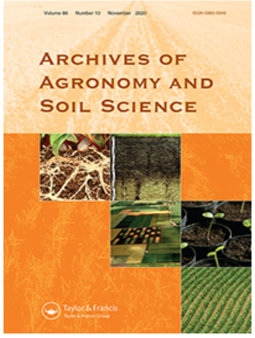

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Rice straw biochar effects on Atterberg limits and aggregate characteristics of an Acrisol in Ghana

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ABSTRACT

The stability and strength of soil aggregates to external forces such as raindrop impact and tillage may be affected by biochar application. In line with this, a three-year field experiment was conducted to investigate the effect of rice straw biochar (0, 15, and 30 t ha^{-1}) on the Atterberg limits (plastic limit, PL and liquid limit, LL), water-dispersible clay content (WDC), and the aggregate characteristics of an Acrisol. Aggregate characteristics were measured on four size classes (1–2, 2–4, 4–8, and 8–16 mm). The 30 t ha^{-1} treatment significantly ($p < 0.05$) increased PL and LL by 27% and 20%, respectively, compared to the control. The plasticity index, WDC and tensile strength were unaffected by biochar addition. For all treatments, there was a decreasing trend in tensile strength with increasing aggregate size. The 15 and 30 t ha^{-1} treatments increased friability by 21% and 38%, respectively, relative to the control. The 30 t ha^{-1} treatment significantly increased workability of the smaller aggregates but marginally increased the workability of the larger aggregates. Thus, there is potential for increased optimum water content at tillage (inferred from the PL) and increased workability after biochar application at 30 t ha^{-1}.

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Friability; workability; dispersible clay; plasticity index; tensile strength

Introduction

Tropical soils are often constrained by low fertility due to the prevalence of weathered clay minerals and high temperatures that enhance oxidation and loss of soil organic carbon (SOC). A considerable amount of research has investigated several ways to improve the fertility, structural integrity and biological status of these degraded soils. Some of these approaches include minimal or no tillage (Inda et al. 2010), straw incorporation (Xu et al. 2012), application of organic amendments (Frimpong et al. 2016) and amendment with pyrolyzed organic residue (biochar) (El-Naggar et al. 2019). Application of biochar to soils has been shown to improve numerous soil properties and functions. For instance, soil water retention, SOC content, pH, bulk density and other soil properties were improved by addition of biochar to different soils in different parts of the world (Blanco-Canqui 2017; Amoakwah et al. 2017b; Atkinson 2018; Wang et al. 2019).

Blanco-Canqui (2017) pointed out that the effect of biochar on the Atterberg limits and soil aggregate characteristics are lacking, and majority of the studies on these properties were

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incubation or short-term experiments. The Atterberg limits (liquid limit, plastic limit and plasticity index) are crucial for civil engineering and agronomic applications such as identification of bearing capacities and shear strength (Ahmed 2018), soil erosion, and identification of the optimum water content for tillage operations (Keller and Dexter 2012; Obour et al. 2017). Aggregate characteristics such as tensile strength (*Y*), friability and workability are important for seedling emergence, root growth, and seedbed production during tillage (Munkholm 2011). The water-dispersible clay content (WDC), indicating the amount of clay in soil that can be dispersed by water, also represents another soil property that is relevant for determining erosion susceptibility (Igwe 2005). These soil properties have been evaluated in few studies (Blanco-Canqui 2017) and less so in tropical soils. In a six-week pot experiment where 100 t ha^{-1} of green waste biochar was applied to an Alfisol, *Y* values decreased by 71% (Chan et al. 2007). Similarly, a twenty-five week incubation study led to a 23% decrease in *Y* after application of 4% sludge biochar to a clayey Ultisol (Zong et al. 2018). Other studies have reported a 52% to 60% decrease in *Y* after applying 6% woodchip and straw biochar, respectively (Zong et al. 2016). In a laboratory experiment with two contrasting soil types, Ahmed and Raghavan (2018) also reported decreases of up to 47% in *Y* for a clay loam amended with 10% wood-derived biochar, and the *Y* of a sandy loam soil was marginally affected. Conversely, a 1.5-year field experiment reported increased tensile strength for all aggregate sizes after application of 5% birch wood biochar to a temperate sandy loam (Khademalrasoul et al. 2014). In addition, Amoakwah et al. (2017a) in a field study showed that applying 20 t ha^{-1} of corn cob biochar to a tropical sandy loam (Haplic Acrisol) strengthened the smaller aggregates (1–2 mm) but weakened the aggregates larger than 4 mm which consequently increased soil friability by more than 100%. Thus, the addition of biochar to soils invariably decreases *Y* values in pot, laboratory and greenhouse studies whereas the effects in field experiments have been neutral to marginal increases in *Y* values.

