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Influence of Sugarcane Bagasse Biochar Amendment on Low Plastic Clay Soil Performance: A Novel Approach for Geotechnical and Geo-environmental Applications

Shailesh Kumar Yadav[1*], Amrit Raj[2] & Ramakrishna Bag[3]
[1]Research Scholar, Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihar, India, 801103; Email: shailesh_2021ce26@iitp.ac.in
[2]Graduate Student, Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihar, India, 801103; Email: amrit_2001ce06@iitp.ac.in
[3]Associate Professor, Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihar, India, 801103; Email: rkbag@iitp.ac.inmail.com
*****Correspondence: shailesh_2021ce26@iitp.ac.in

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ABSTRACT The application of biochar in geotechnical and geoenvironmental engineering remains relatively understudied, particularly concerning its impact on soil properties when mixed with sugarcane bagasse. This study investigates the influence of sugarcane bagasse-derived biochar on the strength and water retention behavior of low plastic clay soil, representing a novel contribution to the field. Biochar, a carbon-rich material produced by the pyrolysis of organic biomass, has garnered attention for its potential to enhance soil properties and mitigate environmental challenges. Five different percentages of bagasse biochar (0%, 1%, 2%, 3.5%, and 5%) were incorporated into the low plastic clay soil to prepare biochar-amended soil specimens. Unconfined compressive strength and water retention tests were conducted to evaluate the mechanical and hydraulic properties of the amended soils. The findings reveal that the water retention capacity of the biochar-amended soil increased with the addition of bagasse biochar. This observation suggests that biochar incorporation enhances the soil's ability to retain moisture, potentially beneficial for mitigating soil moisture fluctuations and supporting plant growth in geoenvironmental applications. Furthermore, the study also highlights a positive impact on the strength properties of the soil with a 22.1% increase for 1% biochar content compared to no-amended after 28 days. This increase in strength was attributed to changes in soil structure, pore distribution, and inter-particle bonding induced by the presence of biochar. In conclusion, Biochar amendment offers potential for enhancing soil water retention and strength properties and the use of sugarcane bagasse-derived biochar in low plastic clay soil presents promising opportunities for geoenvironmental engineering applications.

KEYWORDS Sugarcane Bagasse; Biochar; Water retention; Unconfined compressive strength; Geoenvironmental Applications

1 INTRODUCTION

Biochar is a stable, carbon-rich substance that is produced by gasifying or pyrolyzing biomass at a high temperature in a confined chamber with little or no oxygen accessible (Lehmann & Joseph, 2012; Li et al., 2020). The main sources of raw materials (feedstock) for the synthesis of biochar are wood processing waste, animal manure, municipal solid waste, forestry residue, and agricultural residue (Wani et al. 2022). The use of biochar in geotechnical and geoenvironmental applications is a relatively recent development, with limited research conducted in India. Despite this, biochar shows promise in addressing various environmental and engineering issues. Previous studies indicate that biochar can be effectively utilized as an amendment material for landfill covers and liners, green roofs, embankments, backfills, and bioengineered slopes (Sadasivam & Reddy, 2015; Reddy et al., 2015; Chen et al., 2018; Alotaibi & Schoenau, 2019).

Building a stable and sustainable landfill cover system requires materials that offer adequate strength and water-holding capacity to support overburden loads and facilitate vegetation growth. However, biochar has been found to enhance water retention, though some studies have presented conflicting results. Bordoloi et al., (2020) reported an increase in the water retention capacity of silty sand amended with water hyacinth biochar. Similarly, Ganesan et al., (2020) demonstrated an improvement in the water-holding capacity of sand-clay soil amended with cedar wood biochar. In another study by Yadav and Bag (2023a), an increase in water retention capacity was reported for both low-plasticity clay and silty sand soil when amended with bamboo biochar. However, a study by Jeffery et al., (2015) found no significant improvement in the water retention capacity of sand amended with hay biochar. Similarly, the effect of biochar on soil compressive strength has produced varying outcomes in the past literatures. Williams et al. (2018) reported that pine-derived biochar improved the compressive strength of clay soil. Sarkar et al. (2020) also observed an increase in compressive strength with shrub biochar mixed into clay soil. Yadav and Bag (2023a) found that a 2% bamboo biochar amendment enhanced compressive strength in low-plasticity clay but reduced it in silty sand soil. On the other hand, Jyoti Bora et al. (2021) showed a continuous decrease in compressive strength for silty sand amended with biochar from poultry litter, water hyacinth, and sawdust. Furthermore, Yadav & Bag (2023b) study has reported a continuous decrease in dry density and increase in optimum moisture content with the addition of biochar in soil.

