

Article

Innovations in Green Concrete: Combining Metakaolin and Arundo Grass Biochar for Enhanced Sustainability

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Abstract: Cement production is a major contributor to greenhouse gas (GHG) emissions, driving the need for alternative materials to reduce its environmental footprint and enhance sustainability. This study investigates the use of biochar derived from Arundo grass as a partial replacement for cement in conjunction with metakaolin to enhance the mechanical properties and environmental performance of concrete. Compressive strength analysis and sorptivity analysis were conducted to evaluate the effects of metakaolin on Arundo grass biochar concrete. The findings revealed that incorporating biochar and metakaolin negatively impacted workability. However, a mixture of 5% biochar and 10% metakaolin (by weight of cement) significantly improved early 7-day compressive strength compared to samples containing only 5% biochar and the control mix. Additionally, the sorptivity analysis indicated that this combination maintained comparable absorption rates to the control sample. In terms of sustainability, the partial replacement of cement with 5% biochar and 10% metakaolin reduced CO₂ emissions by 75 kg per cubic meter of concrete, showcasing its contribution to lowering the carbon footprint of concrete production. Overall, this study demonstrates the potential of combining biochar and metakaolin to develop more sustainable concrete solutions with enhanced early compressive strength. However, further research is needed to optimize long-term performance and workability for broader adoption in sustainable construction practices.

Keywords: low-carbon concrete; sustainable concrete; biochar; metakaolin; sustainable construction materials



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1. Introduction

Concrete is the most widely used construction material globally, integral to the creation of foundations, bridges, pavements, and buildings. Made by mixing cement, sand, gravel, and water, concrete's popularity has surged alongside rapid urbanization over the past 50 years, increasing the demand for robust construction materials. Among these, concrete has demonstrated the highest growth rate, outpacing steel twofold and wood sixfold [1]. The process of mixing concrete emits minimal greenhouse gases, its environmental impact is largely due to the cement it requires. Cement production contributes approximately 8% of total global greenhouse gas emissions, primarily from its energy-intensive production process and chemical transformations [2]. In 2021, global cement production reached an astounding 4.4 billion tons, with the United States alone producing 92 million tons, which led to an estimated 1.7 billion tons of CO₂ emissions. Although manufacturing in the United States accounts for less than 1.5% of the country's total human-generated CO₂ emissions, the cumulative effect globally is substantial [3,4].

This significant carbon footprint has sparked an interest in carbon sequestering materials, such as biochar, for construction applications. Biochar, a carbon-rich and porous material produced through the thermal decomposition of biomass in an oxygen-limited environment, has traditionally been used as a soil amendment. However, its potential as a building material is gaining attention. Biochar's porous structure facilitates internal curing,

which enhances the hydration of cement particles, while its stability enables long-term CO₂ sequestration [5]. As a carbon-negative material, biochar could potentially offset up to 12% of global anthropogenic CO₂ emissions by 2050, sequestering 0.3–2 Gt CO₂ annually [6]. Studies also suggest that biochar's carbon-rich composition and internal curing effects can enhance the strength and durability of cement-based materials by reducing porosity [7].

Biochar can be produced from various biomass sources, including agricultural crop residues, forestry residues, wood processing byproducts, municipal waste, and wet waste. Agricultural biomass waste, such as corn stalks, sugarcane bagasse, and soybean husks, is abundant and does not interfere with food production. Forestry residues, including debris left after timber harvesting and wood processing byproducts like sawdust and bark, also serve as viable biomass sources. Municipal waste streams, such as paper, cotton, food scraps, and wood products, alongside wet waste, like treated sewage and animal manure, further expand the range of feedstocks. In the United States, wood and forestry waste generate approximately 12.2 million tons of material annually, representing about 8.3% of landfilled municipal solid waste (MSW) [8]. Fast-growing crops like *Arundo grass* are emerging as sustainable sources for biochar, benefiting from rapid maturation and adaptability across diverse climates [9]. These biomass streams provide a sustainable and economically feasible pathway for producing biochar, offering both environmental and material benefits for construction applications.

In the past decade, researchers have increasingly explored the use of biochar as a partial replacement for cement in concrete. For example, Akhtar and Sarmah [5] found that substituting biochar derived from poultry litter, rice husk, and pulp sludge led to reduced compressive strength but enhanced tensile and flexural strength. Jia et al. [10] investigated the use of biochar derived from municipal solid waste (MSW) at 600 °C as a partial replacement for 1–30% of cement by weight in concrete. Results showed that re-placing less than 5% of cement with biochar increased compressive strength by 9.2%, while 10% replacement significantly enhanced toughness, flexural, and tensile strength by 20%. However, concrete with minimal biochar exhibited reduced freeze–thaw resistance compared to the control and 10% replacement samples, with biochar also promoting calcium carbonate formation. In another study, Ling et al. [11] examined the effect of waste wood biochar dosage and fineness on the mechanical and durability properties of concrete. Results indicated that 1–3 wt.% biochar reduced carbonation depth and chloride ion diffusion while enhancing compressive and flexural strength, with optimal performance observed at 3 wt.% biochar and a particle size of 73.28 µm. The findings highlight biochar's potential to improve cement hydration and support the development of sustainable, high-performance concrete materials.

Revathi et al. [12] aimed to reduce atmospheric CO₂ by incorporating zeolite and bamboo biochar into concrete, leveraging their high pore volume and surface area for enhanced CO₂ absorption. Zeolite (25% and 50%) replaced fine aggregate, while bamboo biochar (0.5%, 1%, and 1.5%) replaced cement. Among the mixes tested, the combination of 50% zeolite and 1% bamboo biochar demonstrated optimal strength and CO₂ absorption properties. Asadi Zeidabadi et al. [13] studied the effect of rice husk biochar and found that both treated and untreated biochar added at 5% enhanced compressive and tensile strength. Gupta et al. [14] noted improved early compressive strength and reduced water sorptivity with wood sawdust biochar replacing 2% of cement, alongside a 6–7% reduction in CO₂ emissions.