The effect of biochar on the Atterberg limits is varied for different soil types even for the same biochar type. The plasticity index (PI) was positively affected (22% increase) in a clayey soil following addition of 4% waste sludge biochar (Zong et al. 2018). Likewise, Malik et al. (2018) found that applying 4% of waste sludge and wheat straw biochar to an Ultisol (clayey Plinthudult) increased the plastic limit (96% and 43%), liquid limit (112% and 96%) and the plasticity index (54% and 59%). Similar increases in the plastic limit (PL), liquid limit (LL) and PI were also observed by Ahmed and Raghavan (2018) for a clay and silt loam soils amended with more than 3% of forest waste biochar. In contrast, Zong et al. (2014) reported decreases in the PL (up to 70%) and LL (about 5%) of a Vertisol after applying 4% wheat straw and waste sludge biochar. For the same biochar types, there were large increases in PI (62% to 70%) for a Typic Plinthudult whereas the waste sludge biochar decreased PI by 9% for the Vertisol.

It is clear from the above that the type of experiment (greenhouse, laboratory or field), soil type and biochar type play pivotal roles in how biochar affects the aggregate properties and the Atterberg limits. It is important, therefore, to investigate further these observations for highly weathered tropical soils under long-term field conditions. Further, the biochar feedstock that is evaluated should be relevant for the region under consideration. In Ghana, rice production has significantly increased in the last few years (MoFA 2015), and consequently, large amount of rice straw residues are available. Crop residues in Ghana are usually left on the field or burnt off after harvest and this practice interferes with later tillage activities. Conversion of rice residues to biochar and its use as amendment to soils may positively affect soil Atterberg limits and aggregate characteristics.

The current study was therefore motivated by the inconsistent data on biochar effect on the soil properties discussed earlier, the expected abundance of rice residues, and the general limited literature available on the subject. Thus, the aim of the study was to investigate the impact of field-applied rice straw biochar on the Atterberg limits (PL, LL, and PI), water-dispersible clay content and aggregate characteristics (tensile strength, friability, and workability) of an Acrisol (sandy clay loam) from the semi-deciduous agroecological zone of Ghana. Conclusions were drawn concerning the optimal rice straw biochar to improve Atterberg limits and aggregate characteristics of a tropical sandy clay loam under field conditions. We hypothesize that the applied biochar will increase SOC with consequent improvements in the Atterberg limits and aggregate properties.

Methodology

Study area description

The experiment was carried out at the University of Ghana's Forest and Horticultural Crops Research Centre, Kade (06° 08′ 37″N; 00° 54′ 10″ W) at an altitude of 180 m above sea level. The Centre falls within the semi-deciduous agroecological zone with two rainy seasons (April to July and September to October). Average annual rainfall and temperature are 1500 mm and of 28 °C, respectively. The soil at the experimental site is a well-drained sandy clay loam, classified as an Acrisol (IWG 2015) and dominated by kaolinite clay mineral. The properties of the soil prior to start of the experiment were clay, silt, and sand contents of 21%, 11% and 68%, respectively, pH (H_2O) of 5.54; electrical conductivity of 36 µS cm^{-1}; soil organic carbon content of 1.33% and nitrogen content of 0.12%.

Biochar characterization

The rice straw biochar used for the study was produced by pyrolyzing rice straw residues in a Lucia stove reactor at a charring temperature of 550 °C for 48 h. After charring, the biochar was air-dried and sieved to 2 mm prior to field application. The biochar had pH of 10.3, 35% organic matter content, and low in poly-aromatic hydrocarbons (Table 1).

