

Influence of wood-derived biochar on the compactibility and strength of silt loam soil

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A b s t r a c t. Biochar is proven to enhance soil fertility and increase crop productivity. Given that the influence of biochar on soil compaction remains unclear, selected physico-mechanical properties of soil amended with wood-derived biochar were assessed. For unamended silt loam, the bulk density, maximum bulk density, optimum moisture content, plastic limit, liquid limit, and plasticity index were 1.05 Mg m^{-3} , 1.69 Mg m^{-3} , 16.55, 17.1, 29.3, and 12.2%, respectively. The penetration resistance and shear strength of the unamended silt loam compacted in the standard compaction Proctor mold and at its optimum moisture content were 1800 kPa and 850 kPa, respectively. Results from amending the silt loam with 10% particle size ranges (0.5-212 μm) led to relative decreases of 18.1, 17.75, 66.66, and 97.4% in bulk density, maximum bulk density, penetration resistance, and shear strength, respectively; a 26.8% relative increase in optimum moisture content; along with absolute increases in plastic limit, liquid limit, and plasticity index of 5.3, 13.7, and 8.4%, respectively. While the biochar-amended silt loam soil was more susceptible to compaction, however, soil mechanical impedance enhanced.

K e y w o r d s: biochar, particle size, bulk density, proctor compaction, plastic and liquid limit, penetration resistance, soil shear strength

INTRODUCTION

Biochar is produced by pyrolysis, a process whereby biomass material is decomposed in the absence of oxygen at temperatures ranging from 250 to 700°C (Yuan *et al.*, 2014). The organic starting material can be drawn from a variety of types of biomass, including wood chips, crop residues, manure, and animal waste. Pyrolysis conditions and feedstock material are responsible for biochar characteristics such as chemical composition, surface chemistry,

nutrient composition, adsorption capacity, cation exchange capacity (CEC), pH, and physical structure (Cimò *et al.*, 2014).

Soil compaction is defined as densification of soil whereby air-filled porosity is reduced, causing deterioration in soil processes. Subsoil compaction is a cumulative process leading to soil packing just below the topsoil (Harris, 1971). As compaction increases soil mechanical impedance, it adversely affects the elongation and proliferation of roots (Boone and Veen, 1994). These changes might result in the alteration of moisture and nutrient availability to crops, thereby increasing or decreasing the agricultural soil productivity.

The changes in soil physical properties lead to changes in soil state under compaction (Chen and Weil, 2011). Soil particle density is 2.6 Mg m^{-3} regardless of its particle size, while for wood-derived biochar (WBC) with a particle size of less than 70 μm it ranges between 0.6 and 1.6 Mg m^{-3} , depending on the wood source (Hu *et al.*, 2016; Yargicoglu *et al.*, 2015). Due to the relatively low true density of biochar, its amendment to soils have been reported to decrease soil bulk density (ρ) (Abel *et al.*, 2013; Andrenelli *et al.*, 2016; Bayabil *et al.*, 2015; Castellini *et al.*, 2015; Liu *et al.*, 2016; Obia *et al.*, 2016). For example, Reddy *et al.* (2015) found the specific gravity of silty clay, WBC (particle sizes < 420 μm), and silty clay amended with 5, 10, and 20% WBC to be 2.6, 0.81, 2.1, 2.0, and 1.8, respectively. Soil optimum moisture content for compaction (θ_{opt}) is the moisture content at which soil reaches its maximum bulk density (ρ_{max}) for a given applied specific load. It has been established that soil compressibility decreases with an increase

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in the WBC amendment and with a decrease in WBC particle size (Reddy *et al.*, 2015). Carter (1990) found crop yield to be correlated to the soil relative bulk density (RBD), *i.e.*, $\frac{\rho}{\rho_{\max}}$ (Håkansson and Lipiec, 2000). Similarly, Zhao *et al.* (2010) showed that a maximum tree height was achieved when $0.60 \leq \frac{\rho}{\rho_{\max}} \leq 0.68$, but these trees were somewhat stunted when $0.78 \leq \frac{\rho}{\rho_{\max}} \leq 0.87$.

