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Mechanical Properties of Freshly Amended Soils with Miscanthus Biochar

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Abstract

Biochar has been shown to have multiple, positive benefits on soil physico-chemical and biological properties. However, mechanical behaviour of biochar-amended soils has been given relatively less attention. Therefore, in this study, we aimed to describe these properties of freshly amended soil with Miscanthus biochar in the context of compaction mitigation through a comprehensive laboratory study. In particular, for the first time, we evaluated the short-term loading and unloading responses of replicated biochar-amended soils using a modified oedometer, using different rates of application of biochar (2, 6 and 10% w/w, dry weight basis), in two types of soil (humus free loam and field loam) prepared at two different (10 and 22% w/w) soil moisture contents. From the experiment, dry density (ρ_d), void ratio (e), compression index (C_c) and relaxation ratio (R) were derived and statistically analysed. The addition of biochar was shown to reduce ρ_d while e increased with the amount of added biochar. The addition of biochar increased C_c and R. The effect of soil moisture content and soil types were also found to be statistically significant on the above parameters. However, field studies are needed to understand the long-term mechanical behaviour of biochar-amended soils and further studies are required to examine the performance of different biochar types and soil types.

Keywords: Compaction, Soil Moisture, Loam, Biochar, Void ratio, Compression index, Relaxation ratio, Dry density

Introduction

Soil compaction is increase in density of soils through collapse of pores, resulting in increased bulk density. It modifies the soil structure and distorts the pore geometry, resulting in poor drainage (Hamza & Anderson, 2005; Batey, 2009; Keller *et al.*, 2013). Compaction alters intrinsic pore size and distribution, creating complex pore tortuosity and connectivity, disrupting the diffusion of air and water (Menon *et al.*, 2015). These physical changes have implications on soil biogeochemical processes, greenhouse gas emissions (e.g. N_2O) and crop production (Beare *et al.*, 2009; Liu *et al.*, 2017).

The problem of compaction is widespread in cultivated soils involving heavy machinery. Globally, compacted areas cover 68 Mha (million hectares) out of which 33 Mha is in Europe and 4 Mha in the Australian wheat belt (Flowers & Lal, 1998; Hamza & Anderson, 2005; Keller *et al.*, 2017). Therefore, more research is needed in mitigating compaction or alleviating compacted soil (i.e. reducing the bulk density) using various soil management options. Such management options may include the addition of organic matter (OM), controlled traffic, mechanical loosening such as deep ripping and crop rotation utilising plants with strong tap roots (Hamza & Anderson, 2005). In particular, the addition of OM is particularly interesting due to its multiple positive impacts on soil properties and soil functions (Victoria *et al.*, 2012).

Soane (1990) suggested a few possible mechanisms by which OM would influence the compressive behaviour of soils. These include i. Enhancing the binding forces (cohesion) between particles and within soil aggregates; ii. Enhancing elasticity (organic materials have a high degree of elasticity or relaxation ratio, R); iii. Dilution effect (reduces bulk density, ρ, of soil, depending on the amount added); iv. Filament effect (related to roots, fungal hyphae and other biological filaments); v. Effect of electrical charge, and vi. Reduction of friction due to the organic coating on mineral particles. These mechanisms operate on different time scales (fresh vs decomposed OM) and also will depend on the type of organic matter (animal or plant origin) and soil conditions (ibid). Also, decomposition of OM will help build water stable aggregates (Tisdall & Oades, 1982; Elliott, 1986; Bronick & Lal, 2005), enhancing the structural stability of soils. Based on this it can be hypothesised that when OM is fresh, dominant mechanisms are likely to be (ii) and (iii) whereas when it is decomposed (humus), other mechanisms (i, iv, v and vi) are likely to contribute to the overall mechanical response. However, other factors, such as the amount of OM and soil moisture (Keller *et al.*, 2013; Menon *et al.*, 2015), are also important parameters to consider to maximise the benefit of OM amendments in managing compacted soils.

Although there are many types of OM available as amendments, biochar and its multiple benefits have gained much attention among researchers across the world. Biochar is produced by pyrolysis of biomass and with this process; approximately 50% of the carbon contained in the original biomass can be retained. Addition of biochar has been shown to have a positive effect on soil hydrophysical, mechanical, chemical, and biological properties (Sohi *et al.*, 2009; Atkinson *et al.*, 2010; Jeffery *et al.*, 2011; Lehmann *et al.*, 2011; Ippolito *et al.*, 2012; Castellini *et al.*, 2015; Ajayi *et al.*, 2016; Burrell *et al.*, 2016; Ajayi & Horn, 2016).