Field experimental layout and treatments

Four consecutive field experiments comprising okra-maize-cowpea-maize rotations were conducted during the period June 2015 to May 2018. The experimental design was a randomized split-plot factorial with irrigation (irrigated and non-irrigated) levels as main plots and biochar levels as subplots with four replications or blocks. The main plots measuring 10.8 × 5 m were divided into three subplots with dimensions of 3.6 × 5 m each. The plots were raised to 15 cm above the natural soil surface to enhance drainage and accommodate access pathways of 0.6 m between the plots. The work presented here considered only the irrigated plots and the biochar levels (3 biochar levels × 4 replications = 12 plots in total). The reason for considering only the irrigated plots was because biochar rather than irrigation possesses the characteristics to alter the soil's Atterberg limits and aggregate characteristics. The biochar application was split into three doses. Before each round of biochar incorporation, the soil was thoroughly wetted with about 8 mm of water and subsequently tilled to a depth of 15 cm using a hoe. The tillage operation was done similarly for the biochar amended plots as well as the control plots. In June 2015, the first 1/3 of the biochar was surface-applied and thoroughly incorporated into the top 15 cm of the soil at rates of 0 t ha^{-1}, 5 t ha^{-1}, and 10 t ha^{-1}. The next 1/3 biochar amount was applied in June 2016 and the final 1/3 amount applied in June 2017. Thus, the total biochar applied before soil samples were taken for the present study summed up to 0 t ha^{-1}, 15 t ha^{-1}, and 30 t ha^{-1}, corresponding to 0%, 0.66% and 1.32% (air-dry weight basis). The treatments are designated hereon as CT, B15, and B30 for the 0 t ha^{-1}, 15 t ha^{-1}, and 30 t ha^{-1} treatments, respectively. Sampling was done in May 2018 after the harvest of the last crop (maize).

Table 1. Characteristics of the rice straw biochar.

%					mg kg^{-1}						
DM	OM	TC	TN	pH	P	K	Ca	Mg	Fe	Na	ΣPAHs
91.8	34.9	25.4	1.0	10.3	1420	17,700	3020	343	2030	1250	6.0

DM, dry matter; OM, organic matter; TC, total carbon; TN, total nitrogen, PAH, poly-aromatic hydrocarbons (calculated as the mathematical sum of 19 PAHs). ΣPAHs denotes the sum of the polycyclic aromatic hydrocarbons.

Soil sampling

A spade was used to extract bulk, minimally disturbed soil samples from each of the 12 plots to a depth of about 15 cm. Four subsamples were taken from each plot and bulked together as a composite sample. The samples were air dried at 25 °C prior to further analyses.

Laboratory measurements

Soil texture and chemical properties

The analyses described below were carried out with air-dried samples that had been sieved using a 2-mm sieve. The texture of the experimental soils was measured by the wet sieving and hydrometer methods as described in Gee and Or (2002). Total carbon content was determined by elemental analyses; the carbon was oxidized to CO_2 at 950 °C with a FLASH 2000 organic elemental analyzer coupled to a thermal conductivity detector. As carbonates were absent, the total carbon was assumed equal to the soil organic carbon (SOC). Soil pH was determined by adding 10 g of sample to 25 mL of deionized water (1:2.5), shaken for 10 min, allowed to settle for 10 min and the pH measured with a pH meter (PHM220, Radiometer Analytical SAS, Lyon). For electrical conductivity (EC), 4 g of sample was added to 36 mL of deionized water, shaken for 1 h, settled for 1 h and the EC determined with an EC meter (CDM210, Radiometer Analytical SAS, Lyon).

Atterberg limits

The plastic limit (PL) and liquid limit (LL) of the treatments were determined using the rolling device (Bobrowski and Griekspoor 1992; McBride 2007) and fall-cone penetrometer (BS 2018) methods, respectively. For plastic limit, the sample was mixed with water until it became plastic and easily molded into two short columns. The two soil columns were placed on the bottom plate of the rolling device and a downward force applied simultaneously with rolling motion until the top plate touched the 3 mm side rails. The soil threads were then remolded and the procedure repeated until they crumbled. The gravimetric water content of the crumbled samples was taken as the PL. This was repeated for three sub-replicates for each experimental plot. The LL was measured with a semi-automated drop-cone penetrometer. Distilled water was added to the sample, mixed thoroughly, and pushed into the cup with a spatula ensuring that there was no air entrapment. The soil in the cup was leveled and the cone placed so it just touched the soil surface. The cone was released automatically for a period of 5 s and the depth of penetration recorded. If the depth of penetration was less than 12 mm, a little more wet soil was added to the cup until the first cone penetrometer reading was around 15 mm. The procedure was repeated three times until the range of penetration values approximately covered 15 to 25 mm. The gravimetric water content corresponding to a cone penetration of 20 mm was taken as the LL. The gravimetric water contents of the samples were obtained by oven drying at 105 °C for at least 48 h.

The plasticity index (PI) was computed as the LL – PL (McBride 2007).