The plastic limit (θ_{pl}) is the water content, in percent, at which soil can no longer be deformed by rolling into a 3.2 mm thread. The moisture content at which soil passes from a liquid to a plastic state is called the liquid limit (θ_{ll}) (Das and Kassimali, 2002). Determined for soils with more than 10% clay content, the plasticity index ($PI = \theta_{ll} - \theta_{pl}$) increases as the soil clay content increases. However, soils with less than 10% clay content can be plastic if organic matter is present (Keller and Dexter, 2012). These consistency limits can provide a means of describing the degree and kind of cohesion and adhesion between soil particles and any biochar amendments with respect to the resistance of the soil to deform or rupture. As the PI value of soil increases, the range of moisture over which the soil is susceptible to compaction by external forces increases (Aksakal *et al.*, 2013). Amendment with 6% coal fly ash ($PS < 2$ mm) significantly ($p < 0.05$) decreased the θ_{ll} and increased the θ_{pl} of clay soil and led to a decrease in soil PI of 35% (Lu *et al.*, 2014). In another study, WBC ($PS < 2$ mm) amended to clay loam soil at a rate of 6% significantly ($p < 0.05$) increased the θ_{ll} of the soil by relatively 8% and the soil θ_{pl} decreased by 14.7% resulting in a 59% increase in the PI (Zong *et al.* 2016). There is a significant and positive correlation between θ_{opt} and θ_{pl} and θ_{ll} (Barzegar *et al.*, 2004; Dexter and Bird, 2000; Mosaddeghi *et al.*, 2009; Mueller *et al.*, 2003). The θ_{pl} , θ_{ll} , and PI can be estimated from the θ_{opt} , as well as the soil clay, silt, and organic matter (OM) content (Wagner *et al.* 1992). Soil ρ_{\max} can be estimated from θ_{pl} for fine-grained soils (Mueller *et al.*, 2003; Oren, 2014). However, there is no existing model to estimate the consistency limits from the soil particle sizes and the percentage of WBC in soils.

Dexter and Bird (2000) defined soil workability for tillage as ‘the water content at which tillage produced the greatest proportion of small aggregates’. Soil workability is related to soil consistency limits and/or Proctor compaction test data (Muller *et al.*, 1990; Wagner *et al.*, 1992). The θ_{opt} or $0.9 \theta_{pl}$ is considered optimal for tillage practices (Dexter and Bird, 2000). Soil structure damage is prevented when tillage occurs at the soil optimal moisture content for tillage (Mueller *et al.*, 2003). The consistency limits of the soil are crucial not only to estimate compressibility and the optimum workable water content range for tillage operations (Zong *et al.*, 2016) but also in agricultural soil irrigation management (Smedema 1993). The Atterberg limits and the Proctor compaction test parameters are agro-

nomically relevant in terms of compaction hazard for soils and tillage. In summary, an increase in soils θ_{ll} , θ_{pl} , and θ_{opt} values not only results in less compactable and more easily tilled soils, but also a wider workable soil moisture range and greater resistance to mechanical forces. Therefore, the first objective of this study was to determine the effects of WBC application on the consistency limits and the Proctor compaction test parameters of a silt loam soil.