Biochar has emerged as a promising material in mortar/concrete, with the potential to reduce CO₂ emissions based on the replacement rate used. While its application in biochar-cement composites is still relatively uncommon in the literature, several studies have demonstrated that biochar can significantly lower CO₂ and other GHG emissions from the mortar and concrete industry [15–17]. Pecha [18] found that replacing 15% of cement by weight with pine wood biochar could reduce the carbon footprint of concrete by 44.5%.

Furthermore, achieving a 32% replacement rate could lead to nearly carbon-neutral concrete, with a 98% reduction in emissions. In a study by Chen et al. [17], the use of

corn straw biochar as an SCM in mortar showed that a 5% replacement resulted in a GHG reduction of 32.4 kg/m³. Similarly, Chen et al. [15] investigated the incorporation of waste wood biochar into concrete mixes, revealing that a 10% addition significantly reduced CO₂ emissions, while a 30% replacement rate could produce fully carbon-negative concrete.

To enable higher incorporation of biochar in concrete, researchers have explored pre-treatment techniques and its pairing with supplementary cementitious materials (SCMs) to optimize both mechanical performance and CO₂ sequestration potential. For instance, Praneeth et al. [19] found that corn stover biochar used alongside fly ash led to increased CO₂ uptake and compressive strength, particularly at early ages. Similarly, Gupta and Kua [20] reported improved performance and cost efficiency when combining biochar with silica fume. In their study, Mishra et al. [21] explored the optimal combination of biochar and high-calcium fly ash to enhance mechanical performance and CO₂ uptake in cement mortar. Using response surface methodology (RSM), the researchers optimized the mix design, showing that up to 5% biochar can enhance performance and carbonation under accelerated conditions, while <1% is effective under normal curing. The carbonation process significantly improves fracture strength and elasticity, stores 50% of ambient CO₂ permanently, and reduces cement usage, offering a sustainable approach to construction materials. Gupta et al. [22] examined the effects of biochar and silica fume, partially replacing cement, on the shrinkage, hydration, strength, and permeability of cement mortar. Biochar from wood waste and coconut shells, used at 5 wt.% cement replacement and 33% silica fume replacement, reduced autogenous and drying shrinkage. Additionally, biochar enhanced hydration, strength, and water permeability, with a biochar–silica fume blend improving 28-day strength while maintaining performance comparable to silica fume-only mortar.

Metakaolin, derived from kaolin clay, has emerged as a promising SCM due to its pozzolanic activity and ability to enhance concrete performance. However, limited research exists on the combined use of biochar and metakaolin in concrete, particularly their synergistic effects on mechanical properties and environmental performance. This gap highlights the need for studies that explore biochar–metakaolin combinations to optimize CO₂ sequestration and improve concrete sustainability. This study addresses this gap by investigating the combined effects of biochar, derived from *Arundo grass*, and metakaolin on the mechanical and environmental properties of concrete. By partially replacing Portland cement with *Arundo grass* biochar and incorporating varying percentages of metakaolin, the research aims to assess their impact on compressive strength, durability, and CO₂ reduction potential. The study will involve characterizing biochar properties and evaluating the mechanical performance of biochar–metakaolin concrete.

2. Materials and Methods

2.1. Materials

2.1.1. *Arundo Grass* Biochar

Arundo grass (Figure 1a) was chosen for biochar production due to its rapid growth rate, high biomass yield, and adaptability to various environmental conditions. *Arundo grass* biochar (Figure 1b) was produced at the “Nexus” research facility at Appalachian State University using slow pyrolysis at a temperature range of 450–500 °C, a process that efficiently sequesters carbon dioxide captured during the growth phase, further enhancing its suitability for environmentally sustainable concrete applications. The key physical properties of the produced *Arundo grass* biochar are summarized in Table 1, while its elemental and chemical compositions are provided in Tables 2 and 3. The particle size analysis results are presented in Figure 2 and Table 4. It should be noted that the biochar used in each sample of this study was first sieved through a U.S. Standard #40 sieve, resulting in a maximum particle size of 425 µm. Utilizing *Arundo grass* biochar passed through a #40 sieve achieves a balance between ensuring adequate particle size for effective dispersion and maintaining optimal performance characteristics in concrete.

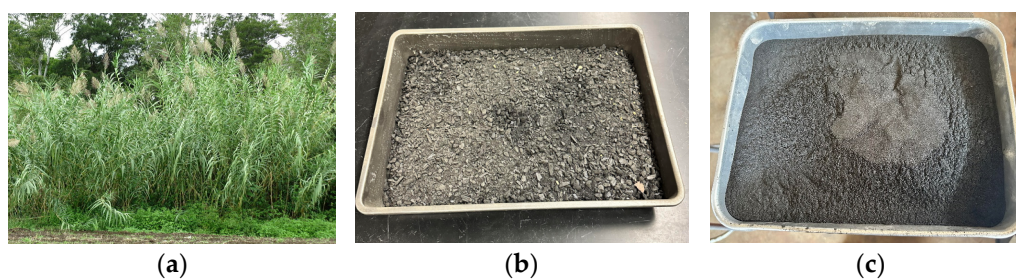


Figure 1. (a) Arundo Grass, (b) Arundo Grass Biochar, and (c) Sieved Arundo Grass Biochar.

Table 1. Physical Properties of Arundo Grass Biochar.

Density	pH	EC (Electrical Conductivity)	MC% (Moisture Content)	BET Surface Area	BET Pore Width
0.2 (gr/cm ³)	8.73	0.21 (mS/cm)	6.7%	323.351 m ² /g	5.300 nm

Table 2. Elemental Measurements of Arundo Grass Biochar.

Element	C	Ca	K	Mg	Fe	P	S	Mn	Al	Na
Meas.*	872,000	9080	15,900	2380	2240	1760	533	201	338	151

Table 3. Chemical Composition of Arundo Grass Biochar.