Water-dispersible clay (WDC)

The WDC was determined on 1 – 2 mm-sieved air-dried aggregates with a modified version of the method described in Pojasok and Kay (1990). Briefly, cylindrical plastic bottles with 10 g of sample and 80 mL of artificial rainwater were rotated end over end for 2 min. Afterwards, the samples were left undisturbed for 4 h and 38 min to allow particles > 2 mm to settle. The dispersed clay remaining in the suspension was siphoned off, transferred into a pre-weighed glass vial and oven dried at 105 °C for 48 h. The dispersible clay content was reported as 'mg clay per g clay' as increasing clay content increases the amount of WDC.

Aggregate strength and friability

For aggregate tensile strength measurements, the bulk samples were air-dried, carefully fragmented by hand into smaller aggregates and sieved to four size classes: 1–2, 2–4, 4–8, and 8–16 mm. For each experimental plot, 15 aggregates were randomly selected for each size class. The total number of aggregates tested was 720 (3 treatments × 4 replicates each × 4 aggregate size fractions × 15 aggregates). Aggregate tensile strength (*Y*, kPa) was determined by crushing each aggregate between two parallel plates until fracture (Dexter and Kroesbergen 1985). The polar force at fracture (*f*, N) was used together with the mean aggregate diameter (*d*, m) to calculate *Y* from Equation (1) (Dexter and Watts 2000).

$$Y = 0.576 \times (f/d^2) \quad (1)$$

The *d* for each aggregate was estimated by $d = d_i(m_0/m_i)^{1/3}$ where d_i is the mean diameter of aggregates of a given size class (e.g. 1.5 and 3 for the 1–2, 2–4 size classes, respectively), m_0 is the dry mass of the individual aggregate and m_i is the mean mass of the batch of 15 aggregates.

The energy at rupture (*E*) for each aggregate was estimated by computing the area under the stress–strain curve (Vomocil and Chancellor 1969). The specific rupture energy (E_{sp}) was estimated as:

$$E_{sp} = E/m_0 \quad (2)$$

Soil friability (*F*) was estimated as the coefficient of variation of *Y* values within a given size class (Watts and Dexter 1998) (Equation (3)):

$$F = \sigma Y/\bar{Y} \quad (3)$$

where σY is the standard deviation of *Y* values for a given size class; and $\bar{Y}$ is the mean of *Y*.

Soil workability (*W*) was computed by a combination of *F* and *Y* as suggested by Arthur et al. (2014):

$$W = F \times (1/Y) \quad (4)$$

Large values of *W* denote an easily workable soil and vice versa.

Statistical analyses

Prior to comparison of the treatments, all the data were evaluated for normality of their distributions and the homogeneity of variances using the Shapiro-Wilk and Brown–Forsythe test, respectively. Differences between the CT and biochar treatments were tested using one-way analysis of variance (ANOVA), after which the Holm-Sidak post-hoc test was used to differentiate between any two treatments. A criterion of $p < 0.05$ was used for statistical significance of treatment effects, unless otherwise stated. Results are presented as mean ± standard error (SE) in tables and figures.

Results and discussion

Soil physical and chemical properties

The soil texture, SOC, pH and EC for the different treatments are presented in Table 2. Despite the initial assumption of homogenous texture throughout the experimental field, the CT plots had higher average clay contents (23%) than the biochar treated plots (22% and 19% for the B15 and B30 plots, respectively) and marginally lower sand contents; silt contents were similar among the treatments. Significant increases in SOC and pH was observed for the B30 treatment compared to CT but the B15 treatment was not significantly different from B30 and CT. The B30 treatment had 42% higher SOC than the CT. Similarly, pH increased by 19% when B30 was compared to the CT. Rice straw biochar tends to have low carbon content (< 40%) compared to other biochar types (Singh et al. 2018), and this was also observed for the biochar used for this study with low carbon content of

Table 2. Soil texture and chemical properties of the treatments (mean ± standard error).

	%				–	$\mu S\ cm^{-1}$
Treatment	Clay	Silt	Sand	SOC	pH–H_2O	EC
CT	23 ± 0.4	10 ± 0.3	66 ± 0.2	1.04 ± 0.06[b]	4.66 ± 0.14[b]	17 ± 0.5[b]
B15	22 ± 0.5	10 ± 0.4	68 ± 0.6	1.12 ± 0.09[ab]	5.14 ± 0.20[ab]	22 ± 3.7[ab]
B30	19 ± 1.0	10 ± 0.3	70 ± 1.1	1.48 ± 0.12[a]	5.55 ± 0.05[a]	37 ± 6.1[a]

SOC = soil organic carbon; EC = electrical conductivity; CT = control; B15 = biochar treatment with 15 t ha^{-1}; B30 = biochar treatment with 30 t ha^{-1}. Differently lettered means are significantly different at $p < 0.05$.