The incorporation of OM into compacted soils reduces their ρ (Ohu *et al.* 1985), and results in a decrease in soil penetration resistance (PR), resulting, in turn, in an increase in root proliferation in compacted soils (Dexter, 2004; Ohu *et al.*, 1985). Soil PR values exceeding 2000 kPa are associated with restricted root growth (Singh and Malhi, 2006). Busscher *et al.* (2010, 2011) showed the application of 44 Mg ha⁻¹ of pecan shell-derived biochar (2% dwb) to decrease the PR (measured at $\theta = 10\%$) of a fine loamy sand from 2.9 to 1.18 MPa. This biochar amendment raised the soil ρ from 1.45 to 1.52 Mg m⁻³ (Busscher *et al.*, 2010; 2011). Bekele *et al.* (2015) also showed the PR of a loamy soil to be lowered by a WBC amendment. In contrast, Eastman (2011) found a 25 Mg ha⁻¹ WBC amendment not to have any significant effect on a silt loam soil PR one year after incorporation (Eastman, 2011). On the other hand, Mukherjee *et al.* (2014) found the PR of a silt loam soil amended with WBC to unexpectedly increase after 2 years, attributing this increase to the influence of post-amendment farm operations on soil physical properties.

Zong *et al.* (2016) showed WBC ($PS < 2$ mm) to have a relatively lower cohesion (c) and greater angle of internal friction (ϕ) than a clay loam soil. These differences significantly reduced c and increased ϕ of the clay loam soil amended with WBC at a rate of 6%. Also, the tensile strength of the clay loam soil decreased from 466 to 233 kPa with the amendment of 6% WBC. These changes were attributed to the alteration in the soil pore structure and the degree of water saturation of the soil amended with biochar (Zong *et al.* 2016). In another study, the tensile strength of a clayey soil decreased from 937 to 353.5 kPa with the amendment of WBC at a rate of 6% dwb (Lu *et al.*, 2014). The shear strength (SS) of a silty clay soil was increased with an increase in the biochar amendment rate from 5 to 10% dwb, as well as with a decrease in biochar particle size from 4.76 to 0.42 mm (Reddy *et al.*, 2015). Since the influence of WDB amendments on the strength of compacted soils is still unclear, the second objective of this study was to determine the PR and SS of a compacted silty loam amended with WBC.

MATERIALS AND METHODS

The biochar in this study was produced by thermal decomposition of forest wastes, including maple (*Acer* sp.) wood, at 500°C. This biochar was purchased from a local market. The brand name of the biochar is Maple Leaf® Charcoal (Charbon de Bois Feuille d'Érable Inc., Sainte-

Table 1. Bulk density (ρ) and percent change in ρ ($\Delta\rho$) of silty loam after amendment with WBC of different particle size ranges, at different rates

Level of biochar amendment (% dwb)	Biochar particle diameter range (μm)					
	PS ₁		PS ₂		PS ₃	
	0.5-212		212-425		425-850	
	ρ (Mg m ⁻³)	$\Delta\rho$ (%)	ρ (Mg m ⁻³)	$\Delta\rho$ (%)	ρ (Mg m ⁻³)	$\Delta\rho$ (%)
2	0.98	-7	1.02	-3	1.03	-2
5	0.91	-14	1.00	-5	1.01	-4
10	0.86	-19	0.90	-14.5	0.93	-12

Values of ρ in bold differ significantly ($p \leq 0.05$) from non-amended silt loam soil. ρ of the silt loam soil is 1.05 Mg m⁻³.

Christine d'Auvergne, QC). The silt loam soil (SLS) was collected from the A horizon (0 – 0.2 m) of a field (coordinates 45.413919 - 73.941469) on the Macdonald Campus Farm, McGill University (Sainte-Anne-de-Bellevue, QC). The soil was air-dried at room temperature and then ground to pass through a 2 mm sieve.

Soil particle size analysis was quantified according to the procedures outlined in ASTM (1984). Biochar particles size was determined by laser diffraction analysis following procedures outlined in (Müller *et al.*, 2004)

Biochar was ground in a blender and sieved in a fume hood to achieve the desired particle sizes. Dry soil and biochar were mixed for 20 min in a soil mixer with the desired composition of biochar in the soil on a dry weight basis (dwb) to achieve a homogeneous mixture. The composition of biochar in the silt loam soil were chosen to be 2, 5, or 10%. These rates of biochar composition in the soil were selected to understand the behaviour of the soil as biochar is added. The application rate corresponded to an application rate in the field of 75, 187.5, and 375 Mg ha⁻¹, assuming a bulk density of soil in the field of 1250 kg m⁻³ with an application depth of 30 cm.