In addition, the literature review confirmed that utilization of biochar in amendment of soil has been invigilated by few researchers in recent years and they reported contradictory results with different biochar and soil types. These studies have concluded that the properties of biochar vary based on the type of feedstock, pyrolysis temperature, heating rate, and the atmospheric conditions within the pyrolysis chamber. Since the properties of biochar varies with feedstock material and also led to change in geotechnical properties of biochar mixed soil (Reddy et al., 2015; Kameyama et al., 2016; Garg et al., 2019; Amorim et al., 2020; Bordoloi et al., 2020; Ganesan et al., 2020; Bora et al., 2021; Huang et al., 2021).

Therefore, further research is needed with biochar produced from other feedstock and waste materials. One such waste material is sugarcane bagasse, which has been relatively overlooked in past studies. Sugarcane bagasse is an agricultural residue produced after extracting juice from sugarcane. Since sugarcane is cultivated in many countries worldwide, this results in a substantial amount of waste (Kameyama et al. 2016). Mostly sugarcane bagasse is burned in the open, releasing tons of carbon dioxide and polluting the environment. This contributes to global warming, glacier melting, rising sea levels, extreme weather conditions, and other environmental issues. Additionally, the open burning of bagasse also produces particulate matter and other harmful pollutants, which can have serious health impacts on local communities (Cozier 2014). To mitigate these effects, it is crucial to explore sustainable alternatives for managing and utilizing sugarcane bagasse, such as converting it into biochar and using it in construction materials. The conversion of biochar not only addresses environmental challenges but also enhance water retention and compressive strength of amended soil making a sustainable growth.

Hence, the current study aims to fill this research gap by investigating the use of bagasse biochar and its impact on water retention and compressive strength of soil. The study focuses on low-plasticity clay soil, chosen for its relevance to landfill cover application. The results of this study will help identify the most effective types and quantities of biochar for use in geotechnical and geo-environmental engineering projects.

2 MATERIALS

2.1 Soil

A local soil sample was collected from an area near IIT Patna for experimental purposes. Initially, the soil contained lumps and roots, so it was cleaned and grounded into fine particles using a motor grinder to prepare it for testing. Prior to conducting any tests, the soil was dried by placing it in a thermostatically-controlled oven set to 110°C for 24 hours.

2.2 Biochar

This study utilized biochar exclusively derived from sugarcane bagasse obtained from an industrial source. Sugarcane bagasse, the fibrous residue left after extracting juice from sugarcane stalks, served as the primary material for producing the biochar. Biochar production involved subjecting bagasse to a pyrolysis process, heating it in an oxygen-deprived environment, which effectively converted the organic components of the bagasse into carbon-rich biochar.

3 METHODOLOGY

3.1 Materials Characterization

The grain size distribution of soil and biochar was analyzed in the lab following ASTM standards. Soil particle sizes were determined using sieve and hydrometer tests, while biochar particle identification was conducted using sieve tests only (ASTM C117, 2009). Moreover, Atterberg's limits tests were determined in the laboratory. Soil samples were mixed with water in different ratios, thoroughly blended, and allowed to equilibrate in a desiccator for 48 hours before testing. The liquid limit (LL) test employed a falling cone apparatus, while the plastic limit test was performed manually following ASTM standard procedures (ASTM D4318 2010). Furthermore, the specific gravity and pH of both soil and biochar were determined (ASTM D854 2014; ASTM D4972 2007). The specific gravity was measured using the density bottle method, while the pH was tested using a potentiometer. Kerosene and distilled water served as the liquids for the specific gravity and pH tests, respectively.

3.2 Preparation of Soil-Biochar Mixtures

Both biochar and oven-dried soil were used to prepare the soil-biochar composite. Five distinct biochar percentages (0%, 1%, 2%, 3.5%, and 5%) were chosen based on previous research (Yadav & Bag 2023a). The oven dried biochar and soil sample were weighted in the right proportion and mixed instantly. The samples were mixed thoroughly until the color difference disappeared, ensuring homogeneity in the mixture. The mixture was stored in a desiccator for further examination.

3.3 Procedure for Water Retention Test

Water retention capability refers to the ability of a material to retain moisture at specific suction levels. In this study, WP4C dew-point potentiometer was used to measure the water retention of the samples. To prepare water retention samples, specimens were created by incorporating 0%, 1%, 2%, 3.5%, and 5% biochar into the soil. The soil and biochar were mixed in dry conditions, and then water equivalent to 1.5 times the liquid limit was added to make the sample fully saturated, resembling a slurry. Each biochar mixed soil sample was poured into WP4C molds, with excess slurry removed and the mold surfaces cleaned. The molds were then stored in a desiccator to equilibrate before measuring suction using the WP4C potentiometer.