25.4% (Table 2). This partly explains the minimal increase in SOC for the B15 treatment. For a similar soil type, addition of 20 t ha^{-1} of corn cob biochar increased SOC by 66% (Amoakwah et al. 2017a) perhaps due to the higher fraction of total C (39%) in corn cob biochar. Aside increases in SOC, soil pH increase after biochar application to weathered tropical soils is well reported in literature (e.g. Amoakwah et al. 2017a; Zong et al. 2018). The alkaline nature (pH of 10.3) of the applied biochar combined with the acidic nature of the soil led to the increases in soil pH. Eduah et al. (2019) investigated the P-desorbability of different soil and biochar types in Ghana and concluded that biochar amendment increased the P-desorbability in acid soils. The soil used in this study was part of the acidic soils used in the study above (Soil A, Eduah et al. 2019). Increased SOC and pH for acidic soils low in SOC is important for maintaining soil functions and increasing the availability of plant nutrients. For example, the availability of phosphorus is significantly improved when soil pH is higher than 5.5 (as was the case for the B30 treatment). Nelson et al. (2011) reported increased P availability for two soils amended with 2% corn cob biochar for 56 days. Soil electrical conductivity (EC) increased consistently with increasing biochar application rate; 30% and 117% increases for the B15 and B30 treatments, respectively, compared to the CT. Increase in EC is attributed to the release of weakly bound cations and anions on the biochar surface during dissolution (Chintala et al. 2014)

Biochar effect on the Atterberg limits

The Atterberg limits (PL and LL) reflect the behavior of soils as they go through different water states from dry to wet. These limits, in combination with the plasticity index, are crucial for multiple soil applications (agronomic, industrial and engineering). Applying 15 t ha^{-1} of biochar to the sandy clay loam soil had no impact on the plastic limit (PL), liquid limit, or the plasticity index (Figure 1). Following application of 30 t ha^{-1}, the PL and LL increased by 27% and 20%, respectively, when compared to the control treatment (Figure 1). There was no significant effect of biochar on the plasticity index (PI). The PI of all the samples ranged from 0.11 to 0.12 g g^{-1} implying that all treatments were of the same plasticity class (medium plasticity, $0.07 < PI < 0.17$ g g^{-1}) according to the classification proposed by Jumikis (1984). The no effect of biochar on the Atterberg limits for the B15 treatment can be attributed to the marginal increase in SOC (8%) and the slightly higher clay content for the CT treatment compared to the biochar treatments. There is often a strong relationship between the Atterberg limits and SOC for similarly textured soils (Keller and Dexter 2012) and this was also reflected in the strong correlations between the SOC and PL (correlation coefficient (r) = 0.78; $p < 0.05$) and LL ($r = 0.80$; $p < 0.05$). This is because SOC increases the soil specific surface area of soils. Consequently, the B30 with significantly improved SOC content compared to the CT (despite the lower clay content) had higher water contents at the PL and LL. Previous studies using straw or wood biochar have reported contrasting effects of biochar on PL and LL. Malik et al. (2018) showed that applying 4% of wheat straw biochar to a clayey Ultisol increased PL and LL by 43% and 96%, respectively. Conversely, Ahmed and Raghavan (2018) found minimal to negative effect on PL and LL when a clay-textured soil was amended with forest waste biochar at a rate below 3%. Significant positive effect on the PL and LL was seen when the biochar rate was increased to 6%. The lack of biochar effect on the PI in our study may be attributed to the similar increases in LL and PL after biochar application, and perhaps due to the relatively low application rate (0.66% and 1.32% for the

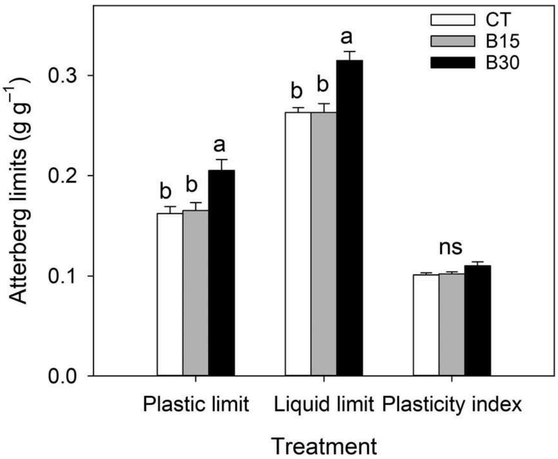

Figure 1. Rice straw biochar effect on the Atterberg limits of a sandy loam soil. Error bars represent standard error of the mean (n = 3). CT = control; B15 = biochar treatment with 15 t ha^{-1}; B30 = biochar treatment with 30 t ha^{-1}. Differently lettered means are significantly different, and ns denote no significant differences between the treatments at $p < 0.05$.