The ρ determinations were performed by dividing the oven-dry mass of the silt loam, WBC, or WBC-amended silt loam by its volume. The ρ_{max} and θ_{opt} were determined through the standard Proctor compaction test, following the procedure of ASTM (2007).

Soil consistency limits were determined according to (ASTM 2010).

The PR of the compacted silt loam in the standard Proctor mold was determined by a penetrometer (FieldScout, SC900 Soil Compaction Meter) according to ASAE (2013) with a penetrometer cone diameter of 12.83 mm and a cone angle of 30°. Torvane (Humboldt, H4221 Geovane Soil Shear Strength Tester) was used to determine the SS of the soil compacted in the compaction mold according to ASAE (2016).

Analysis of variance (ANOVA) and the Duncan Multiple Range Test were used for testing mean differences SAS, (v. 9.2, SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

The sieve analysis showed that the silt loam was a well-graded soil having 100, 66, 47.2, 12.1, 8, and 4.6% finer after sieves of 2000, 850, 425, 150, 106, and 75 μm , respectively. The hydrometer analysis showed that the silt loam soil contained 17% clay, 77% silt, and 6% sand. The WBC was sieved into three particles size (PS) ranges: 0.5-212 μm (PS₁), 212-425 μm (PS₂), and 425-850 μm (PS₃). The smallest particle size of 0.5 μm was determined by a laser diffraction method.

The ρ of the silt loam, and PS₁, PS₂, and PS₃ of the biochars were 1.05, 0.29, 0.31, and 0.33 Mg m⁻³, respectively. New values of ρ and percent change in ρ ($\Delta\rho$) upon amendment of the silt loam with different rates of WBC of different particle size ranges are shown in Table 1.

The ρ_{max} and the corresponding θ_{opt} of the silt loam were 1.69 Mg m⁻³ and 16.5%, respectively. Figure 1 shows the influence on the ρ_{max} and corresponding θ_{opt} of the amended soil, when silt loam was amended with WBC of different particle sizes (PS₁, PS₂ or PS₃) each at a rate of 10% (dwb). Figure 2 shows the influence on the amended soil ρ_{max} and corresponding θ_{opt} , when silt loam was amended with PS₁ WBC at different rates (2, 5, 10% dwb).

Table 2 illustrates the differences in relative bulk densities of the silt loam soil amended with WBC. The silt loam soil has an $\frac{\rho}{\rho_{\text{max}}}$ of 0.62 and, as expected, the WBC

amendment led to no significant change ($p < 0.01$) in the soil $\frac{\rho}{\rho_{\text{max}}}$. Therefore, given that the values of $\frac{\rho}{\rho_{\text{max}}}$ fall in the

safe range of $0.60 \leq \frac{\rho}{\rho_{\text{max}}} \leq 0.68$ (Håkansson and Lipiec,

2000), no structural damage was found to occur.

The influence of the variation in particle size and application rate of WBC amended to silt loam on ρ_{max} and θ_{opt} values, along with their percent change, are presented in Table 3. Applications of PS₁, PS₂, and PS₃ size WBC

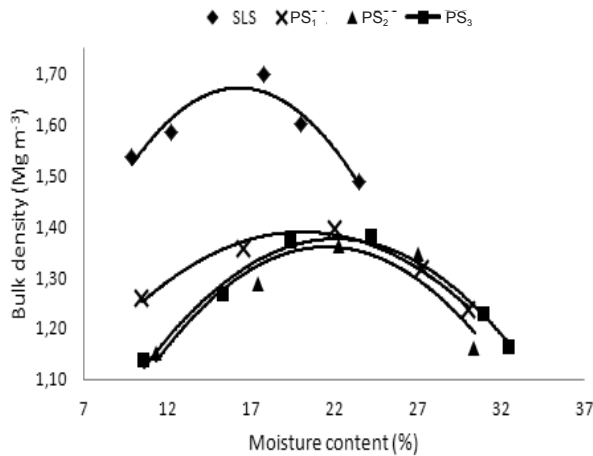


Fig. 1. Influence of amending a silt loam soil with 10% biochar of different particle diameters (e.g., PS₁, PS₂, and PS₃) on the compaction curves of the soil.