XRF Results	
Fe ₂ O ₃	2.675
Al ₂ O ₃	9.266
SiO ₂	14.45
Sum of SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ : 26.391	
CaO	21.73
K ₂ O	35.865
P ₂ O ₅	10.731
MnO	2.262
SO ₃	1.891
TiO ₂	1.13

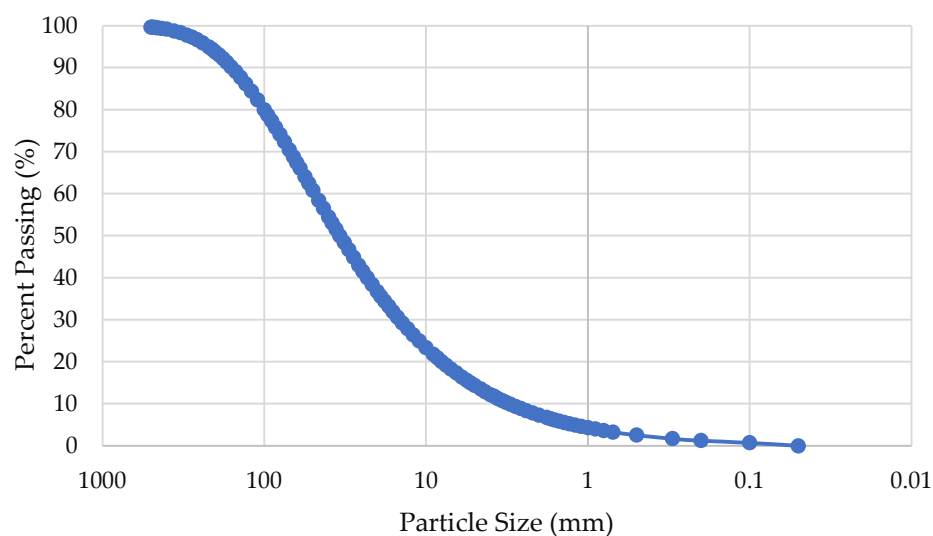


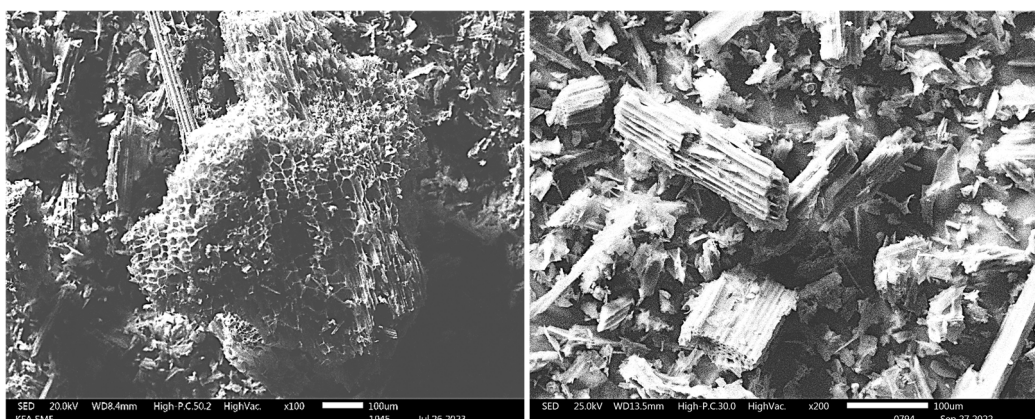
Figure 2. Particle Size Distribution of Arundo Grass Biochar.

Table 4. Particle Size Distribution of Arundo Grass Biochar.

Name	D ₁₀	D ₅₀	D ₉₀	Mean Size	Span
	μm	μm	μm	μm	μm
G-Biochar 2 min	2.7337	44.4747	128.3401	57.96	2.824
G-Biochar 5 min 2/2	1.732	12.537	77.4207	30.388	6.037

The porous structure of Arundo grass biochar, classified by pore size into micropores (≤ 2 nm), mesopores (2–50 nm), and macropores (≥ 50 nm), is a key factor in its performance in concrete [22]. The surface area and pore size distribution were measured with nitrogen adsorption at 77 K, using a Quanta chrome Autosorb-1 (Quantachrome Instruments, Boynton Beach, FL, USA) instrument after degassing 58 the samples for 18 h at 200 °C. The non-local density functional theory (NLDFT) model was applied to determine pore size distribution and volume from the adsorption data [23], with results shown in Table 1. The high BET surface area of 323.35 m²/g and an average pore width of 5.3 nm provide abundant interaction sites within the concrete mixture, improving bonding and potentially enhancing both strength and durability.

Scanning electron microscopy (SEM) analysis (Figure 3) revealed that Arundo grass biochar has a porous, honeycomb-like microstructure with angular and elongated particles. This morphology, formed by the release of volatiles during pyrolysis, makes it an excellent interlocking agent in concrete, where the pores also create adsorption sites for CO₂. Additionally, these pores help retain water in the mix, which aids in secondary hydration and further hardens the cement paste.

**Figure 3.** Arundo Grass Biochar SEM Image.

Energy dispersive X-ray spectroscopy (EDS) analysis (Figure 4) confirmed the elemental composition of the Arundo grass biochar, with primary elements including calcium, oxygen, and potassium, and lower levels of magnesium, aluminum, chromium, iron, manganese, and silicon. The relatively low silicon and aluminum content, however, may limit pozzolanic activity, potentially impacting the strength and durability of the biochar–concrete blend.

Arundo grass biochar exhibits properties that make it a valuable addition to concrete applications aimed at enhancing sustainability and reducing carbon emissions. With a carbon content of 87.2%, this biochar offers significant carbon sequestration potential, supporting environmental goals by effectively capturing and storing carbon. Its high carbon content also contributes to the durability and stability of concrete composites, as carbon-rich biochar is known to exhibit stable chemical bonds that enhance long-term performance. Chemically, the biochar’s composition includes notable quantities of potassium (K), calcium (Ca), and magnesium (Mg), as indicated by its elemental measurements, alongside oxides such as SiO₂, Al₂O₃, K₂O, and Fe₂O₃. These components provide additional benefits in

concrete applications, as elements like potassium and calcium can improve the material's strength and resilience. Furthermore, with a relatively high BET surface area of $323.35 \text{ m}^2/\text{g}$ and a pore width of 5.3 nm , Arundo grass biochar offers ample surface area for interactions with cement particles. This porosity and surface area distribution not only enhance the binding potential with cement but also facilitate internal curing, improving hydration and thus the mechanical properties of the resulting concrete. Additionally, a pH of 8.73 and the moderate electrical conductivity (0.21 mS/cm) suggest that this biochar is compatible with cement-based materials, as the slightly alkaline nature and low conductivity minimize interference with the cement hydration process. Given these properties, Arundo grass biochar holds promise for sustainable concrete formulations, acting as both a partial cement substitute and a carbon-sequestering agent, potentially reducing the overall environmental impact of concrete production.