Specifically, Castellini *et al.* (2015) demonstrated the impact of biochar (a feedstock made of mixed fruit trees prunings) on physical and hydraulic properties of clay soil, and they suggested a significant increase in water retention close to saturation for the highest level of biochar (30g/ kg), but no corresponding significant difference in ρ, saturated hydraulic or unsaturated conductivity. In another long-term pot experiment using four types of biochars (woodchip biochar, straw biochar, and two vineyard-pruning biochars) in three soil types (Chernozem, Cambisol and a coarse-textured Planosol), Burrell *et al.* (2016) showed that coarse-textured Planosol soil benefitted the most through the addition of these biochars by reduced bulk density particularly by the woodchip biochar and both improved aggregate stability and plant-available water by the addition of straw biochar. Similarly, in a simulated compaction experiment, Liu *et al.* (2017) found that addition of maize straw biochar significantly reduced ρ, increased porosity and water holding capacity. However, an earlier field study showed no significant effects of biochar on hydrophysical soil properties 30 months after biochar incorporation (Hardie *et al.*, 2013). These studies show that any improvement in soil physical conditions will depend on the type of biochar, the amount added, time of application and when the observations have been taken. In particular, the hydrophysical effects of biochar tend to change over time (Hardie *et al.*, 2013; Castellini *et al.*, 2015; Burrell *et al.*, 2016) while data on the mechanical behaviour of biochar-amended soil is sparse. A notable exception is a recent study by Ajayi and Horn (2017) which reported an improvement in the mechanical resilience of aggregates 100 days after amending a sandy soil with woodchip biochar. However, biochar is usually added through broadcasting and incorporation before other agricultural operations involving heavy machines. A long waiting period after incorporation is, therefore often not being practised in a typical intensive farming scenario.

To use biochar to alleviate the compaction in soils, we need to describe the mechanical behaviour of biochar-amended soil under simulated traffic loading and unloading regimes. Therefore, the overarching aim of this laboratory study was to describe the mechanical behaviour of freshly amended soils with biochar under two soil moisture contents. The mechanical behaviour of biochar-amended soils can be expressed using changes in ρ (total mass to the total volume), and dry density (ρ_d; dry mass to the total volume), void ratio (e; volume of void to the total volume of solids), compression index (C_c; changes in e in response to the applied vertical load, σ_v) and relaxation ratio (R; ratio of ρ in presence and absence of σ_v).

In particular, for a given soil type, we tested the following hypotheses:

1. The effect of biochar on ρ_d and e will depend on the rate of biochar application. Thus, a higher rate of biochar application will produce a lower ρ_d (or higher e) due to the porous nature of biochar and the dilution effect.
2. Biochar-amended soils will have a high value of C_c and R as most organic amendments have a high degree of elasticity.

To this end, the following objectives were formulated:

1. Quantify the variation of ρ_d, and e with vertical compressive stress σ_v in response to soil types, soil moisture contents and rate of biochar application.
2. Determine C_c and R and evaluate the data in response to the rate of application of biochar under varying soil and soil moisture contents.

The vertical stress will be applied under one-dimensional conditions. Since all soils tested will be partially saturated, total stresses only will be quoted as the soil was partially saturated, and the compression index is defined in this context. Interpretation of suction effects and effective stresses are beyond the scope of this paper.

Materials and Methods

Soils and sample preparation

Two types of soil were used in the study. The first soil (S1) was made in the laboratory using a pure form of medium size sand (150-700μm), silt (5-75μm) and kaolin (<2μm) clay (50:25:25 w/w), representing a humus free loam soil. This material was chosen to eliminate the influence of organic matter (OM) and the presence of pre-existing natural soil aggregates. A second soil (S2) was a 2 mm sieved loam topsoil (sand: silt: clay = 40: 44: 16) collected from 0-20 cm from the Leeds University farm, U.K. Both plastic and liquid limits were determined according to British Standards (BS 1377-2:1990) protocols as 11% and 22% for S1, and 25% and 37% for S2.