Thereafter, each mold was placed individually into the WP4C equipment. The WP4C device proceeded to equilibrate the moisture in the air above the specimen with that inside the specimen itself. It measures the dew point temperature by cooling a mirror until condensation forms. Using this dew point temperature along with the specimen's temperature, the device calculated the water potential (suction) of the specimen. Once equilibrium was achieved, the WP4C emitted an audible signal. The mold was then removed to measure its weight, and both suction and temperature were also noted. The mould was then placed in a controlled environment to evaporate moisture. After few minutes, the mould was gain placed in WP4C equipment for suction measurement. This process continued until the consecutive differences in suction and mold weight became very low. The mold was then placed in an oven for 24 hours to dry. Thereafter, gravimetric water content (GWC) was calculated and plotted alongside suction for all percentages of biochar addition to observe variations in the water retention curve.

3.4 Compaction Procedure of Biochar Amended Soil

The soil-biochar samples taken from the desiccator were prepared for the compaction test. Water was added in different proportions and thoroughly mixed to ensure even moisture distribution. After mixing, the moist samples were placed back in the desiccator for 48 hours to achieve uniformity. Subsequently, the samples were removed from the desiccator and subjected to the standard Proctor test. This process was repeated for five different moisture content levels corresponding to each specific percentage of biochar added. Similarly, three sets of experiments were performed for each biochar case to ensure repeatability. After the Proctor tests were completed, the maximum dry density (MDD) and optimum moisture content (OMC) were calculated from the test data.

3.5 UCS Specimen Preparation Procedure

The unconfined compressive strength (UCS) samples were prepared using the MDD and OMC data. The UCS samples has dimensions of 76 mm in length and 38 mm in diameter. The required sample amounts for the UCS specimens were calculated based on specimen volume and MDD. Additionally, the weights of biochar and soil were calculated based on their respective proportions for each case (Figure 1a). Then, the soil and biochar were thoroughly mixed in their dry state. The mixture was then combined with water at the OMC, mixed again, and placed in a desiccator inside a plastic packet to achieve homogeneity. Thereafter, the moist sample were brought to a manually operated UCS sampler (Figure 1b), and it was statically compressed to obtain UCS specimen. Similarly, three identical UCS specimens were prepared for each percentage of biochar to obtain an average result.

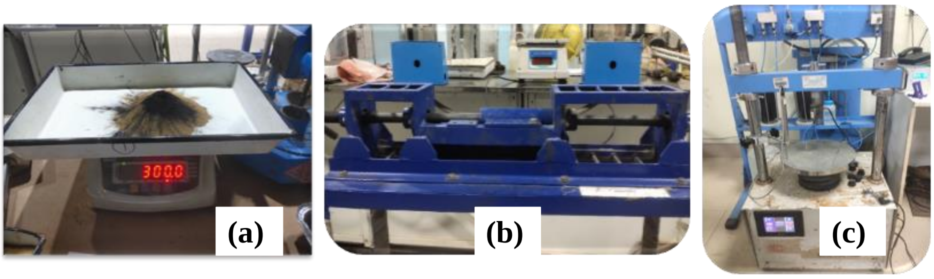

Figure 1. (a) Weighing soil and biochar proportion (b) UCS sampler and (c) loading frame.

The prepared UCS specimens were wrapped in plastic and placed in an environmentally controlled desiccator for curing. Curing periods of 0, 7, 15, and 30 days were selected for the UCS specimens. Once each curing period was completed, the UCS specimens were tested in a load frame (Figure 1c). Loading proceeded uniformly at a rate of 1.25 mm per minute until the specimens failed. Load versus displacement data were automatically recorded by the data logger associated with the loading frame. The load and displacement data were used to plot stress-strain curves. The peak stress value observed in the stress-strain plot was recorded as the UCS value for each specific case.

4 RESULTS

4.1 Material Properties

The grain size distribution curves for soil and biochar are shown in Figure 2(a, b). The grain size distribution results for the soil indicate that about 88.5% of the soil passed through a 75-micron sieve, highlighting its finer nature. Further analysis indicates that 14.23% of the soil grains passed through a 2-micron sieve, demonstrating that the majority of the particles are silty. Additionally, sieve analysis of the biochar showed that approximately 72% of the biochar particles passed through a 75-micron sieve. This suggests that the majority of biochar particles were fine as well. Moreover, the specific gravity of the soil was measured at 2.69. In contrast, biochar exhibited a specific gravity of 1.509, indicating its significantly lighter density compared to soil. Additionally, the Atterberg's limits of soil were examined and tests revealed that the soil had a liquid limit of 31.46% and a plastic limit of 19.75%. The soil's plasticity index was measured at 11.71%. Subsequently, this data was plotted on the Plasticity Chart, classifying the soil as low plasticity clay (CL) according to the Unified

Soil Classification System (USCS). Additionally, the soil was found to be slightly acidic, with a pH of 6.33, indicating its potential influence on nutrient availability and microbial activity. In contrast, the biochar was determined to be basic, with a pH of 7.34, which can help neutralize acidic soils and enhance soil fertility.