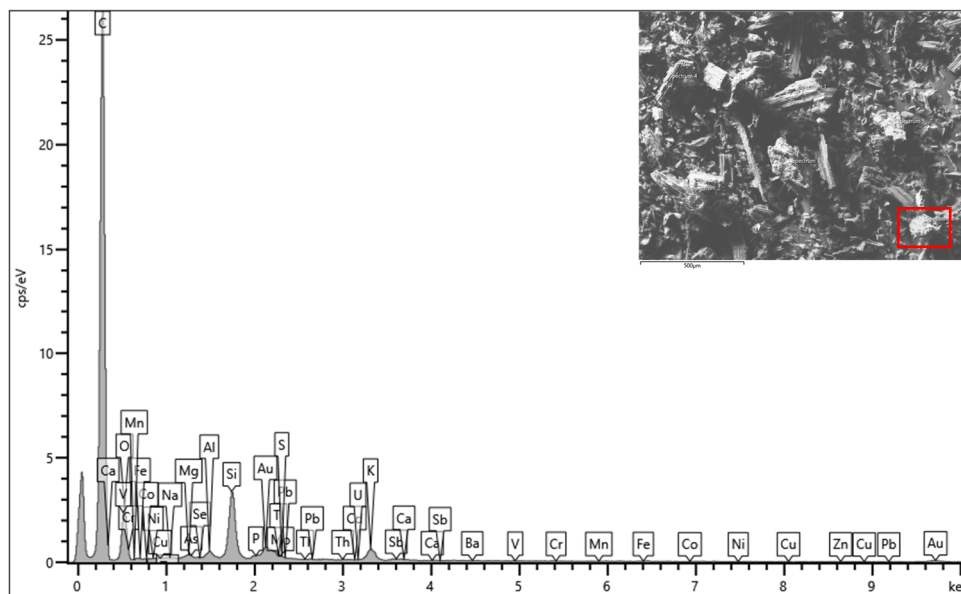


Figure 4. Arundo Grass Biochar EDS Results.

2.1.2. Metakaolin

Metakaolin, is widely utilized in both structural and decorative concrete applications for its ability to improve mechanical properties, durability, and surface finish [24,25]. In this study, metakaolin plays a crucial role in enhancing the strength and stability of the biochar-concrete mixtures, providing both pozzolanic activity and filler effects that contribute to the material's overall performance. The high reactivity of metakaolin, attributed to its fine particle size and specific surface area, promotes a denser concrete matrix by reacting with calcium hydroxide, which is a byproduct of cement hydration. This reaction forms additional calcium silicate hydrate (C-S-H), a compound that is key to concrete strength and longevity.

Metakaolin's specific properties further substantiate its effectiveness. With a specific gravity of 2.6 and a BET surface area of $15 \text{ m}^2/\text{g}$, this metakaolin is finely divided, enabling better dispersion within the concrete mix. Its bulk density ranges between 0.3 and 0.4 g/cm^3 , indicating its suitability for blending with other fine materials in the mixture. The particle size distribution— D_{10} ($<2.0 \text{ }\mu\text{m}$), D_{50} ($<4.5 \text{ }\mu\text{m}$), and D_{90} ($<25 \text{ }\mu\text{m}$)—ensures that a substantial portion of the particles are ultra-fine, maximizing the pozzolanic reaction and the packing density in the cement matrix. These characteristics not only enhance the concrete's compressive strength but also improve its resistance to chemical attack, shrinkage, and permeability, making metakaolin an optimal choice for high-performance biochar-concrete mixtures in sustainable construction applications.

The physical properties and chemical composition of metakaolin used in this study are provided in Tables 5 and 6, respectively.

Table 5. Physical Properties of Metakaolin.

Specific Gravity	BET m ² /g	Bulk Density gr/cm ³	D ₁₀	D ₅₀	D ₉₀
2.6	15	0.3–0.4	<2.0 μm	<4.5 μm	<25 μm

Table 6. Chemical Composition of Metakaolin.

Element Name	%
SiO ₂	52–55%
Al ₂ O ₃	41–44%
Fe ₂ O ₃	<1.9%
TiO ₂	<3.0%
SO ₄	<0.05%
P ₂ O ₅	<0.2%
CaO	<0.2%
MgO	<0.1%
NaO ₂	<0.05%
K ₂ O	<0.75%
LOI	<0.5%

2.1.3. Portland Cement

The chemical composition of cement used in this study is provided in Table 7. The Portland cement used is certified to meet the requirements of ASTM C-150 [26] and AASHTO M-85 [27] for type I and II.

Table 7. Chemical Analysis of Portland Cement.

Element Name	%
SiO ₂	20.6%
Al ₂ O ₃	4.8%
Fe ₂ O ₃	3.7%
CaO	65.2%
MgO	1.2%
SO ₃	2.8%
LOI	1.5%
Insoluble Residue	0.10%
Alkalies (Na ₂ O eqv.)	0.46%
Potential Compounds	
C ₃ S	64%
C ₂ S	11%
C ₃ A	6%
C ₄ AF	11%

2.1.4. Coarse and Fine Aggregates

A coarse aggregate of gravel with a specific gravity of 2.68 and a maximum particle size of 19 mm (0.75 in) and a fine aggregate with a specific gravity of 2.35 and a fineness modulus of 2.58 were used in this study. Figure 5 presents the particle size distribution of sand and gravel used in this study.

