Research Article

Biochar and Fly Ash Role in Improving Mechanical and Physical Properties of Vertisol

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Abstract | Ameliorative effects of soil amendments on the physico-mechanical properties of vertic soils were studied. The potential soil amendments were fly ash (FA) and three types of biochar (straw biochar (SB), woodchips biochar (WCB), waste water sludge biochar (WSB). The physical and mechanical parameters of vertic soil like soil consistency limits like plastic limit (PL), liquid limit (LL) and plasticity index (PI), tensile strength (TS), shear strength (cohesion (*C*) and angle of friction (φ)) were studied. Results showed that amendments had improved soil physico-mechanical properties. No specific trends were observed for consistency limit, however, PI decreased for all the amendments applied and LL showed correlation with φ and TS. Significant reduction ($p \leq 0.05$) in the coefficient of linear extensibility (COLE) was found for all amendments and the effect of WSB and FA was more pronounced. The values of TS decreased for all amendments while a reduction of 37%, 43.99% and 61.32% was observed at 2, 4 and 6% of applied SB amendment. The *C* values decreased significantly for all the amendments and effect of SB and WCB was more prominent, as compared to other amendments. No specific trends, however was observed for φ. Pearson correlation indicated that all the properties *i.e.*, COLE, TS, *C*, and φ, were significantly correlated with each other. Both fly ash and biochar significantly improved the physico-mechanical parameters of vertisols. However, low doses (2%) of straw biochar were more beneficial by keeping in view the availability and economic level of the landholders.

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Introduction

Improvement of soil quality is a supreme objective in agriculture for optimum production. Many efforts have been made so far to enhance the physical quality of soil which affects the soil productivity. Soil physical parameters mostly represent the soil structure which indeed affects many soil quality indicators like soil chemical, physical and biological properties. Vertic soils, also known as expansive soils are famous for their poor physical conditions. These soils contained high amount of expansive clays (>35%) known as montmorillonite and somewhat smectite which cause swelling and shrinkage, stickiness and high swelling potential and pressure (Moustakas, 2012; Zaffar et al., 2014). Vertic soils are hard to manage due to their poor physical conditions including heavy texture, low hydraulic conductivity, high swelling pressure and evolution of cracks on drying and stickiness in wetting (Vaidya and Pal, 2002; Brierley et al., 2011; Pal et al., 2012; Moustakas, 2012; Ito and Azam, 2013). Despite the fact that these soils are difficult to manage, are being cultivated in many areas of the world as a major resource for crop production. Vertisols are found in about 80 countries and covers an area of approximately 2.4% of total earth surface (Dudal and Eswaran, 1988). Total area of vertisols in Pakistan is about 16700 km^2 (Kotli and Rajanpur series) and contains expanding type clay minerals (montmorillonite), 0.2 to 0.6% O.M, and calcareous in nature (10-15% lime). In Northern China, vertic soils cover an area of 3.1×10^7 ha and locally called as Shajiang black soils and are distributed in Huaibei Plain, Jiaolai Plain, Yishu Plain and Xuhuai Plain (Li et al., 2011). The grains (wheat, maize and peanuts) and vegetables are major crops of these areas, but low physical quality of these soils hinders agricultural production.

Several amendments have been introduced to improve the low fertility status and physical condition of soils. These amendments include use of many organic and inorganic inputs, industrial wastes, tillage management, crop rotation, wetting/drying cycle and synthetic polymers in the soil (Pagliai et al., 2004; Puppala et al., 2007; Yazdandoust and Yasrobi, 2010; Akcanca and Aytekin, 2012; Lu et al., 2014). Among the organic amendments, biochar had been widely used to improve the physical status of vertic soils. Recently, use of biochar to agricultural soils is gaining popularity due to its beneficial effect on soil properties (Chemical, biological and physical). Many studies has highlighted the positive effects of biochar on crop production (Chan et al., 2008; Kimetu et al., 2008), soil microbes (Das et al., 2008) and many other soil physical and chemical properties (Yanai et al., 2007; Devereux et al., 2012; Lin et al., 2012; Lu et al., 2014). Previous studies indicated that biochar improved the quality of soil (physical and mechanical) like hydraulic conductivity, bulk density, water retention capacity, aggregation and aggregate stability, soil resistance to penetration, total porosity and pore size distribution (Aggelides and Londra, 2000). Similarly pH, swelling behaviors, shear strength parameters, compaction and Atterberg limits were also reported to be improved due to application of biochar (Lu et al., 2014; Zong et al., 2014).