Amendment with biochar at different soil moisture contents

The biochar used in the study was produced from *Miscanthus x giganteus*, subjected to fast pyrolysis at 450°C (BTG, Enschede, Netherlands) with a moisture content of 0.57% (i.e. before amending to soil) and a water holding capacity of 461.40% (w/w). The reported average skeletal density for Miscanthus is 1.68 (range =1.39-1.96) g/cm^3 whereas the average envelope density is 0.28 (range 0.26-0.29) g/cm^3 (Brewer *et al.*, 2014; Brewer & Levine, 2015). The average envelope density obtained in our laboratory testing was

0.23±0.11 g/cm^3. The average internal biochar porosity may therefore be estimated as (1.68-0.23)/1.68 = 86%.

The rate of application of biochar depends on climatic and soil texture, and different rates can be found in the literature. However, a recommended rate is 2 % (w/w) while higher rates are also common (Filiberto & Gaunt, 2013; Peake *et al.*, 2014).

The experiment was started with preliminary load tests on S1 with different moisture levels (5, 10, 20 and 40% w/w) to find out optimum moisture content for the subsequent experiments. Based on the data obtained it was decided to use 10% w/w as soil strength was found to be maximum at this moisture content (also the plastic limit is 11%) for further experimentation with different biochar rates, i.e. (0, 2, 6 and 10 % soil dry weight basis) . These rates will be equivalent to 30, 90 and 150 t/ha (based on a soil bulk density of 1500 kg/m^3 and 0.1m soil depth) for 2, 6 and 10% rates. However, the dry density (as shown in Figure 2 later) data showed no significant difference between 6 and 10% biochar rates for S2 at 10% w/w soil moisture content and hence discontinued the 6% rate in the subsequent experiments using S2. However, for S2, we used 10% as well as 22% soil moisture content (average field moisture content at the time of collection and due to higher plastic and liquid limits compared with S1) with 0, 2 and 10% biochar rates. Note that the soil samples and biochar were dried first to remove any moisture (gravimetric method), followed by elevating the moisture levels to required levels adding the required amount of water incrementally after mixing the soil with biochar with a spatula and kept in sealed container for 24 hours as incubation period to achieve a uniform moisture content distribution. To the best of our knowledge, there is no recommended incubation period, and a recent review suggested this can vary from 0-6 months (O'Connor *et al.*, 2018). Three replicates were used for all tests.

Mechanical Loading Tests

A conventional oedometer one-dimensional consolidation test apparatus (BS 1377-5:1990) was adapted for the determination of the magnitude and the rate of compression in the process of loading and unloading. In the apparatus, a cylindrical specimen (h= 20 mm, d = 75 mm) contained within a steel ring was subjected to a dead load applied using a lever system and the change in the height of the specimen was monitored using a micrometre dial gauge as a function of time. A conventional test using this apparatus for the investigation of consolidation behaviour of soils, involved drainage of water from the specimen. However, in the current tests compression took place by the expulsion of air, allowing acceleration of the test process. Therefore, the standard porous discs normally used in the apparatus were replaced with perspex discs to avoid absorption of water from the samples by the discs. However, this also meant that if the water were squeezed out of the matrix into the larger pore spaces, it could not drain away.

A load sequence of 12.5, 25, 50,100, 200, 400 and 800 kPa was used, and also at each step of loading, the sample was unloaded to zero and then loaded up to the next increment of the load. At the last increment of loading (800 kPa), the load was unloaded in two steps, 800 to 400 kPa, and then 400 to 0 kPa. The time step between loading stages was 15 minutes as little change was observed after this period after application of a load. This also simulated the real world situation where the loading time is very short (e.g., slow moving agricultural machinery).

Calculation of ρ_d, e, C_c and R

Fig. 1 presents the phase relationship diagram, which was used in this study to calculate the value of ρ_d and e of the specimen. The initial height of the sample was the same for all tests and was set by loosely filling the material to the top of the oedometer sample ring. This will have led to some variation in initial density due to operator error. However, this is expected to have a minor effect on the densities achieved under loading. The change in sample height, recorded from the oedometer readings, enabled calculation of sample volume (before and after compaction). After the oedometer test, the samples were oven-dried to obtain the dry weight gravimetrically.

