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Sustainable Soil Stabilization: Evaluating the Potential of Biochar for Expansive Soil Subgrade Improvement

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Abstract

Biochar, a carbonaceous recalcitrant product obtained through biomass pyrolysis, has emerged as a promising soil amendment with the potential to positively impact soil physical properties. This review aims to provide a comprehensive analysis of the effects of biochar on various soil physical characteristics. We delve into the available literature to gather and analyze data on the significance of biochar in improving soil physical properties. Additionally, we explore the underlying mechanisms responsible for these improvements and identify areas that require further investigation. The review emphasizes the importance of understanding the impact of biochar on soil physical properties to optimize its use in sustainable subgrade practices. Based on the review, it is evident that applying biochar at 1-2% (W/W) reduces soil bulk density and enhances soil porosity and infiltration rate, thereby increasing total soil porosity. However, the impact of biochar on soil physical properties is influenced by factors such as the soil type, the specific type of biochar used (based on feedstock and pyrolysis conditions), and the rate of biochar application. Further research is needed in these areas to gain a comprehensive understanding of the effects of biochar on soil physical properties.

Keywords: Biochar, soil physical properties, porosity, pyrolysis

1. Introduction

Soil stabilization is a widely employed technique in road, pavement, and foundation construction to enhance the engineering properties of soil, including strength, volume, stability, and durability, while reducing pavement thickness and overall cost. Soil, being abundantly available, has been historically used in the construction of various civil engineering structures, such as monuments, tombs, and dwellings. The study of the engineering behavior of different soil types holds great significance, as all civil engineering structures must be built upon and supported by soil. The primary purpose of soil stabilization is to increase the bearing capacity of the soil and minimize settlement and deformation. In cases where problematic soils are present, soil improvement technologies are necessary to enhance the existing ground or fill materials. Biochar, a carbon-rich material produced through the thermochemical conversion of biomass, offers a potential solution. Biomass from diverse sources, including agricultural waste, logging residues, wood production waste, and urban wood-waste, can be used to produce biochar (Garcia-Perez et al., 2010). To address this problem and improve soil physical properties and fertility, increasing the soil organic carbon content is essential. One approach to achieve this goal is the integrated use of organic and synthetic fertilizers. This strategy aims to replenish soil organic matter and enhance its ability to support beneficial microorganisms, promote better nutrient and water retention, and ultimately increase crop yields. By adopting sustainable agricultural practices that focus on maintaining and increasing soil organic carbon, we can mitigate soil degradation and meet the growing demand for agricultural products while safeguarding the future of food supply.

While biochar has been widely employed in agricultural and environmental remediation projects for carbon capture, its application in civil engineering outside of environmental remediation is still relatively unexplored. Recent studies have begun to investigate the effects of biochar on soil mechanical properties (Lu et al., 2014; Reddy et al., 2015; Yargicoglu and Reddy, 2017) and its potential use as a construction material (Gupta and Kua, 2017).However, it is essential to consider that the properties and quality of biochar are significantly influenced by the type of feedstock and production process used (International Biochar Initiative, 2015). Moreover, the specific soil properties, microbial activity, and atmospheric conditions can also impact the effectiveness of biochar in amending soils (Latifi et al., 2015; Latifi et al., 2016). Further research and understanding of these factors are crucial for successful and efficient soil stabilization with biochar in civil engineering applications. Soil physical conditions play a crucial role in determining soil productivity for crop production. Factors such as water holding capacity, aeration, and soil strength directly influence the root activity and, subsequently, crop growth (Benjamin et al., 2003). All of these positive effects on soil physical properties contribute to better root growth and ultimately higher crop yields. Soil organic matter plays a vital role in maintaining the health and productivity of the soil ecosystem. Soils with higher concentrations of organic matter exhibit better physical properties and higher yields compared to soils with low organic matter content (Bowman et al., 1990). With a rapid increase in the global human population over recent decades, the demand for food, fiber, and raw materials has grown significantly, necessitating an urgent need to enhance agricultural production and ensure food security. Consequently, agriculture has intensified, leading to increased decomposition of organic matter and subsequent degradation of soil physical properties (Middleton et al., 1992; Reynolds et al., 2002).Anthropogenic activities, particularly those associated with harsh agro-climatic conditions, such as high temperatures, further exacerbate the issue. High temperatures accelerate the decomposition of soil organic matter, which otherwise serves as a natural soil conditioner, resulting in soil degradation (Raul et al., 1997). Biochar is a carbonaceous product obtained by subjecting biomass to high temperatures in the absence or limited presence of oxygen, a process known as pyrolysis. This results in its unique physical properties, such as high porosity and a large surface area (Van Zwieten et al., 2010). Due to its aromatic structure and crystalline graphitic sheets, biochar is highly resistant to decomposition, making it recalcitrant in the soil for extended periods, ranging from 10 to 1000 times longer than organic matter (Christopher et al., 2010).The properties of biochar vary depending on the type of biomass used as feedstock and the specific pyrolysis conditions, including charring time, rate, and temperature (Mukherjee and Lal, 2013). For instance, biochar derived from woody feedstock tends to be coarser and more recalcitrant compared to that produced from agronomic residues. Furthermore, biochar produced at higher temperatures tends to have fewer nutrients and higher micro-porosity, whereas biochar produced at lower temperatures contains more nutrients and fewer micro-pores (Lehmann et al., 2009).It is essential to recognize that different types of biochar possess distinct properties, and their impact on soil physical properties varies depending on the specific soil type and prevailing climatic conditions (Herth et al., 2013). Consequently, the effectiveness of a particular biochar in enhancing soil physical properties is influenced by these factors, highlighting the need for tailored and context-specific approaches to optimize the use of biochar as a soil amendment.