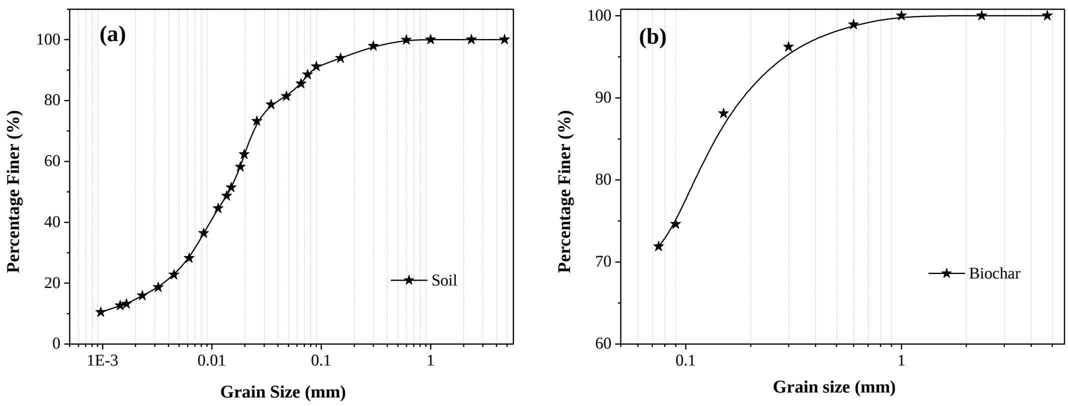

Figure 2. Grain size distribution curve of (a) low plastic clay soil and (b) bagasse biochar.

4.2 Effect of Biochar on Water Retention Capacity

Figure 3 shows the Soil Water Characteristic Curve (SWCC) of biochar-amended soil. The results show that the SWCC increased with the addition of biochar, indicating an improvement in the water retention of the specimens. The reason for this can be attributed to the larger surface area of biochar, which allows it to absorb and retain more water molecules. The lower suction ranges have shown higher gravimetric water content (GWC) and as suction increased, the GWC decreased for each biochar-amended case. This occurred because the specimen released moisture with heating, leading to a decrease in water content. Additionally, the GWC corresponding to a particular suction increased with the addition of biochar, indicating a higher water-holding capacity. For example, the maximum increase in GWC was approximately 6.35% in 5% biochar amended soil at 1.25MPa suction. Therefore, this advocates that bagasse biochar has a significant capacity for water retention and could support vegetation growth.

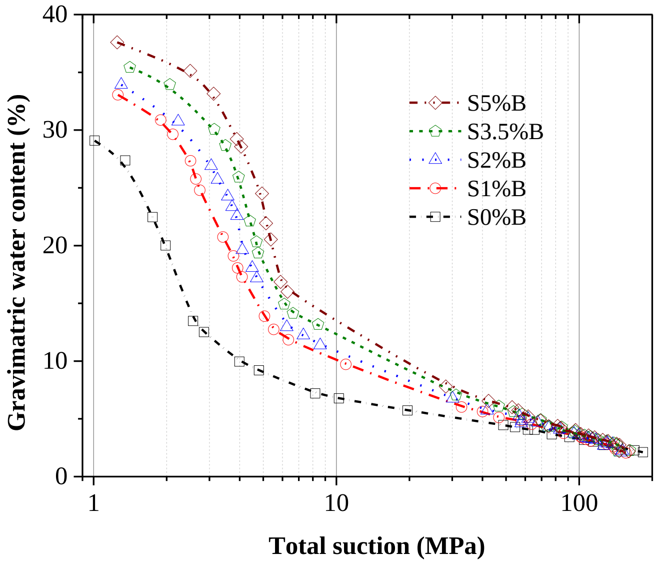

Figure 3. Soil water retention curve of soil amended with varying amount of biochar.

Furthermore, the permanent wilting point represents a crucial parameter in plant physiology. It signifies the soil moisture level at which plants are unable to extract water due to high soil tension, leading to wilting and potential mortality. Typically observed at approximately 1.5 MPa (15 bars) of suction, this threshold indicates a critical limit where the soil's water content is insufficient to sustain plant life. The GWC determined at 1.5 MPa is shown in Figure 4. The results indicate that the addition of biochar significantly increases the GWC of the amended soil, suggesting that the amended material can provide sufficient water to support plant growth.