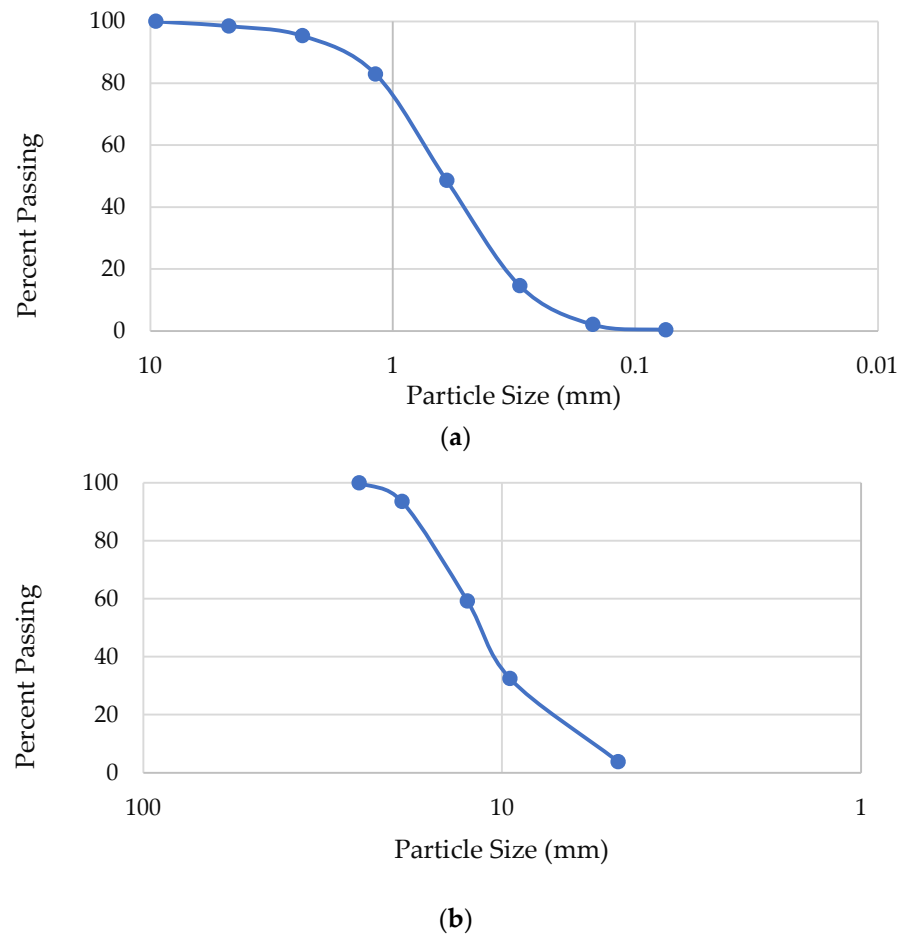


Figure 5. Gradation of (a) Sand, (b) Gravel.

2.2. Concrete Mixture Preparation

Different mix ratios were designed to examine the effect of metakaolin on the physical and mechanical properties of biochar concrete, as shown in Table 8. Mix designs followed American Concrete Institute (ACI) standards, with a water-to-binder ratio of 0.5, considering both cement and biochar as cementitious components. The concrete was formulated to achieve a slump range of 1–3 inches, suitable for pavement and slab applications, without the addition of superplasticizers or water reducers.

Table 8. Concrete Mix Design (Weight in kg).

Mixture ID	Cement	Water	Sand	Gravel	Biochar	Metakaolin	W/C	W/SCM
Control	11.1	5.5	20.0	27.5	0	0	0.5	0.5
5BC	10.5	5.5	20.0	27.5	0.6	0	0.52	0.5
5BC5MK	9.9	5.5	20.0	27.5	0.6	0.6	0.55	0.5
5BC7.5MK	9.7	5.5	20.0	27.5	0.6	0.8	0.57	0.5
5BC10MK	9.4	5.5	20.0	27.5	0.6	1.1	0.59	0.5

During mixing, the dry ingredients were combined for 2 min, after which water was added, and mixing continued for an additional 5 min to ensure a uniform blend. Samples were cast in cylindrical molds (100 mm × 200 mm) and cured following ASTM C192/C192M-07 standards [28] in a moist environment for 7 and 28 days. Prior studies suggest that optimal improvements in concrete strength and durability can be achieved with metakaolin replacement levels between 7 and 15% [25,29]. For this study, a fixed biochar content of 5% and three metakaolin replacement levels (5%, 7.5%, and 10%) were

selected to comprehensively analyze the impact of metakaolin on the performance of biochar concrete, focusing on both short-term and long-term mechanical properties.

2.3. Testing

2.3.1. Bulk Density, Absorption, and Volume of Voids

The density and volume of permeable voids of hardened biochar concrete were evaluated in accordance with ASTM C642-21 [30]. The procedure involved immersing a cured concrete specimen in water, measuring its weight in air and while submerged, and calculating the density based on the volume of water displaced. Additionally, the void content was determined by measuring the oven-dried weight of the specimen, the saturated surface-dry weight, and the submerged weight. These measurements allowed for the calculation of the volume of permeable voids in the concrete, providing insight into its porosity. This test was performed on specimens that had undergone 28 days of curing.

2.3.2. Compressive Strength

The compressive strength of the biochar concrete samples was tested following the procedures outlined in ASTM C39 [31], the Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (Figure 6). For this analysis, three cylindrical samples measuring 4 inches in diameter and 8 inches in height (100 mm × 200 mm) were tested for each mixture type at both 7 and 28 days of curing.



Figure 6. Compressive Strength Testing of Biochar Metakaolin Concrete.

2.3.3. Sorptivity

The sorptivity of the biochar concrete samples was analyzed in accordance with ASTM C1585 [32], the Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. From the larger 4 inch × 8 inch (100 mm × 200 mm) cylindrical samples, smaller cylinders measuring 2 inches (50 mm) in diameter and 4 inches (100 mm) in height were cut for testing. These samples were conditioned at 50 °C for 3 days, followed by a further conditioning period at room temperature for 15 days to ensure uniform moisture content. To prepare the samples for testing, the edges of each specimen were sealed with duct tape to prevent water ingress, while the top was covered with plastic, allowing a small air pocket to remain trapped. Each sample was then placed in a container with its bottom exposed, and water was added until it reached 3 mm above the bottom of the sample. The initial rate was measured over a period of 6 hours, and the secondary rate was measured over a period of 7 days. Absorption (I) was calculated using Equation (1):

$$I = \frac{m_t}{a \times d} \quad (1)$$

where m_t is the change in mass in grams at the specific time interval, a is the exposed area of the specimen in mm^2 , and d is the density of water in g/mm^3 .