2. Materials & Methods

The black cotton soil examined in this study was collected from the site. The soil selection for this study encompasses a significant portion of the south-western region of India and is predominantly utilized in the construction of soil-related structures like foundation, slopes and embankments. Prior to analysis, any impurities present in the soil were manually removed. The soil underwent characterization to determine its fundamental and index properties, including consistency limits, grain size distribution, pH, specific gravity, etc. The production of biochar is mainly dependent upon two important factors- biomass used and pyrolysis. it is generated through the thermal conversion of biomass feedstock, employing various techniques such as pyrolytic processes at different temperature ranges. The biochar procured in this study was obtained from industries. It was produced through the pyrolysis process, involving heating coconut wood waste to high temperatures with minimal oxygen. The biochar was derived from wood waste materials through pyrolysis conducted at 500 °C for duration of 5 hours. The biochar obtained from the vendor initially had large-sized pellets that were retained in a 4.75 mm sieve (Fig. 1b). For the small-scale laboratory tests conducted in this study, the obtained biochar was subsequently crushed into a smaller size, passing through a 4.75 mm sieve, using a mechanical grinder (Fig. 1c).

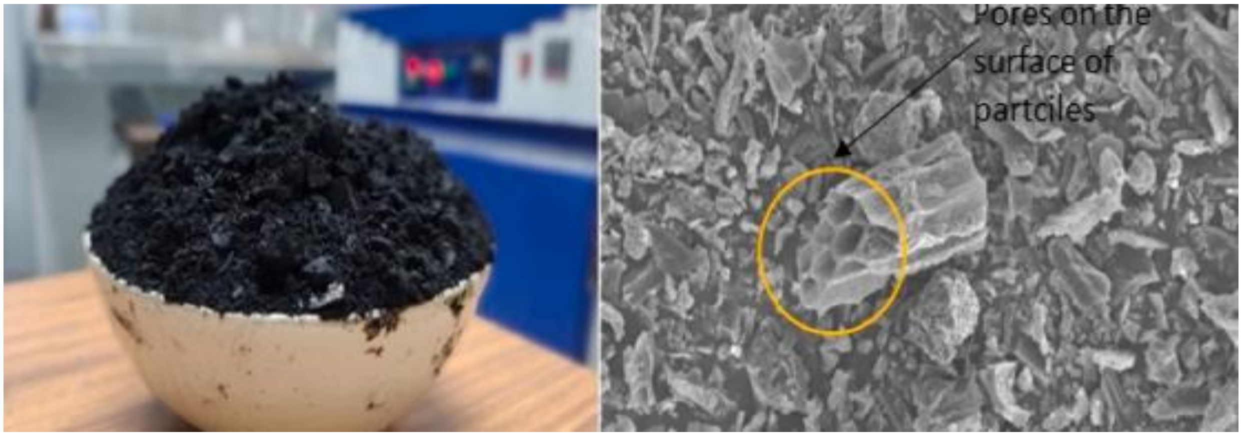

Fig. 1. Coir Biochar & SEM image of biochar

3. Results & Discussions

The effect of different types and rates of biochar application on soil porosity in various soils is illustrated in the following table. It highlights the diverse impacts that biochar can have on soil porosity, emphasizing the need for careful consideration of the specific biochar and soil type when applying biochar as a soil amendment. Soil porosity, which represents the ratio of pore volume to the total soil volume, is a critical soil attribute that significantly influences plant growth. Application of biochar leads to an overall increase in soil porosity, but the extent of this increase depends on the type of biochar used and the specific soil type in which biochar is applied (Herth et al., 2013). The relative contribution of these three types of pores to the total increment of soil porosity varies based on the type of biochar and soil type (Leonard Githinji, 2013). The rise in soil porosity can be attributed to the highly porous nature of biochar itself (Mukherjee et al., 2013).The bulk density of soil plays a crucial role in determining various soil properties and significantly impacts plant growth. For instance, soils with high bulk density (>1.6 Mg cm^-3) have reduced water absorption capacity and create greater penetration resistance for plant roots, ultimately affecting soil characteristics and plant growth (A.M. Goodman and A.R. Ennos, 1998).According to Mukherjee et al. (2013), the application of biochar results in a decrease in soil bulk density due to the high porosity of biochar. When biochar is added to the soil, it significantly reduces the bulk density by increasing the pore volume, allowing for better soil structure. Additionally, Leonard Githinji (2013) found that increasing the rate of biochar application further contributed to a significant decrease in bulk density, highlighting the potential of biochar to improve soil physical properties and enhance plant growth.