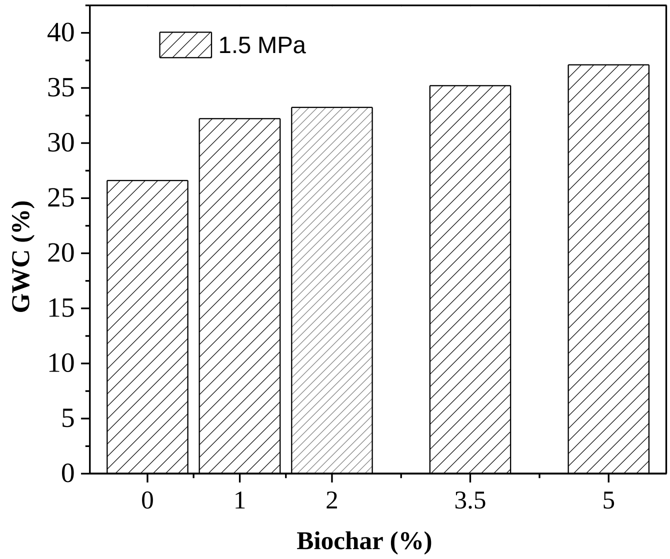

Figure 4. Variation in GWC with biochar content at permanent wilting point.

4.3 Effect of Biochar on Compaction characteristics

The compaction test result of biochar amended soil is shown in Figure 5. The findings for the unaltered soil indicated that the optimal moisture content (OMC) was 17.3% and the maximum dry density (MDD) was 1.72 g/cc. The addition of biochar to the soil resulted in a reduction in MDD and an increase in OMC. Specifically, with a 5% biochar addition, there was the greatest decrease in MDD to 1.58 g/cc and an increase in OMC to 19%.

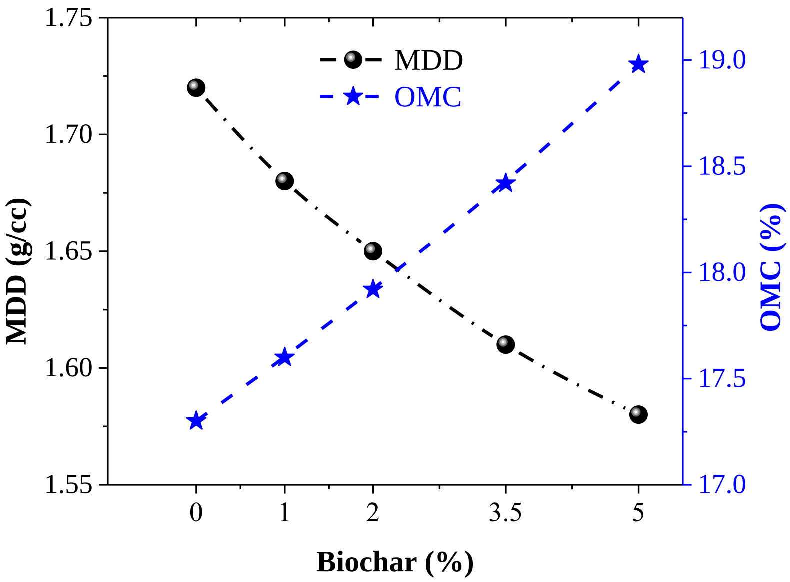

Figure 5. Variation of MDD and OMC of soil with biochar content.

The decrease in MDD of biochar-amended soil was due to the replacement of heavier soil particles with lighter biochar particles. The smaller specific gravity of biochar reduced the overall weight of the system, resulting in a decrease in MDD. Additionally, biochar particles have water-holding properties, which led to an increase in OMC as the biochar content increased.

4.4 UCS Results of Biochar Amended Soil

The UCS test results for soil amended with 0%, 1%, 2%, 3.5%, and 5% biochar at various curing periods (0, 6, 14, and 28 days) are presented in the following sections. The weight of the UCS specimens was measured both before and after the curing period. The observed difference in weight was minimal, ranging from 1% to 3%. These changes in weight were attributed to moisture evaporation and redistribution within the UCS specimens.

4.4.1 Effect of Biochar on UCS at 0 Days

Figure 6 depicts the stress-strain response of soils amended with biochar at zero days of curing.