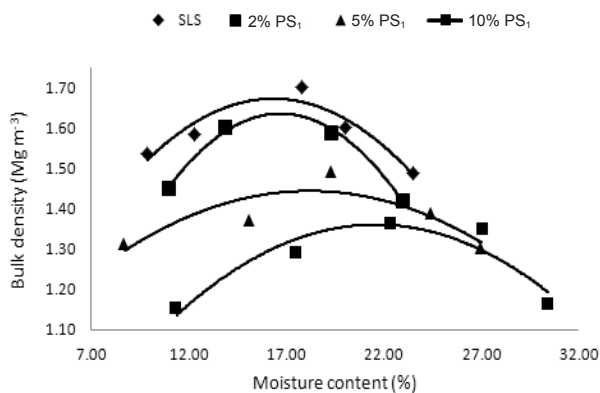


Fig. 2. Influence of amending a silt loam soil with biochar of a specific particle diameter range (e.g., PS₁) at different rates (e.g., 2, 5, 10%) on the compaction curves of the soil.

Table 2. Effect of the WBC particle size and application rate on silt loam maximum bulk density ($\frac{\rho}{\rho_{\max}}$) and optimum moisture content (θ_{opt})

Level of biochar amendment (% dwb)	Biochar particle diameter range (μm)		
	PS ₁	PS ₂	PS ₃
	0.5-212 μm	212-425 μm	425-850 μm
2	0.6	0.62	0.65
5	0.59	0.7	0.67
10	0.61	0.66	0.68

Relative bulk density $\frac{\rho}{\rho_{\max}}$ of non-amended silt loam were 0.62.

at a rate of 5% and 10% (dwb) had a statistically significant ($p \leq 0.05$) effect on ρ_{\max} and θ_{opt} compared to the non-amended silt loam, clearly indicating that the addition of WBC, regardless of particle sizes, to soil extended the range of the soil workability without causing compaction.

The θ_{pl} , θ_{ll} , and PI of the non-amended SLS were 17.1, 29.3, and 12.2%, respectively. Table 4 illustrates the variations in consistency limits of the SLS amended with WBC at various rates and of different particle sizes. The effect of WBC application on soil PI was not consistent. The PI values for the PS₁-WBC amendments varied with application doses. Amendment of the silt loam with 5 or 10% PS₁-WBC led to a significant ($p \leq 0.05$) increase in PI over the non-amended soil. In contrast, for the same amendment rates, the PS₂-WBC and PS₃-WBC amendments led to no significant ($p > 0.05$) increase in PI . Given the important role of the value of θ_{ll} in PI , the aforementioned difference in the response can be attributed to the relatively lesser increase in θ_{ll} of the PS₂-WBC and PS₃-WBC-amended silt loam, compared to that of the PS₁-WBC amended soil. The increase in θ_{pl} for the three particle sizes ranges is on the order of 1-7 units, whereas the increase in θ_{ll} for the PS₁-WBC amendment was greater than that for either the PS₂-WBC or PS₃-WBC amendments. This inconsistency minimized the effect of WBC amendment on PI values for the PS₂-WBC or PS₃-WBC-amendments. According to Mapfumo and Chanasyk (1998), a $PI < 7$ indicates low plasticity of a soil, whereas $7 < PI < 17$ indicates medium plasticity, and $PI > 17$ indicates high plasticity. Unlike clay soils, which exhibit high plasticity and are therefore highly prone to compaction, the silt loam used in this study exhibited medium plasticity and was therefore – given the narrow moisture range within which deformation could occur – less prone to severe compaction. The WBC-amended silt loam became less plastic as WBC itself is non-plastic (Downie *et al.*, 2009). Moreover, the increase in θ_{pl} and θ_{ll} could be attributed to the high absorptive capacity of the WBC for water due to its significant void content and large surface area (Guo *et al.*, 2014). This increased affinity to water would result in a WBC-amended soil requiring more water to behave in a plastic or liquid manner than the non-amended silt loam. In conclusion, PS₁-WBC applied at rates of 5 and 10% increases PI , thereby increasing the range of moisture within which soils are most susceptible to compaction, and, in turn, decreasing the workability of the soil under tillage operations by increasing structural damage to the soil. On the other hand, the same amendments decreased the ρ_{\max} , which is a positive influence of improving compacted soil. Increasing the water content at θ_{opt} over θ_{ll} and θ_{pl} may imply that the soil is more easily tilled in higher moisture content conditions without any deformation and also provides a higher workable range.