B15 and B30 treatments). Other studies (Zong et al. 2016, 2018) that reported increases in PI for similar tropical soils (Ultisols and Plinthudults) for different biochar types (waste sludge, wheat straw biochar, and forest waste biochar) had significantly higher biochar application rates (4% to 10%).

Biochar effect on aggregate characteristics

Water-dispersible clay (WDC)

The content of WDC of 1 to 2 mm aggregates is widely used as an indicator of soil structural stability (Munkholm 2011). The WDC for the B15 and B30 treatments were 11% and 6% higher than that of the control. These increases were, however, not statistically significant (Table 3). Higher WDC indicates weaker soil aggregates that are easy to break down, whereas lower WDC values reflect aggregates that are resistant to failure when exposed to external forces such as wetting, raindrop impact and tillage. Several soil properties affect the WDC; prominent among them are clay content and type, SOC, and soil water content (Czyz et al. 2002; Kjaergaard et al. 2004; Arthur et al. 2012). The effect of clay and water contents can be excluded from this study since WDC was scaled by clay content, and the clay mineralogy and aggregate water content were similar for all treatments (Table 3). The higher SOC recorded for the B30 treatment had no impact on the WDC. Although not expected, this observation agrees with the general inconsistent effect of biochar carbon on WDC. Some studies have reported increased WDC values after soil amendment with wood biochar (Khademalrasoul et al. 2014; Soinne et al. 2014). Other studies such as Hansen et al. (2016), have reported a decreased WDC after amending a sandy loam soil with 5% straw biochar. Amoakwah et al. (2017a) also reported marginal increases in WDC after adding 20 t ha^{-1} of corn cob biochar to a sandy loam. These conflicting trends and the lack

Table 3. Water-dispersible clay (WDC) for 1 – 2 mm aggregates and water content for different aggregate size classes for control and biochar treatments (mean ± standard error).

	WDC	Aggregate water content (%)			
Treatment	mg g clay^{-1}	1–2 mm	2 – 4 mm	4–8 mm	8–16 mm
CT	18.7 ± 1.0^{ns}	0.96 ± 0.48^{ns}	1.07 ± 0.10^{ns}	0.97 ± 0.04^{ns}	1.00 ± 0.08^{ns}
B15	20.8 ± 2.1	1.02 ± 0.67	1.00 ± 0.05	1.00 ± 0.04	1.06 ± 0.06
B30	19.9 ± 2.1	1.09 ± 0.46	1.06 ± 0.06	1.05 ± 0.05	1.16 ± 0.09

CT = control; B15 = biochar treatment with 15 t ha^{-1}; B30 = biochar treatment with 30 t ha^{-1}. ns denote no significant differences between the treatments at $p < 0.05$.

of an effect of SOC on WDC in this study are possibly due to the complicated relationship between the WDC and other soil properties such as pH and EC. Previous studies suggest that as pH increased and EC decreased, the WDC becomes higher (Khademalrasoul et al. 2014). In this study, while pH increased, the EC also increased and this probably counterbalanced the effects and led to the same WDC for the three treatments.

Aggregate water contents

The water content of all the aggregate sizes (1–2, 2–4, 4–8, and 8–16 mm) under air-dry conditions was ~1%, and the applied biochar did not affect the aggregate water content (Table 3). This is likely due to the increased SOC content of the biochar treatments, which apparently neutralized the higher clay content in the control. Secondly, the impact of SOC on water content of air-dry samples is greatly reduced when clay content exceeds 20% (Arthur et al. 2015). This is because the contribution of 0.48% more SOC (as is the case for B30 compared to CT) to the specific surface area of the sample will be insignificant compared to the contribution of 20% clay content.