2.3.4. Carbon Reduction

The production of clinker, the main component of Portland cement, emits approximately 0.527 tonnes of CO₂ per ton, primarily from the calcination process, which accounts for 50% of emissions. Additional emissions result from the combustion of fossil fuels and electricity consumption. Key energy-intensive stages include clinker burning (25%), finish grinding (40%), raw grinding (20%), and auxiliary grinding (15%) [33]. Cement production emits 800–1000 kg of CO₂ per ton [34]. In contrast, metakaolin production generates significantly less CO₂, with approximately 330 kg per ton, about one-third of Portland cement's emissions [35]. Biochar, with its high carbon content, further supports carbon sequestration.

This study explored combining metakaolin (5, 7.5, and 10%) and biochar (5%) to lower concrete's carbon footprint while maintaining performance. A simple carbon reduction analysis was performed to evaluate the environmental benefits of these additives.

2.3.5. Statistical Analysis

The experimental data from each test were analyzed using JMP Pro 16 software to assess the influence of varying metakaolin percentages on the outcomes. A lettering system (A, B, AB, . . .) was employed to identify statistically significant differences between the results, ensuring clarity and precision in interpreting the data trends.

3. Results

3.1. Bulk Density, Absorption, and Volume of Voids

The bulk density of concrete is presented in Figure 7, while Figure 8 illustrates the absorption and volume of permeable voids. The results reveal that substituting cement with biochar reduced the 28-day bulk density of concrete from 2.311 g/cm³ to 2.268 g/cm³. This decrease aligns with expectations due to the lower density of biochar compared to Portland cement. An increase in bulk density was observed with the addition of 5%, 7.5%, and 10% metakaolin, with the highest density of 2.307 g/cm³ achieved in the sample containing 5% biochar and 10% metakaolin. According to the lettering system generated using JMP Pro 16 software, sample 5BC is assigned the letter B, signifying that its density is statistically different from the control sample. Furthermore, samples 5BC7.5MK and 5BC10MK are assigned the letter A, the same as the control, indicating that they statistically have the same bulk density as the control.

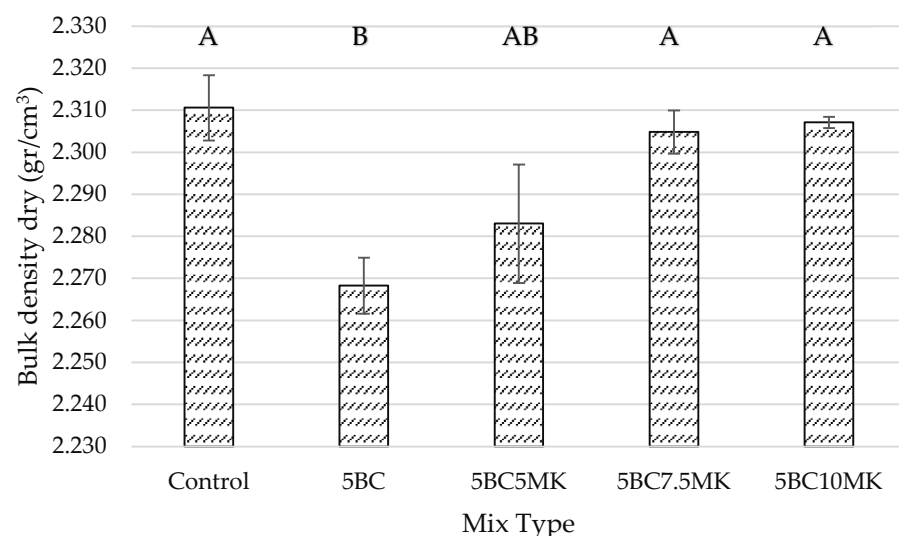


Figure 7. Bulk Density. (Letters A and B represent statistically distinct outputs for bulk density. AB indicates no statistically significant difference between mix types).

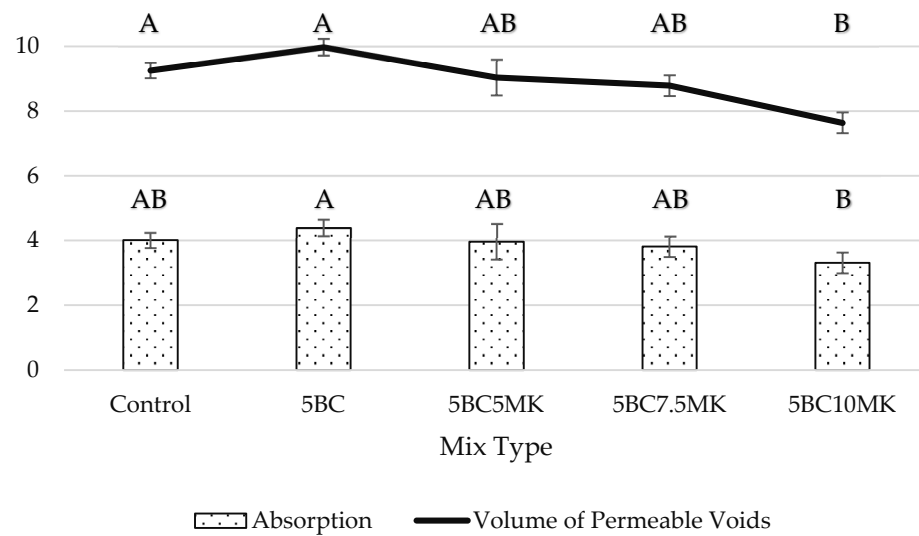


Figure 8. Absorption and Volume of Voids. (Letters A and B represent statistically distinct outputs for absorption and volume of permeable voids. AB indicates no statistically significant difference between mix types).