For sample S1, the specific gravity of the coarse sand, silt and clay were taken as 2.65 based on the supplier data sheets. For sample S2 the same value of 2.65 was adopted as this is generally representative for soils. However, biochar is a highly porous material, and its density may be attributed to variations in the source material and internal porosity. Since the choice of its specific gravity has a significant effect on the value of *e* calculated, and the biochar itself may swell on absorption of water, it was decided to adopt the simple approach of computing a 'biochar inclusive void ratio', e_b, (i.e. assuming both its skeleton and internal porosity constitute beneficial void space). In the context of the biological functioning of the soil, this may be justified as the biochar will provide space for biota and water, considering its gravimetric water holding capacity of 461.4%, and internal porosity of around 85%.

The biochar inclusive e_b was calculated using the equation below.

$$e_b = \frac{H - H_s}{H_s} \qquad (1)$$

where; H = total height of sample and H_s = height of soil mineral solids, given by:

$$H_s = \frac{1}{A\gamma_w}\left(\frac{m_{sand}}{G_{s_{sand}}} + \frac{m_{silt}}{G_{s_{silt}}} + \frac{m_{clay}}{G_{s_{clay}}}\right) \qquad (2)$$

where; m_{sand}, m_{silt}, m_{clay} are the dry mass of sand, silt and clay; $G_{s_{sand}}$, $G_{s_{silt}}$, $G_{s_{clay}}$ are the specific gravity of sand, silt and clay; A is area of specimen/oedometer's ring; and γ_w is the weight density of water.

The value of C_c was determined by changes in e_b with the changes in total vertical stress (load) applied to a sample. It describes the relationship (i.e. slope of the line) between e_b and log (σ_v). In addition to this, the relaxation ratio (R) was also derived, which is the bulk density (ρ) of the test material under specified stress to the ρ after the stress has been removed (Soane, 1990). The R value is an effective way to check the recovery of soils under various loading regimes. Thus, a soil that recovers would be better for combating compaction from agricultural machinery.

Statistical analysis

The data were found to be normally distributed and based on that two-way ANOVA was used to compare soil or moisture (factor 1) under different biochar application rates (factor 2) and along with Tukey HSD (Honest Significant Difference) to compare different rates of applications within each group (S1W1, S2W1 and S2W2) of data. GraphPad Prism (ver. 7) was used to perform the statistical analyses and create some figures.

Results

Dry density (ρ_d)

The addition of biochar decreased ρ_d (after maximum loading), in both soils, S1 and S2 at all soil moisture levels (Fig. 2) and the reduction in ρ_d was proportional to the amount of biochar added. While comparing the dry density of S1 and S2 for the same moisture content, it was clear that the dry density reduced gradually but linearly with the amount of biochar for both soils. The dry density for S1 was larger than the dry density of S2 throughout (Fig. 2a). Two-way ANOVA showed statistically greater significant effects ($P < 0.0001$) for both soil and biochar treatments. The comparison of ρ_d from different biochar treatments revealed the statistically significant difference between rates of biochar in S1W1 (Table 1) whereas, for S2W1, this was true except for the 6% vs 10% rate of biochar.

Fig. 2b compares two different moisture content levels (W1 and W2) within the same soil type (i.e. S2) in which there was a similar gradual decrease in ρ_d with increase in biochar rate. The ANOVA showed significant effects of biochar ($P<0.0001$) and soil moisture ($P = 0.0442$). When different rates of biochar were compared within S2W1, the 10% rate of biochar differed significantly from both 0 and 2% rates. For the S2W2, the results were similar except there was no difference between 0 and 2% biochar.

Biochar inclusive void ratio (e_b)

Fig. 3 (a-f) shows the changes in e_b in the process of loading and unloading. For simplicity, pairwise comparison of 0 (e) and 10% biochar additions (e_b) are described here. Fig. 3a & b, thus, show the responses in e and e_b for S1 with 10% moisture content, Fig. 3 c & d for S2 with 10% moisture content and, finally Fig. 3 e & f for S2 with 22% moisture content. All additions of biochar nearly doubled the value of e_b in all cases.

The degree of change in e_b was always greater for S1W1 compared to S2W1 under 10% biochar (compare Fig. 3b & d) at the end of the test, and both achieved very similar values of e_b. The results showed that, in general, the soils with biochar had a larger initial value of e_b but were more compressible both in terms of recoverable and unrecoverable deformations, when compared to the soils without biochar.