Tensile strength

Aggregate tensile strength (*Y*) is relevant for evaluating the stability of soil structure and its susceptibility to erosion (Watts and Dexter 1998). Tensile strength of the aggregates for each treatment decreased with increasing aggregate sizes (Figure 2(a)). This is a well-known trend for natural soils (Munkholm et al. 2001) due to the prevalence of preexisting micro cracks in larger aggregates that combine into fracture surfaces when exposed to mechanical stress. For all aggregate sizes and biochar treatments, there was no significant effect of biochar on tensile strength. Aside the 1–2 mm aggregates that showed a trend of decreasing *Y* values with increasing biochar rate, there was no consistent trend in *Y* for the remaining aggregate classes (Figure 2). Generally, *Y* is reported to decrease upon application of biochar. However, the majority of the studies either were incubation-studies or had very high application rates of biochar. For example, Zong et al. (2018) reported results from an incubation study where there was 23% and 71% decrease in *Y* values when a clayey Ultisol was amended with 6% wood chip and straw biochar. Also, Chan et al. (2007) as well as Ahmed and Raghavan (2018) reported decreased *Y* values when an Alfisol and a sandy loam were amended with 100 t ha^{-1} of green waste biochar and 10% wood biochar, respectively. The inconsistent trends in *Y* values observed in this study following biochar application have also been reported in other studies. For example, Amoakwah et al. (2017a) applied 20 t ha^{-1} corn cob biochar in a 6-month field experiment on a Haplic Acrisol and

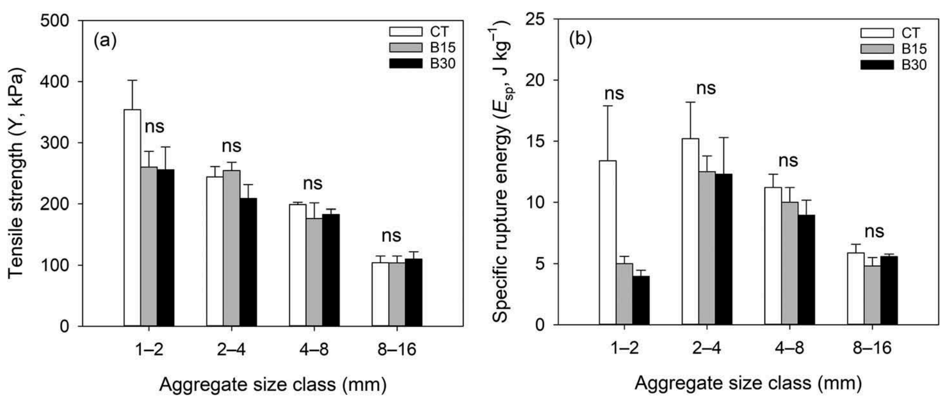

Figure 2. Effects of different application rates of rice straw biochar on (a) tensile strength and (b) specific rupture energy for various air-dried aggregate classes. CT = control; B15 = biochar treatment with 15 t ha^{-1}; B30 = biochar treatment with 30 t ha^{-1}. Error bars represent standard error of the mean (n = 3). ns denote no significant differences between the treatments at $p < 0.05$.

observed increased *Y* for the 1–2 mm aggregates, similar *Y* for the 2–4 mm aggregates and significantly decreased *Y* for the larger aggregates (4–16 mm) after biochar application.

The specific rupture energy (E_{sp}) reflects the strength of dry aggregates. The E_{sp} in the present study tended to decrease with increasing biochar rate but the decreases were not significant. For the 1–2 mm, E_{sp}, decreased by 63% and 70%, respectively, for the B15 and B30 plots compared to the CT. For the larger aggregate sizes, the decreases were minimal (<20%) (Figure 2(b)). Among the aggregate size fractions for a given treatment, E_{sp} tended to decrease with aggregate size for aggregates ≥2 mm. These observations are consistent with the findings of Amoakwah et al. (2017a) where E_{sp} decreased systematically with increasing aggregate size after amending a sandy loam with corn cob biochar. As aggregate size increases, the structural hierarchy collapses and makes the aggregates susceptible to mechanical stresses and easy to rupture (Schjønning et al. 2012); this explains the trend of decreased E_{sp} with increased aggregate size.