In contrast to organic amendments many industrial by-products are also suitable for soil reclamation. Amendments like fly ash, lime, gypsum, zeolites and silica fumes were reported to ameliorate the physical structure of vertic soils and reduced swelling behavior of expansive soils (Kalkan, 2011; Blissett and Rowson, 2012; Razmi and Sepaskhah, 2012). Coal fly ash is produced from coal during energy production and has been applied to soils for many years. Fly ash has tendency to improve soil physical characteristics by increasing water holding capacity, decreasing soil strength as well as improving soil texture and bulk density (Kumar and Sharma, 2004; Lu and Zhu, 2004; Jala and Goyal, 2006). Biochar are the by-products of agro-based industries and when used as ameliorating agent in the soil, poses no threat to the environment and ultimately increases the physical status of soil. On the other hand, less data is available to check the role of fly ash on the physical characteristics of vertic soils. Fly ash, sewage sludge and biochar are abundantly available and application of these by-products to problematic soils will not only improve the soil physical, chemical and mechanical status but will also help to solve their waste disposal problem. In this study the effect of amendments (biochar made from different biomass material and wastewater sludge, and fly ash) were determined on the problematic vertic soil of Northern China. A pot experiment was conducted with the aim to find out the possible positive effects of biochar, wastewater sludge and fly ash on physico-mechanical parameters including soil consistency limits, swelling and shrinkage behavior and soil strengths on the typical vertic soil.

Materials and Method

Soil description

The effect of amendments on the typical vertic soil was evaluated by conducting a pot experiment. Soil samples were taken from Shandong province (N34°35′45.5″; E118°19′19.3″) of Northern China from 20 cm depth. Soil was cleaned off the stones, gravels and plant debris followed by air drying. The air dried soil was thoroughly mixed and passed through 2 mm sieve. Basic physico-chemical properties of the soil were completed. The studied soil was Shajiang-Aquic Camosols as classified according to Chinese Soil Taxonomy (Li et al., 2011). The X-ray diffraction (XRD) analysis of soil samples showed that soil mineralogy consists of montmorillonite, kaolinite, muscovite and quartz as main mineral phases as depicted in the Figure 1.

Experimental protocol

Four soil amendments; straw biochar, woodchips biochar, wastewater sludge biochar (SB, WCB and WSB) and fly ash (FA) were used to improve the physical