The impact of metakaolin on concrete density is significant. Its finer particle size promotes better packing within the concrete matrix, enhancing overall density. Furthermore, the pozzolanic reaction between metakaolin and calcium hydroxide produces additional hydration products, reducing porosity and increasing density. Metakaolin also requires less water for hydration compared to traditional cement, contributing to a denser and more compact concrete microstructure. This improved microstructure is often associated with enhanced mechanical properties, such as increased strength and durability, making metakaolin a valuable additive for high-performance concrete.

Additionally, the highest absorption and volume of voids were observed in samples containing 5% biochar. However, these values decreased with the addition of metakaolin, with the sample containing 5% biochar and 10% metakaolin exhibiting the lowest absorption and void content. This indicates the effectiveness of metakaolin in improving the impermeability and overall quality of biochar-incorporated concrete.

3.2. Compressive Strength

The compressive strength of all samples was evaluated at both 7 and 28 days of curing, with three samples tested per mix design, resulting in a total of 15 samples. Figure 9 illustrates the average compressive strength for each mix type after 7 and 28 days of curing.

The incorporation of 5% biochar led to a reduction in compressive strength compared to the control, from 37 MPa to 32 MPa for 7-day strength and from 49 MPa to 42 MPa for 28-day strength. This is in line with the results from previous studies, confirming the negative impact of biochar on concrete's strength due to increased porosity and reduced cement hydration caused by biochar particles. Additionally, biochar may adsorb water during mixing, leaving less free water available for cement hydration. This can hinder the formation of critical hydration products such as calcium silicate hydrate (C-S-H), which is primarily responsible for the strength and durability of concrete.

The addition of 5% and 7.5% metakaolin increased the compressive strength; however, it was not enough to restore the compressive strength to that of the control. Metakaolin, a highly reactive pozzolan, reacts with calcium hydroxide (CH) released during cement hydration to form additional C-S-H and other strength-enhancing phases like calcium aluminate hydrate (C-A-H). However, at lower metakaolin contents, the amount of these secondary hydration products may not be sufficient to offset the negative effects of biochar, such as increased porosity and reduced cement particle hydration. A significant improvement was observed with an increase to 10% metakaolin, achieving 7-day and 28-day strengths of 36 MPa and 46 MPa, respectively.

This improvement suggests that the higher metakaolin content contributes to the formation of a denser microstructure. At 10% metakaolin, the increased pozzolanic reactions likely compensate for the biochar-induced porosity, enhancing the overall matrix density. Moreover, metakaolin's high alumina content may interact with biochar particles to stabilize hydration products or reduce the potential for weak zones around biochar inclusions.

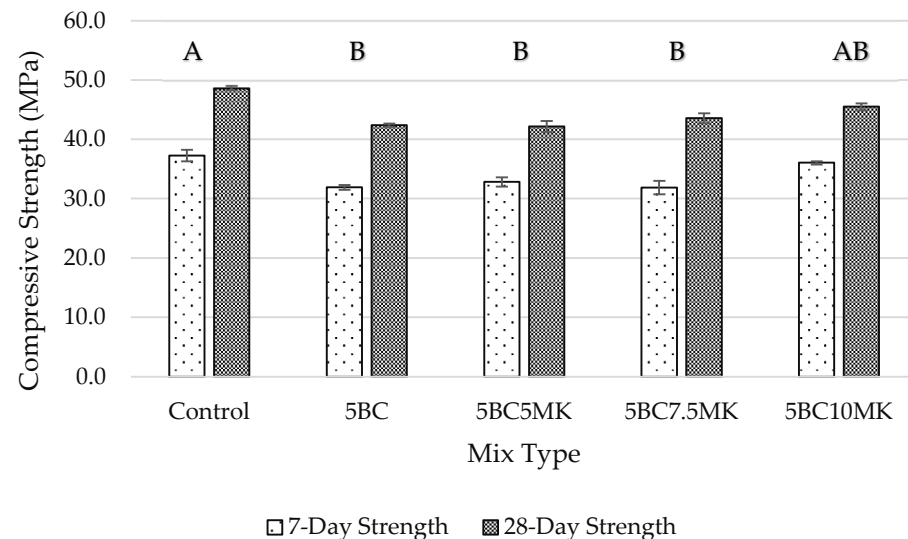


Figure 9. Compressive Strength at 7 and 28 Days. (Letters A and B represent statistically distinct outputs for compressive strength. AB indicates no statistically significant difference between mix types).

3.3. Sorptivity

Figure 10 illustrates the rate of absorption results. The addition of biochar reduces the initial rate of absorption due to its porous structure, which can act as internal reservoirs for water during the mixing process. These pores trap and retain water, making it less readily available for immediate capillary absorption. Additionally, biochar's ability to absorb and hold water at the microscopic level creates a localized "buffer zone", slowing down the ingress of external water into the concrete matrix during the initial phase. This phenomenon may also contribute to more efficient hydration of nearby cement particles by ensuring sustained moisture availability, which can enhance early-age strength and accelerate setting times. In contrast, metakaolin increases the initial rate of absorption due to its fine particle size and high surface area. These characteristics promote capillary action, facilitating faster initial water ingress. Furthermore, metakaolin's pozzolanic reactivity may lead to the early consumption of calcium hydroxide (CH) and formation of secondary hydration products like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). However, the rapid water absorption associated with metakaolin may also increase the risk of shrinkage or cracking if not properly mitigated.

Biochar addition leads to a reduction in the secondary rate of absorption, which indicates that it contributes to the formation of a denser and more impermeable matrix over time. This behavior is likely due to the ongoing hydration of cement facilitated by the retained water within the biochar's porous network. Additionally, biochar may act as a filler material, reducing the overall pore connectivity within the concrete matrix and thus limiting the pathways for long-term water ingress. The improved microstructure also enhances the concrete's resistance to environmental factors such as freeze–thaw cycles, sulfate attack, and chloride penetration, which are critical for long-term durability. On the other hand, metakaolin's contribution to the secondary rate of absorption is more complex. While metakaolin initially facilitates faster water ingress, its pozzolanic reaction progressively consumes CH and forms additional C-S-H and C-A-H phases. This process results in a refined pore structure and densification of the matrix.