Aggregate friability and workability

The friability of soil aggregates provides crucial information on the ease of producing a favorable seedbed for tillage operations. It indicates the suitability of a soil to support crop growth and minimize the energy required for tillage (Munkholm 2011). Across all aggregate size classes, there was a consistent trend of increasing aggregate friability with biochar application, albeit not significant (Figure 3(a)). Friability increased averagely by 21% and 38% for the B15 and B30 plots when compared to the CT across all aggregate sizes. According to the classification of Imhoff et al. (2002), addition of 30 t ha^{-1} biochar changed the friability class of the soil in the study area from 'slightly friable (0.2–0.5)' to 'friable (0.5–0.8)' for all aggregate classes. It seems that the increases observed are probably related to the SOC content of the various treatments (Table 2) as a positive correlation between SOC and friability has been reported in several studies (Munkholm 2011; Obour et al. 2017). For this study, SOC explained between 56% and 90% of the variation in aggregate friability. The effect of biochar on friability in literature is not clear and seems to depend on soil texture as well as biochar type. Amoakwah et al. (2017a) reported a two-fold increase in the friability of a sandy loam after applying 20 t ha^{-1} of corn cob biochar. On the other hand, applying 10% of wood-derived biochar to a clay soil halved the friability of a clay soil, and increased the friability of a sandy loam soil by 33% (Ahmed and Raghavan 2018).

Soil workability is desirable during tillage as it describes the condition of the soil when tillage operations do not lead to soil structural damage. There was an increasing trend in the workability index

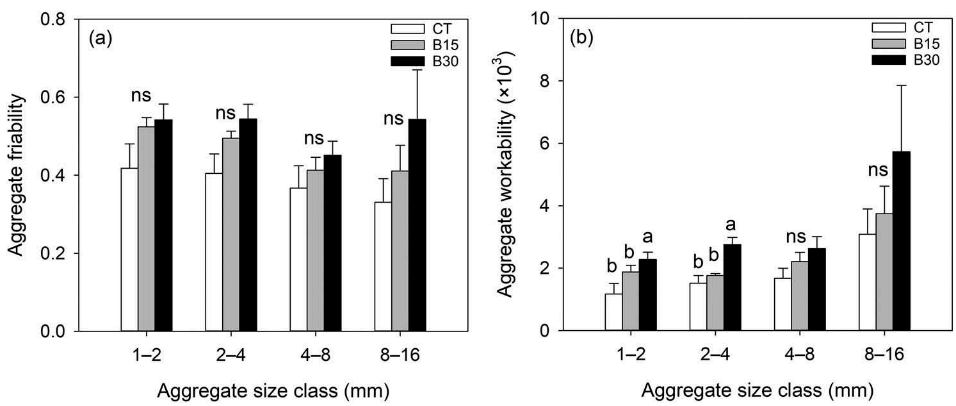

Figure 3. Effects of different application rates of rice straw biochar on (a) aggregate friability and (b) workability for various air-dried aggregate classes. CT = control; B15 = biochar treatment with 15 t ha^{-1}; B30 = biochar treatment with 30 t ha^{-1}. Error bars represent standard error of the mean (n = 3). Differently lettered means are significantly different, and ns denote no significant differences between the treatments at $p < 0.05$.

with increasing biochar application rate (Figure 3(b)). For 1–2 and 2–4 mm aggregates, the index of workability significantly increased by 94% and 82% after applying 30 t ha^{-1} of biochar. Although the B15 treatment increased the workability index by 16% to 60% for the various aggregates, these did not result in significant difference from the CT (Figure 3(b)). The workability index considered here combines the *Y* and the friability (Equation (4)). Despite the lack of an effect of biochar on *Y* and statistically insignificant increases in friability, it was interesting to note that the workability index was positively affected by biochar for the smaller aggregates. For the two smaller aggregate sizes, the workability indexes were positively correlated to the SOC; $r = 0.59$ ($p < 0.05$) and $r = 0.45$ ($p = 0.14$) for the 1–2 and 2–4 mm aggregates, respectively. Watts and Dexter (1998) pointed out that, for low SOC soils (as is the case for the CT treatment in the present study); the difficulty in conducting tillage activities on such soils is mainly due to the attendant low structural stability, less micropores and fewer cracks.

Conclusions

In a three-year field experiment, we evaluated the impact of rice straw biochar applied at 0, 15, and 30 t ha^{-1} to a sandy clay loam soil and demonstrated that biochar did not significantly affect aggregate water content, the fraction of dispersible clay, or the aggregate tensile strength. There was, however, a significant increase in SOC, which was reflected in increased plastic limit and liquid limit for the 30 t ha^{-1} biochar treatment compared to the control; but the plasticity index was unaffected. The trends of increasing friability observed led to significant improvements in the soil workability index for the 30 t ha^{-1} biochar treatment.

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