Soil aggregation is the process by which soil colloidal particles are bound together through net attractive forces. This property is of utmost importance in terms of soil structure. Well-aggregated soil exhibits a good structure, providing an ideal medium for nutrient and water movement within the soil, facilitating uptake by plants (Borselli et al., 1996). Microorganisms play a crucial role in enhancing soil aggregation. Certain polysaccharides secreted by these microorganisms further promote the adherence of soil colloidal particles (Dorioz et al., 1993).When biochar is applied to the soil, it offers a refuge to microorganisms, protecting them from predators and desiccation. In turn, these microorganisms actively contribute to soil aggregation by secreting polysaccharides, thereby fostering a more stable and well-structured soil (Angers et al., 1993).The application of biochar can significantly influence soil aggregation by creating a favorable environment for beneficial microorganisms, leading to improved soil structure and overall soil health. This, in turn, positively impacts nutrient and water movement within the soil, ultimately benefiting plant growth and crop productivity. Soil water retention capacity refers to the maximum amount or quantity of water that a soil can hold or retain, and it is a critical property from both farmers' and plant growth perspectives. Soils with high water retention capacity require less frequent irrigation for crops and promote better plant growth. Biochar application has been shown to significantly enhance the available water content of the soil, increasing it by up to 97%, and the saturated water content by 56% (Uzoma et al., 2011).Studies have demonstrated that soil amended with biochar can retain 15% more moisture compared to untreated soil (Laird et al., 2010). The effect of biochar on water retention capacity is dependent on soil texture, as described by E. H. Tryon (1948). Sandy soils experience a significant increase in water retention capacity with biochar application, while loamy and clay soils may exhibit little to no increase. Experimental findings by Herth et al. (2013) support the idea that biochar application increases soil water retention capacity due to improved soil porosity and the adsorptive nature of biochar. Furthermore, Uzoma et al. (2011) noted the presence of hydrophilic functional groups on the surface of the graphyne sheet of biochar and within its pores, which also contribute to enhanced water retention capacity. Overall, biochar application can be a valuable strategy to improve soil water retention capacity, benefiting agricultural productivity and promoting better plant growth, especially in sandy soils or those with poor water-holding abilities.