Table 3. Effect of WBC particle size and application rate on silt loam maximum bulk density (ρ_{max}) and optimum moisture content (θ_{opt})

Level of biochar amendment (% dwb)	Biochar particle diameter range (μm)											
	PS ₁				PS ₂				PS ₃			
	0.5-212				212-425				425-850			
	ρ_{max} (Mg m ⁻³)	$\Delta\rho_{max}$ *	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)	ρ_{max} (Mg m ⁻³)	$\Delta\rho_{max}$ **	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)	ρ_{max} (Mg m ⁻³)	$\Delta\rho_{max}$ (%)	θ_{opt} (%)	$\Delta\theta_{opt}$ (%)
2	1.64	-3	18	+8.33	1.64	-3	16.7	+1.2	1.59	-6	17.9	+7.8
5	1.54	-9	19.5	+15.4	1.42	-16	18.7	+11.8	1.51	-11	19	+13.2
10	1.39	-17.75	21	+21.4	1.36	-20	22	+1.37	1.37	-19	22.5	+26.7

*Relative % difference, **absolute difference (%), values of ρ_{max} and θ_{opt} in bold differ significantly ($p \leq 0.05$) from non-amended silt loam soil. ρ_{max} and θ_{opt} of non-amended silt loam were 1.69 Mg m⁻³ and 16.5% respectively.

Table 4. Influence of WBC particle size and application rate on silt loam plasticity parameters

Level of biochar amendment (% dwb)	Biochar particle diameter range (μm)											
	PS ₁				PS ₂				PS ₃			
	0.5-212				212-425				425-850			
	θ_{pl} *	θ_{ll} *	PI *	ΔPI **	θ_{pl}	θ_{ll}	PI	ΔPI	θ_{pl}	θ_{ll}	PI	ΔPI
	(%)											
2	18.0	31.0	13	+0.8	17	29.7	12.7	+0.5	18	30.1	12.1	-0.1
5	20.3	39.3	19	+6.8	19.7	36.0	16.7	+4.5	20	32.0	12.0	-0.2
10	22.4	43.0	20.6	+8.4	22.3	37.3	15.0	+2.8	23.7	35.0	11.3	-0.9

θ_{pl} , θ_{ll} and PI of non-amended silt loam are 17.1, 29.3 and 12.2%, respectively. Other explanations as in Table 3.