Biochar Inclusive Void Ratio (e_b) *and Compression index* (C_c*)*

At each loading step, the value of e_b was calculated and plotted (Fig. 4 a-c) for all treatment combinations. The relationship between e_b and the logarithm of pressure followed was closely linear in all cases. This is a typical pattern that can be expected for many soil types. For all cases, as expected, the biochar inclusive void ratio was lowest in the absence of biochar and highest at 10% rate of application and in between for the other two treatments (2 vs 6%).

The C_c for the soil was calculated based on the slope of the lines and is given in Fig. 5. It was found that C_c increased with the increase in biochar content in all cases. The effect of soil types and biochar rates on C_c was statistically significant ($P < 0.0001$ for both), including their interactions ($p = 0.0072$). Tukey multiple pairwise comparisons also (Table 2) also showed the statistically significant difference between different levels of biochar additions except 0 vs 2%, and 2 vs 6%. For S2W2, all except 0 vs 2% addition of biochar treatments was significant.

The ANOVA showed a significant effect of biochar ($P < 0.0001$) and soil moisture content ($P < 0.0001$). However, the interaction between the two variables was not significant. Here also, pairwise comparisons were significant except 0 vs.2% in S1W1 (Table 2). Also, the C_c was very similar for S2W1 with 10% biochar and S2W2 with 2% biochar.

Relaxation ratio (R*)*

The relaxation ratio is the ability of soil to restore its bulk density after the external pressure is removed. The R values obtained under each load are provided in Fig. 6 (a-c), which showed that the R values increased with the applied load, following an approximately logarithmic relationship. It consistently showed that as the biochar rate increased, the relaxation ratio increased. At the maximum load of 800kPa, the relaxation ratio for 10% biochar treatment was >1.08, whereas it was 1.04 and 1.02 for 2% and control (without biochar).

For convenience, to compare the performance of different samples, average R values for all treatments were computed across the loading range under different biochar application rates, as visualised in Fig. 7. In general, R values increased with the rate of biochar. The ANOVA showed the statistically significant effect of biochar ($P<0.0001$) and soil ($P<0.0001$) was found under the same moisture content (W1). For the same soil type (i.e. S2), effects of biochar ($P<0.0001$) and moisture content ($P<0.0001$) on R were statistically significant.

When comparing different rates of biochar within the two soil types on R (Table 3), it was found that at 10% biochar, R differed significantly from both 0 and 2% rates of biochar application. The difference in R between 0 and 2% was significant for S1W1, but not significant for S2W1. Comparisons of R within the same moisture levels were similar. At 10% biochar, R was significantly different from those at 0 and 2% rates of biochar application when compared within the same soil type under two different moisture contents (Table 3). It also suggested the difference in R between 0 and 2% was also significantly different.

Discussion

Biochar is regarded highly as a soil amendment, and several benefits have been reported in the literature, however little attention has been given to mechanical behaviour (Atkinson *et* *al*., 2010) of biochar-amended soils, except in a few recent studies (Peake *et al*., 2014; Castellini *et al*., 2015; Burrell *et al*., 2016; Ajayi & Horn, 2016, 2017; Liu *et al*., 2017). An important difference between the current study and the previous studies is how samples were prepared. In some studies, measurements were taken after several days to months using pre-incubated samples whereas others measured physical properties several months after biochar incorporation under field conditions. For instance, Ajayi and Horn (2017) amended biochar with soil and incubated for 100 days. In their previous study (Ajayi & Horn, 2016) samples were incubated for 30 days. Our investigation, in contrast, considered the mechanical behaviour of soil 24 hours after amendment with biochar. This short period was chosen mainly to equilibrate moisture within the samples, and there is no recommended incubation period (anytime within 0-6 months) (O'Connor *et al*., 2018). Furthermore, time of observation is also important as some studies reported no significant change in hydro-physical properties several months after incorporation (Hardie *et al*., 2013; Castellini *et al*., 2015; Burrell *et al*., 2016), indicating that temporal dynamics in these properties depend on biochar type, soil and environmental conditions.