Table 1. Soil Stabilization in similar research works

S.N	Stabilizer used	% Used	Soil Type	Refrence
1.	Bottom Ash	0-8 %	Expansive	(Muthukkumaran & Joseph, 2014)
2.	Bagasse	0-2 %	Expansive	(Krishnan et al., 2022)
3.	Biochar From Agro Waste	1-3 %	Expansive	(K. Wang et al., 2021)
4.	Biochar Plant Based	1-5 %	Expansive	(Villarreal & Wang, 2021b)
5.	Biochar From Waste Wood	0-10%	Soil	(Sadasivam & Reddy, 2015)

4. Conclusions

The application of biochar as a stabilizing agent in expansive soil subgrades has garnered significant attention due to its potential to enhance soil properties while promoting environmental sustainability. This comprehensive review highlights the key effects of biochar amendment on expansive soil, focusing on physical, mechanical, chemical, and durability characteristics relevant to subgrade applications.

I. Improvement in Physical and Plasticity Characteristics

Biochar has been found to significantly alter the physical and plasticity characteristics of expansive soil. Studies indicate that incorporating biochar reduces the plasticity index (PI), which is beneficial for mitigating soil shrink-swell behavior. This reduction is primarily attributed to biochar's porous structure and ability to regulate soil moisture retention, thereby decreasing the soil's water absorption capacity. Additionally, biochar increases the optimum moisture content (OMC) and decreases the maximum dry density (MDD), suggesting a modification in soil compaction behavior that could influence field performance.

II. Reduction in Swelling and Shrinkage Behavior

The expansive nature of black cotton soil poses a major challenge for subgrade applications, as swelling and shrinkage cycles lead to pavement distress. Biochar amendments have shown a significant reduction in the free swell index (FSI) and swelling potential, likely due to its ability to absorb excess water and mitigate hydration-induced expansion. This effect is further enhanced when biochar interacts with cementitious binders or bacterial solutions, forming a more stable soil matrix.

III. Enhancement in Strength and Load-Bearing Capacity

The incorporation of biochar leads to an improvement in the unconfined compressive strength (UCS) and California bearing ratio (CBR), both of which are critical parameters in subgrade design. Experimental studies suggest that biochar-modified soil exhibits a gradual increase in UCS over curing time, indicative of pozzolanic reactions that contribute to long-term strength gain. The enhancement in CBR values signifies an increase in load-bearing capacity, making biochar-treated soil more suitable for supporting pavement structures.

IV. Microstructural and Chemical Modifications

Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses of biochar-stabilized soils reveal key microstructural changes that contribute to improved performance. The biochar particles fill void spaces, densifying the soil structure and reducing permeability. Additionally, chemical interactions between biochar's carbon-rich compounds and soil minerals contribute to the formation of cementitious compounds, further stabilizing the subgrade.

V. Environmental and Economic Considerations

Beyond engineering benefits, biochar utilization in soil stabilization presents environmental advantages by reducing the dependency on conventional stabilizers such as lime and cement, which have high carbon footprints. The use of biochar, often derived from agricultural or industrial waste, promotes waste valorization and sustainable construction practices. Economically, biochar offers a cost-effective alternative to traditional soil stabilizers, particularly in regions where biochar feedstocks are readily available.

VI. Challenges and Future Research Directions

Despite the promising outcomes, several challenges remain in the practical implementation of biochar-stabilized expansive soils for subgrade applications. Variability in biochar properties, such as particle size, surface chemistry, and feedstock origin, can lead to inconsistencies in performance. Further research is needed to standardize biochar production and optimize its dosage for different soil types. Additionally, long-term durability studies under field conditions, including the impact of cyclic loading and extreme weather, are necessary to validate laboratory findings. Overall, biochar emerges as a sustainable and effective stabilizer for expansive soil subgrades, offering improvements in strength, swelling control, and environmental sustainability. While promising, further interdisciplinary research integrating geotechnical engineering, material science, and environmental sustainability is essential to fully harness biochar’s potential in infrastructure development. Future advancements in biochar-engineered composites and microbial-assisted stabilization techniques could further enhance its efficacy in subgrade applications

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