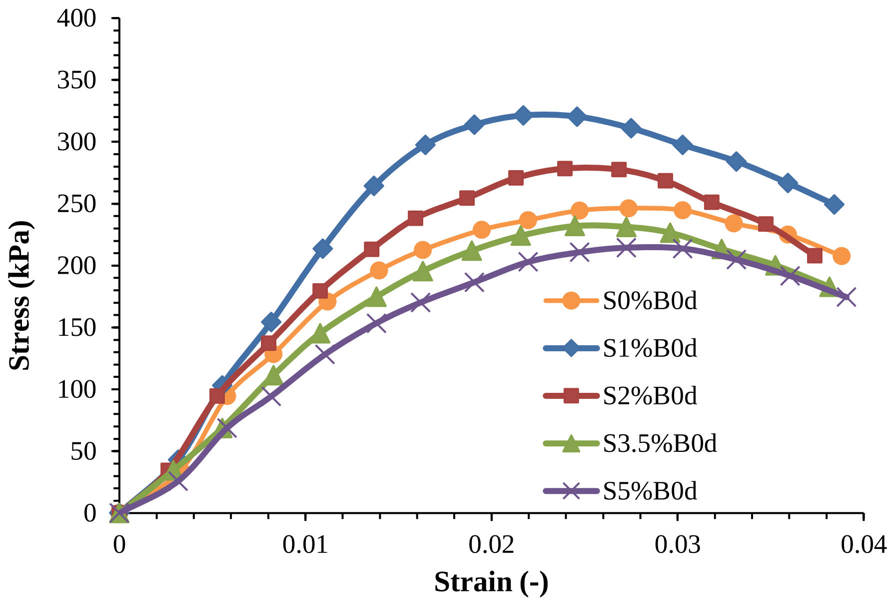

Figure 6. Stress-strain curves for soil amended with varying amounts of biochar at zero days of curing.

The stress-strain curve indicated a maximum increase in peak stress value by 33.10% for the soil with 1% biochar addition compared to non-amended soil. Adding 2% biochar resulted in a slight decrease in peak stress compared to the 1% biochar-amended case, but it remained higher than the peak stress of the non-amended soil. The addition of 3.5% and 5% biochar to the soil led to a decrease in peak stress, with values found to be lower than the peak stress of the non-amended soil. Therefore, the results suggest that a 1% biochar amendment has shown a significant enhancement in the UCS of biochar-amended soil at zero days of curing.

4.4.2 Effect of Biochar on UCS after 7-Days Curing Period

Figure 7 presents the results of UCS specimens tested after 7 days of curing. The stress-strain curve illustrates that the curing period increased the peak stress across all biochar-amended soils. Specifically, the soil amended with 1% biochar exhibited the highest peak stress value among the tested conditions. The stress for the 1% biochar content increased by 23.4% compared to the 0% biochar content. Additionally, the 2% biochar amendment showed notable improvement compared to the non-amended soil. The addition of 3.5% and 5% biochar also increased the peak stress with curing time; however, they remained lower than the non-amended case.

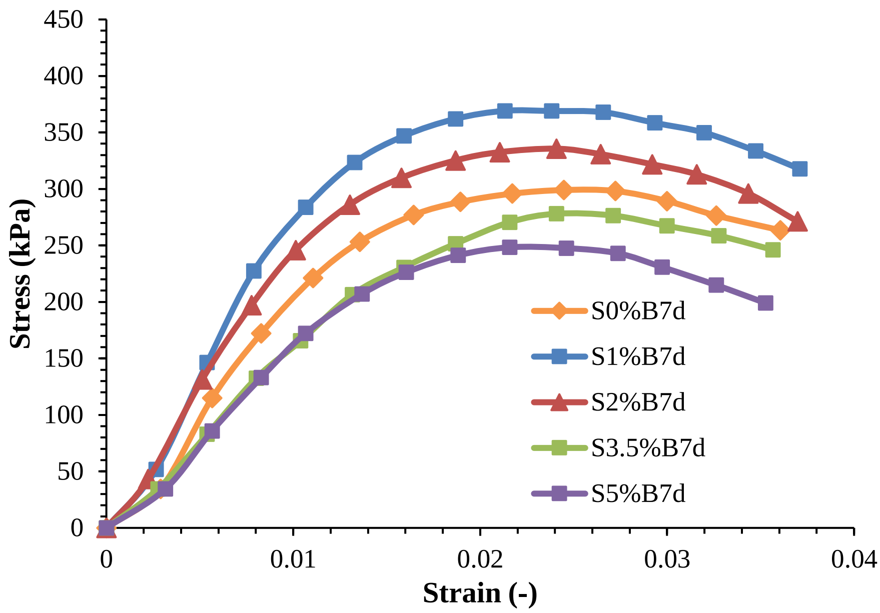

Figure 7. Stress-strain curves for soil amended with varying amounts of biochar at seven days of curing.

