Feasibility of Using Biomass Bottom Ash for Civil Infrastructures," **Journal of Building Engineering**, Vol. 69, 2023, Article 106889.

di Summa, D., Ruscica, G., Savi, P., Manacorda, A., and Montanari, A., "Biochar-Containing Construction Materials for Electromagnetic Shielding in the Microwave Frequency Region: The Importance of Water Content," **Clean Technologies and Environmental Policy**, Vol. 25, 2023, pp. 1099-1108, <https://doi.org/10.1007/s10098-021-02182-0>.

Eliche-Quesada, D., Felipe-Sesé, M. A., Martínez-Martínez, S., and Pérez-Villarejo, L., "Comparative Study of the Use of Different Biomass Bottom Ash in the Manufacture of Ceramic Bricks," **Journal of Materials in Civil Engineering**, Vol. 29, No. 12, 2017, Article 04017238, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002078](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002078)

Fenta AA, Ali AN. Development of biochar/HDPE composites and characterization of the effects of carbon loadings on the electromagnetic shielding properties. **Heliyon**. 2024 Jan 11;10(2):e24424. doi: 10.1016/j.heliyon.2024.e24424. PMID: 38293532; PMCID: PMC10826733.

Schlupp, F., Page, J., Djelal, C., and Libessart, L., "Use of Biomass Bottom Ash as Granular Substitute in Mortar," **Journal of Building Engineering**, Vol. 75, 2023, Article 106927, <https://doi.org/10.1016/j.jobe.2023.106927>.

García-Maraver, A., Mata-Sanchez, J., Carpio, M., and Jiménez, J. A., "Critical Review of Predictive Coefficients for Biomass Ash Deposition Tendency," **Journal of the Energy Institute**, Vol. 90, 2017, pp. 214-228, <https://doi.org/10.1016/j.joei.2016.02.002>.

Giro-Paloma, J., Ribas-Manero, V., Maldonado-Alameda, A., Formosa, J., and Chimenos, J. M., "Use of Municipal Solid Waste Incineration Bottom Ash and Crop By-Product for Producing Lightweight Aggregate," **IOP Conference Series: Materials Science and Engineering**, Vol. 251, 2017, Article 012126, <https://doi.org/10.1088/1757-899X/251/1/012126>.

Gupta, S., Kua, H. W., and Koh, H. J., "Application of Biochar from Food and Wood Waste as Green Admixture for Cement Mortar," **Science of the Total Environment**, Vol. 619, 2018, pp. 419-435, <https://doi.org/10.1016/j.scitotenv.2017.11.030>.

Huang, B., Gao, X., Xu, X., Song, J., Geng, Y., Sarkis, J., Fishman, T., Kua, H., and Nakatani, J., "A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials," **One Earth**, Vol. 3, 2020, pp. 564-569, <https://doi.org/10.1016/j.oneear.2020.10.010>.

Maljaee, H., Madadi, R., Paiva, H., Tarelho, L., and Ferreira, V. M., "Incorporation of Biochar in Cementitious Materials: A Roadmap of Biochar Selection," **Construction and Building Materials**, Vol. 302, 2021, Article 122757, <https://doi.org/10.1016/j.conbuildmat.2021.122757>

Kayali, O., "Fly Ash Lightweight Aggregates in High Performance Concrete," **Construction and Building Materials**, Vol. 22, No. 12, 2008, pp. 2393-2399, <https://doi.org/10.1016/j.conbuildmat.2007.11.002>.

Legan, M., Gotvajn, A. Ž., and Zupan, K., "Potential of Biochar Use in Building Materials," **Journal of Environmental Management**, Vol. 309, 2022, Article 114704, <https://doi.org/10.1016/j.jenvman.2022.114704>.

Li, H., Wang, L., Zhang, Y., Yang, J., Tsang, D., and Mechtcherine, V., "Biochar for Sustainable Construction Industry," in **Advances in Biochar Utilization**, 2023, pp. 15-32, <https://doi.org/10.1016/B978-0-323-91873-2.00015-7>.

Liu, J., Li, H., Harvey, J., Zhang, H., and Tian, Y., "Application of Biochar on the Runoff Purification Performance of Porous Asphalt Pavement," **Transportation Safety and Environment**, Vol. 3, No. 4, December 2021, Article tdab026, <https://doi.org/10.1093/tse/tdab026>.

Ma, F., Dai, J., Fu, Z., Li, C., Wen, Y., Jia, M., Wang, Y., and Shi, K., "Biochar for Asphalt Modification: A Case of High-Temperature Properties Improvement," **Science of the Total Environment**, Vol. 804, 2022, Article 150194, <https://doi.org/10.1016/j.scitotenv.2021.150194>.