Particle size distribution is also an important factor when whole plant biomass is used for biochar production, such as the *Miscanthus* biochar we used. This biochar exhibited a large degree of heterogeneity in size, shape and strength; each can significantly impact the mechanical behaviour. Importantly, the biochar was not subjected to any size modification (e.g. by crushing), which is often unnecessary and not being practised widely. However, if the size of the biochar is small enough, it can fill the macropores (>75µm) as suggested by Ajayi and Horn (2017). If provided with sufficient incubation period after mixing the biochar, this would also promote aggregation providing additional mechanical resilience to soils as these authors demonstrated. Ajayi and Horn (2017) found that long-term incubation (100 d) of finely prepared (750µm sieved) biochar led to the formation of more permeable and pliable aggregates, thus less prone to collapse or rupture. They also observed that biochar amendment increased porosity, decreased bulk density and soil's mechanical resilience improved significantly, similar to our results.

The underlying rationale for using a soil without any aggregates or organic matter (S1) was an indirect way to identify the contribution of biochar in isolation. Since this study did not use fine-grained biochar, the observed results can be explained by the elasticity and dilution effect exhibited by bulky and porous organic materials. Most organic materials possess elastic behaviour and high relaxation ratio (Soane, 1990). If we assume 10% w/w addition of biochar with an envelope density of 0.23 g/cm^3 to the soil, then 1g of soil solids will have a volume of 1/2.65 = 0.38 cm^3, while the biochar will have a volume of 0.1/0.23 = 0.43 cm^3. Therefore, for the envelope component, biochar will have a value of e_b = 0.43/0.38 or approximately 1.1. Under small loads (Figure 3) e_b increased by ~0.5-1.0 over and above 1.1, indicating significant additional interparticle void space. However, at the largest load (800kPa) most of this extra void space appears to be lost leaving the gain in e_b primarily due to the biochar itself (i.e., the internal porosity of biochar), possibly reduced slightly due to some minor crushing of the material. At loads typical of farm vehicles (~100kPa) additional void space remained at approx. 0.3. It is noticeable that samples significantly drier than the plastic limit (S2W1) were less compressible than those with moisture contents closer to the soil plastic limit. This was expected as the soil aggregates should be stronger; however, the initial and final biochar inclusive void ratio of, e.g. S2W1 was smaller than that of S2W2. This may be due to the absorption of water by the biochar, which would swell, but simultaneously reduce the moisture content of the soil mineral phase.

The effects may depend on the type of material used in biochar production and soil types used in the experiments, making it challenging to compare studies. In a study where different biochars were compared (woodchip, straw and vine-prunings) under different soil types (Chernozem, Cambisol and coarse textured Planosol), Burrell *et al.* (2016) identified biochar-soil combinations to improve physical properties. They authors found straw biochar to be suitable for improving the aggregate stability of a coarse-textured Planosol, whereas woodchip biochar showed no effect on bulk density on Chernozem (Burrell *et al.*, 2016). In our study addition of biochar decreased bulk density. The reason could be due to the difference in the timing of these observations; the findings of Burrel et al. (2016) were based on measurements carried out after several months after adding the biochar whereas our results were based on biochar-soil mixtures incubated for 24 hours.

The rate of application of biochar influences the physical and hydraulic properties, although rates of more than 50 g /kg did not significantly influence soil hydrophysical or mechanical properties (Ajayi & Horn, 2016, 2017). Through pairwise statistical tests we could show the impact of soil moisture and biochar levels for ρ_d , C_c and R. For instance, earlier results from both soils on ρ_d suggested no significant difference between 6 and 10% biochar application under low soil moisture content (W1). This helped eliminate 6% biochar for the following experiments at greater moisture content (W2).

Based on the findings, it is safe to conclude that there is a substantial gain in void ratio and compression index when biochar is added to soils. However, it is also important to understand how mechanical behaviour would change after different periods of incorporation under repeated trafficking conditions. It is important to consider biochar characteristics in future studies as it depends on biomass feedstock and pyrolysis temperature (Sohi *et al.*, 2009). Also, the effect of biochar may change over time, and it needs to be verified using long-term monitoring studies under a variety of soil and environmental conditions.

Conclusions

This study compared different rates (2, 6 and 10% w/w, dry weight basis) of Miscanthus biochar application in two soil types under two moisture content levels. Results showed a positive benefit with improvements the dry density and void ratio, simultaneously increasing the compression index of biochar-amended soils. These effects could be explained by the dilution effect provided by organic materials. Biochar-amended soils had improved relaxation ratios, a property linked to the elasticity of the material. The effect of biochar addition was significantly influenced by the moisture levels and soil types.

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