4.4.3 Effect of Biochar on UCS After a 14-Day Curing Period

The stress-strain response of UCS specimens cured for 14 days at varying biochar contents is displayed in Figure 8.

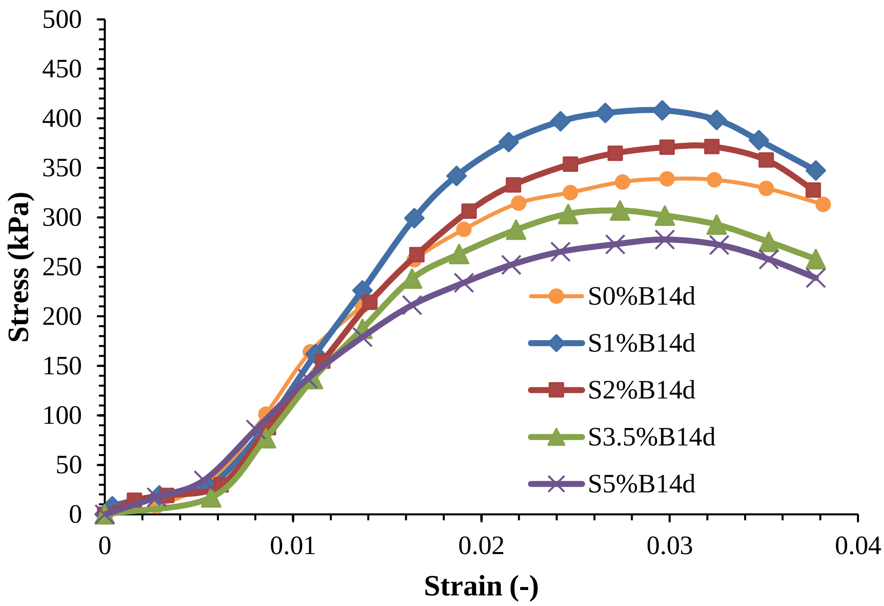

Figure 8. Stress-strain curves for soil amended with varying amounts of biochar at fourteen days of curing.

The findings demonstrate that, as previously observed, the peak stress for all biochar content increased with the curing period. Additionally, the highest growth was noted in UCS specimens treated with 1% biochar. The stress increased by 21.2% for 1% biochar content compared to 0% biochar, whereas it decreased by 32.4% for the 5% biochar content compared to 1%.

4.4.4 Effect of Biochar on UCS After a 28-Day Curing Period

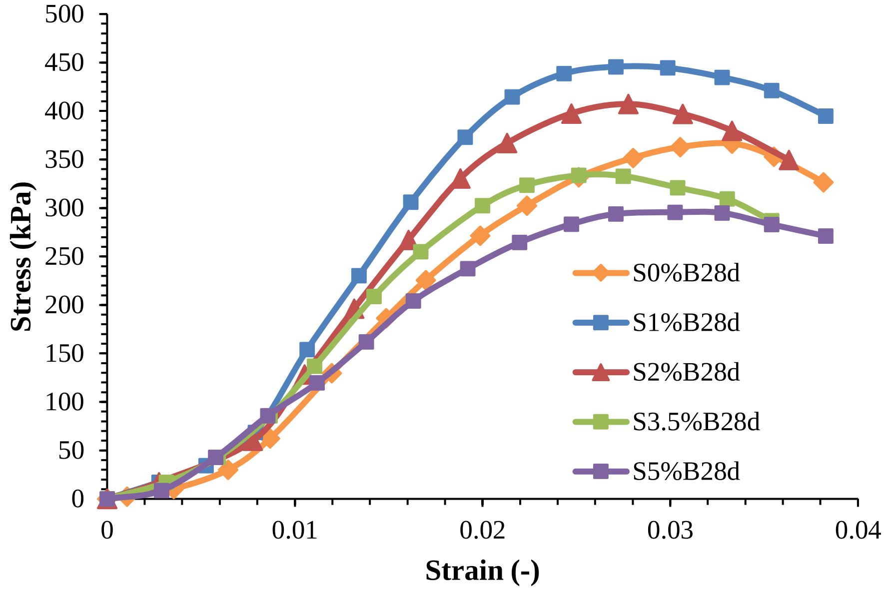

Figure 9. Stress-strain curves for soil amended with varying amounts of biochar at twenty-eight days of curing.

Figure 9 illustrates the stress-strain response of UCS specimens cured for 28 days with varying biochar contents. Similar to specimens cured for 7 and 14 days, those cured for 28 days also showed increased strength across all biochar contents. Specifically, the soil treated with 1% biochar content exhibited the highest peak stress, which increased by 22.1% compared to no-amended specimen.