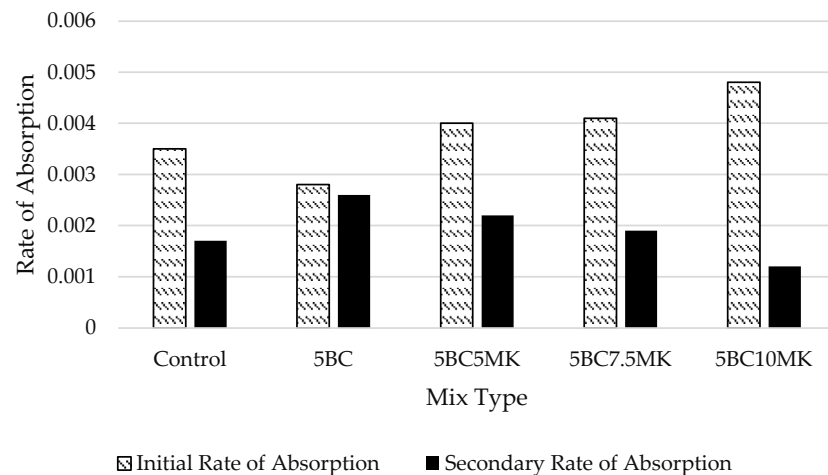


Figure 10. Rate of Absorption.

The observed behaviors highlight the complementary roles of biochar and metakaolin in influencing the absorption characteristics of concrete. Biochar excels in reducing long-term water ingress and improving durability, while metakaolin enhances the early-age reactivity and strength development. The interplay between these materials suggests potential for hybrid systems where biochar and metakaolin are optimized together to balance early and long-term performance.

3.4. Carbon Emissions Reduction

This study investigated the incorporation of Arundo grass biochar (5%) and varying percentages of metakaolin (5%, 7.5%, and 10%) as partial cement replacements to reduce the carbon footprint of concrete production. The environmental impact assessment is based on the average CO₂ emissions for Portland cement type I/II (approximately 0.9 kg CO₂ per kilogram), metakaolin (0.33 kg CO₂ per kilogram), and the carbon sequestration potential of Arundo grass biochar. With a carbon content of 80%, 1 kg of biochar corresponds to 3.67 kg of CO₂ sequestration. Figure 11 illustrates the CO₂ reduction achieved by biochar-incorporated concrete, both with and without metakaolin supplementation. The results emphasize biochar's role in significantly reducing the carbon footprint of concrete while showcasing the additional contributions of metakaolin in low-carbon concrete technologies. This study highlights the potential of synergistic material combinations to achieve sustainable construction solutions without compromising performance.

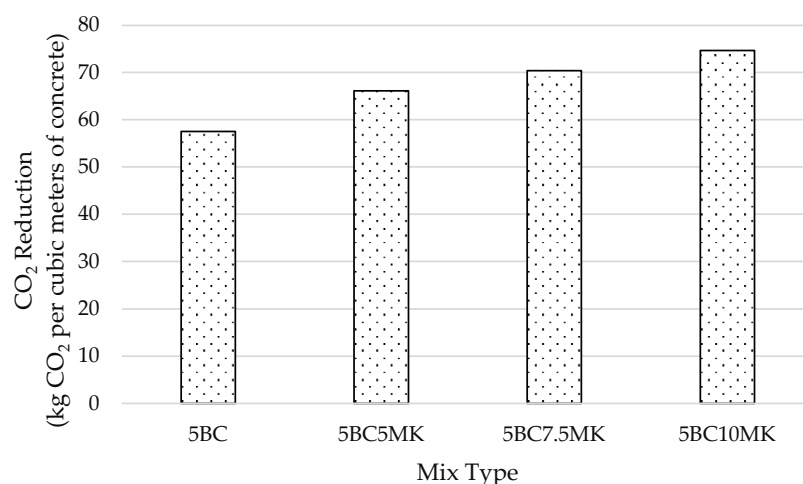


Figure 11. CO₂ Reduction of Biochar Concrete with/without Metakaolin.

4. Conclusions

This research investigated the effects of biochar and metakaolin on the density, compressive strength, sorptivity, and carbon footprint of concrete. The key findings are as follows:

- Substituting cement with biochar reduced the 28-day density of concrete. However, adding metakaolin significantly increased the density due to its finer particle size and pozzolanic reactivity, which enhanced the microstructure and mechanical properties of the concrete. The combination of biochar and metakaolin also improved impermeability by reducing absorption and void content, thereby enhancing the overall quality of the concrete.
- Incorporating 5% biochar reduced the compressive strength of concrete. However, the addition of 10% metakaolin significantly improved strength, achieving levels comparable to the control. This finding indicates that higher metakaolin content can offset the negative effects of biochar, contributing to better density and mechanical performance.
- The inclusion of 5% biochar decreased the initial rate of absorption and improved long-term durability by forming a denser and less permeable matrix. Conversely, metakaolin increased the initial absorption rate due to its fine particle size and reactivity but refined the pore structure over time through pozzolanic reactions. This complementary behavior highlights the potential of combining biochar and metakaolin to optimize both early-age performance and long-term durability, offering a balanced approach to sustainable construction materials.
- A significant reduction in CO₂ emissions was achieved with biochar-incorporated concrete and further enhanced by metakaolin supplementation. This underscores the potential of biochar and metakaolin as synergistic components in low-carbon concrete technologies that balance.

5. Future Work

Future studies should explore the long-term durability of biochar–metakaolin concrete under extreme environmental conditions, such as freeze–thaw cycles, chloride ingress, and sulfate attack. Additionally, microstructural and chemical analyses using advanced techniques, such as scanning electron microscopy (SEM) and X-ray diffraction (XRD), could provide deeper insights into the interactions among biochar, metakaolin, and cement hydration products. Finally, investigating the scalability of these materials for industrial applications and assessing their economic feasibility will be critical for promoting widespread adoption in sustainable construction practices.

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