Maljaee, H., Madadi, R., Paiva, H., Tarelho, L., and Ferreira, V. M., "Incorporation of Biochar in Cementitious Materials: A Roadmap of Biochar Selection," **Construction and Building Materials**, Vol. 283, 2021, <https://doi.org/10.1016/j.conbuildmat.2021.122757>.

Mensah, R. A., Shanmugam, V., Narayanan, S., Razavi, N., Ulfberg, A., Blanksvärd, T., Sayahi, F., Simonsson, P., Reinke, B., Försth, M., et al., "Biochar-Added Cementitious Materials—A Review on Mechanical, Thermal, and Environmental Properties," **Sustainability**, Vol. 13, 2021, Article 9336, <https://doi.org/10.3390/su13169336>.

Natalio, F., Corrales, T. P., Feldman, Y., Lew, B., and Graber, E. R., "Sustainable Lightweight Biochar-Based Composites with Electromagnetic Shielding Properties," **ACS Omega**, Vol. 5, No. 50, 2020, pp. 32490-32497, <https://doi.org/10.1021/acsomega.0c05357>.

Punlert, S., Laoratanakul, P., Kongdee, R., and Suntako, R., "Effect of Lightweight Aggregates Prepared from Fly Ash on Lightweight Concrete Performances," **Journal of Physics: Conference Series**, Vol. 901, 2017, Article 012086, <https://doi.org/10.1088/1742-6596/901/1/012086>.

Raja, P., Murugan, V., Ravichandran, S., Behera, L., Mensah, R., Mani, S., Kasi, A. K., Babu, K. N. B., Sas, G., Vahabi, H., and Das, O., "A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings," **Macromolecular Materials and Engineering**, Vol. 308, 2023, <https://doi.org/10.1002/mame.202300086>.

Rondón-Quintana, H. A., Reyes-Lizcano, F. A., Chaves-Pabón, S. B., Bastidas-Martínez, J. G., and Zafra-Mejía, C. A., "Use of Biochar in Asphalts: Review," **Sustainability**, Vol. 14, No. 8, 2022, Article 4745, <https://doi.org/10.3390/su14084745>.

Shuvo, A., and Sharmin, S., "Carbon Emission Scenario of Conventional Buildings," **Journal of Construction Engineering, Management & Innovation**, Vol. 4, 2021, <https://doi.org/10.31462/jcemi.2021.03134150>.

Osman, A. I., Farghali, M., Dong, Y., et al., "Reducing the Carbon Footprint of Buildings Using Biochar-Based Bricks and Insulating Materials: A Review," **Environmental Chemistry Letters**, Vol. 22, 2024, pp. 71–104, <https://doi.org/10.1007/s10311-023-01662-7>.

Sun, L., Yao, C., Guo, A., and Yu, Z., "A Review on the Application of Lignocellulosic Biomass Ash in Cement-Based Composites," **Materials**, Vol. 16, 2023, Article 5997, <https://doi.org/10.3390/ma16185997>.

Tosti, L., Zomeren, A., Pels, J., and Comans, R., "Technical and Environmental Performance of Lower Carbon Footprint Cement Mortars Containing Biomass Fly Ash as a Secondary Cementitious Material," **Resources, Conservation and Recycling**, Vol. 134, 2018, Article 10.1016/j.resconrec.2018.03.004.

Yaashikaa, P. R., Kumar, P. S., Varjani, S., and Saravanan, A., "A Critical Review on the Biochar Production Techniques, Characterization, Stability, and Applications for Circular Bioeconomy," **Biotechnology Reports**, Vol. 28, 2020, Article e00570, <https://doi.org/10.1016/j.btre.2020.e00570>.

Woo, B.-H., Jeon, I.-K., Yoo, D.-H., Kim, S.-S., Lee, J.-B., and Kim, H.-G., "Utilization of Municipal Solid Waste Incineration Bottom Ash as Fine Aggregate of Cement Mortars," **Sustainability**, Vol. 13, 2021, Article 8832, <https://doi.org/10.3390/su13168832>.

Zhang, Y., He, M., Wang, L., et al., "Biochar as Construction Materials for Achieving Carbon Neutrality," **Biochar**, Vol. 4, 2022, Article 59, <https://doi.org/10.1007/s42773-022-00182-x>.

Zhao, S., Huang, B., Shu, X., and Ye, P., "Laboratory Investigation of Biochar-Modified Asphalt Mixture," **Transportation Research Record**, Vol. 2445, No. 1, 2014, pp. 56–63, <https://doi.org/10.3141/2445-07>.

10.29327/2152495.8.26-1