4.4.5 UCS Variation with Biochar Content and Curing Period

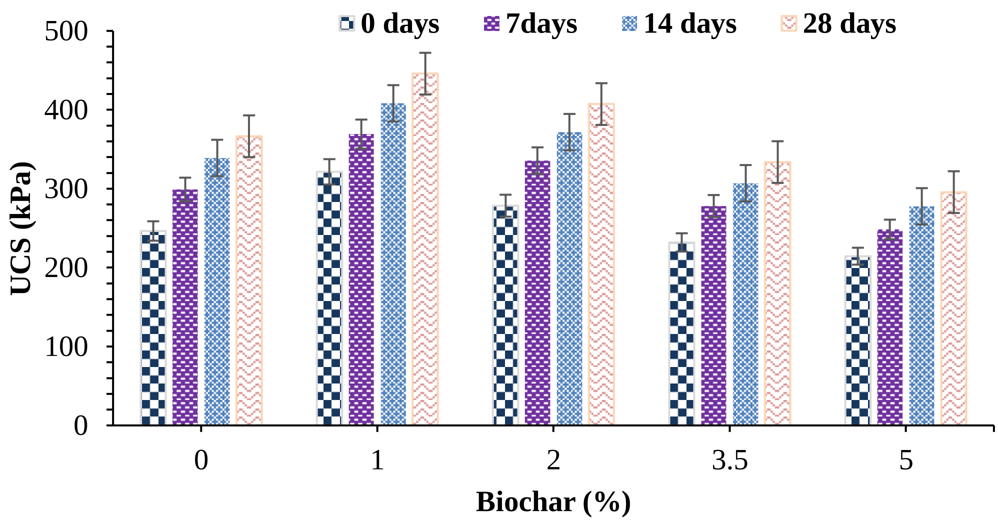

Figure 10. The variation in UCS value of soil with biochar content and increment of curing days.

Figure 10 summarizes the changes in UCS values of soil with varying levels of biochar addition and increasing curing periods. The findings indicate that initially, adding biochar enhances UCS strength up to 1% concentration, but beyond this, strength decreases with higher biochar content. Interestingly, specimens with 2% biochar still exhibited higher UCS values compared to the non-amended samples. Moreover, longer curing periods consistently increased UCS values across all biochar-amended specimens, with the most significant increase observed in the 1% biochar-amended samples. The UCS value for 1% biochar amended case found to be increased by 15.6% after 7 days of curing, by 25.2% after 14 days, and by 37.6% after 28 days, compared to no curing period.

5 DISCUSSION

The addition of bagasse biochar to the soil has reduced the MDD of the amended soil due to its lower specific gravity and porous nature. In contrast, biochar addition has increased the OMC of the soil. It has occurred due to the porous nature of biochar which has enhanced the moisture holding capacity of the mixture. The increase in GWC with biochar addition at the permanent wilting point suction indicates that the amended soil can better support vegetation growth. In addition, the increase in UCS value for the 1% biochar amendment was attributed to efficient pore filling and enhanced bonding between soil and biochar particles. Moreover, the biochar samples contained a definite amount of calcium, which facilitates the formation of stable calcite minerals during the curing period and contributes to strengthening the biochar-amended soil specimens. These findings align with those of Yadav and Bag (2023), who also reported that adding bamboo biochar increased the water retention capacity of soil. Moreover, the incorporation of a small amount of biochar not only improved water retention but also enhanced the compressive strength of the soil. This improvement is attributed to the efficient interlocking between soil and biochar particles, which enhances the structural integrity of the soil. The presence of calcium ions in the biochar plays a crucial role during the curing period, further enhancing the compressive strength of soil. Calcium ions contribute to the pozzolanic reactions, which lead to the formation of additional cementitious compounds, thereby increasing the soil's compressive strength. This dual benefit of enhanced water retention and improved compressive strength makes bagasse biochar a promising amendment for geotechnical and geoenvironmental engineering projects, supporting both structural stability and vegetation growth.

6 CONCLUSION

The study focused on the use of sugarcane bagasse-derived biochar and its effect on the water retention and compressive strength of low-plasticity clay soil. The results showed that the addition of biochar increased the water retention capacity, with the maximum increase observed at the highest biochar content. The compressive strength also increased with a small amount of biochar (1% w/w). The enhanced water retention and strength properties make this composite material suitable for geotechnical and geoenvironmental applications. However, further examination of biochar-amended soil is required to understand its shear strength and other properties before its field application.

DISCLAIMER

The authors states that there are no conflicts of interest.

AVAILABILITY OF DATA AND MATERIALS

The data and materials used in this research will be provided by authors upon reasonable request.

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