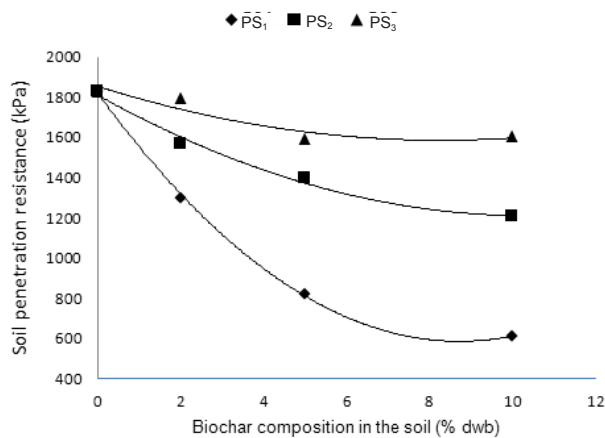


Fig. 3. Influence of the WBC amendment rate and particle size on the penetration resistance of a WBC amended silt loam.

The PR and SS of the silt loam were determined under conditions of ρ_{max} and θ_{opt} , *i.e.*, at the peak of the compaction curve. The compacted silt loam had a PR of 1827 kPa while the silt loam amended with 10% PS₁-WBC had a PR of 610 kPa. The decrease in PR measured at the soil ρ_{max} and θ_{opt} for silt loam amended with 2, 5, or 10% WBC of different particle size ranges (PS₁, PS₂, and PS₃) is illustrated in Fig. 3. It should be noted here that the amended soil θ_{opt} and ρ_{max} were different at each PR and SS measurement point due to the presence of WBC in the soil matrix. The compacted non-amended silt loam exhibited a SS of 858 kPa, compared to the much lower SS of the silt loam amended with 10% PS₁-WBC (221 kPa). This decrease in SS is attributable to the reduced cohesion of silt loam particles amended with the carbonaceous material. Also, the amended silt loam (10% PS₁-WBC) was compacted at θ_{opt} = 21.4%, whereas the non-amended silt loam was compacted at θ_{opt} = 16.5%. The differences in the moisture content of the soil when the shear vane test was conducted resulted in a decrease in the shear strength value of the compacted soil (Fig. 4).

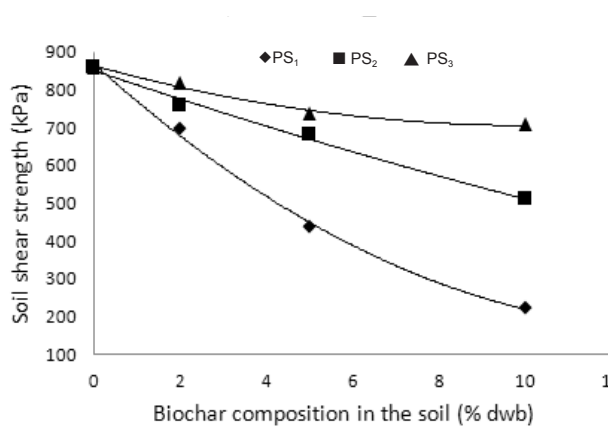


Fig. 4. Influence of the WBC amendment rate and particle size on the shear strength of a WBC-amended silt loam.

CONCLUSIONS

1. Biochar-amended soil showed a decline in bulk density and maximum bulk density and an increase in optimum moisture content relative to the non-amended soil. Moreover, the plastic limit and liquid limit were altered by the presence of biochar in the soil matrix. These changes in soil mechanical properties might adversely affect soil workability; therefore, this parameter should be quantified before modeling begins.

2. Specific particle sizes and quantities of biochar applied to a particular soil texture should be investigated and a predictive equation should be developed to recommend the quantity and particle size of biochar to be applied to a specific soil texture to improve its mechanical properties and, consequently, soil workability.

3. The influence of biochar on the changes in soil maximum bulk density and optimum moisture content resulted in a decrease in the penetration resistance and shear strength of compacted soil measured at the soil maximum bulk density and optimum moisture content. The shear strength within a soil matrix is the result of interparticle resistance. Until now, data on the effect of biochar on the penetration resistance and shear strength values along the compaction curve for soils amended with varying particle sizes of WBC were not available.

4. Before modeling techniques are employed, further investigations are required to fully assess the effects on soil porosity and strength of amending different compaction-prone soils.

Conflict of interest: The Authors do not declare conflict of interest.

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