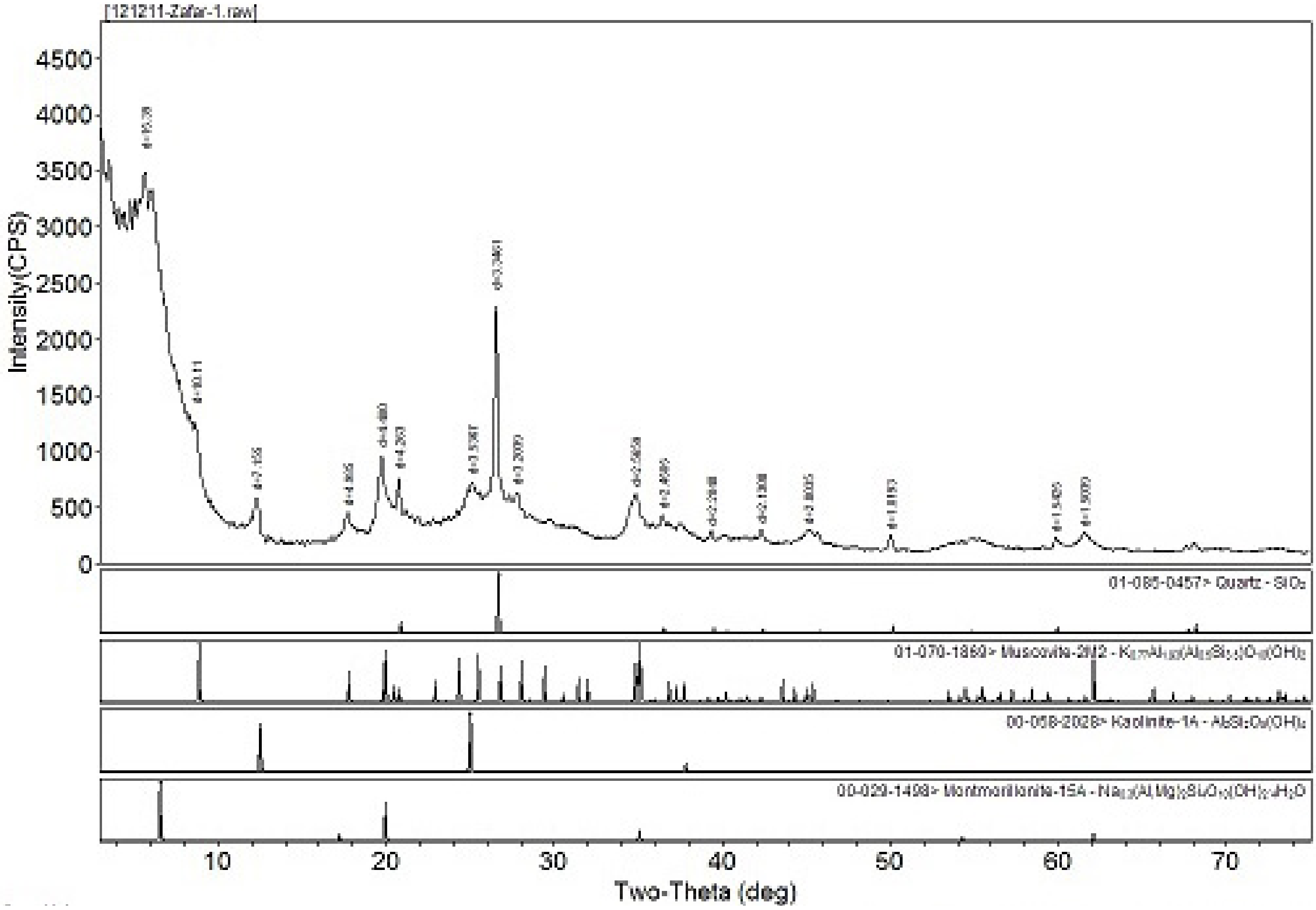

Figure 1: *XRD pattern of studied soil.*

properties of studied soil. Three types of biochars; straw biochar, woodchips biochar and wastewater sludge biochar (SB, WCB and WSB) were purchased commercially and were made by slow pyrolysis at 500 ˚C for 2 h in a factory scale reactor. These biochars were produced from naturally available biomass source. In order to get similar size: the biochars were ground and passed to 2 mm sieve. The fly ash was obtained from electricity generating plant (Lu et al., 2013). The mixture of soil and amendments were prepared in dry state by mixing the required amount of vertic soil and amendments on % weight basis. In all, 39 pots (all treatments with three replications) were filled with 3 kg of soil and amendments and labeled with control (CK), straw biochar (SB2% (50 tons/hac), SB4% (100 tons/hac) and SB6% (150 tons/hac), woodchips biochar (WCB2%, WCB4% and WCB6%), wastewater sludge biochar (WSB2%, WSB4%, and WSB6%) and fly ash (FA2%, FA4% and FA6%). The pots were placed in glass house in a completely randomized design for incubation over a period of 90 days. During the incubation, pots were irrigated with distilled water at regular intervals and maintained at 75% water holding capacity on weight basis. After three months, pots were transported to laboratory and soils were crushed and passed through 2 mm sieve. To check the result of amendments on vertic soil different physical and mechanical properties were tested on treated samples.

Determination of soil physical and chemical properties: Standard methods were followed to measure soil physical and chemical properties (Bao, 2000). A combination of wet sieving and pipette methods were adopted to determine particle size distribution. Soil reaction was determined by using 1:2.5 soil to water ratio with a pH meter. Dichromate oxidation method was used to measure OM while NH_4 acetate method was adopted for CEC. Soil extract was taken by using NH_4 acetate solution in a vessel which was placed on shaker for 30 minutes and then samples were filtered by using the Whatman No. 42 filter paper. 50 ml aliquot of filtrate was transferred to a Kjeldhal flask and 3 g NaCl and 20 ml 40% NaOH was added. This solution was distilled in an Erlenmeyer flask containing 10 ml of boric acid indicator solution to about 75 ml on a distillation unit. At the end distilled solution was titrated against 0.1N HCl solution and CEC was calculated through the following formula (Berg et al., 1978).

$$\text{CEC in meq per 100 g of soil} = [\text{ml HC1 (sample)} - \text{ml HC1 (blank)}] \times \text{N of HC1} \times 5 \times \frac{100}{\text{wt. of sample}}$$

Rapid N Cube Nitrogen Analyzer was used to determine total N by adopting dumas method (Li et al., 2014). Total P was measured calorimetrically as ammonium molybdate–ascorbate and total K by atomic absorption spectrophotometer after three acid digestion. The determination of total P and total K was carried out by using the wavelengths of 880 nm and 767 nm respectively. The NH_4 acetate solution was used as an extractant in a vessel containing 2 g of soil sample placed on shaker for 30 minutes and then samples were filtered by using the Whatman No. 42 filter paper. The atomic absorption spectrophotometer was calibrated by using the standards solutions of Ca, Mg and Na. At the end Ca, Mg and Na were determined in biochar and soil samples (Berg et al., 1978).

Determination of consistency limits: The consistency limits; liquid limit and plastic limit (LL and PL) of the studied soil were determined by the ASTMD 4318 procedure (American Society for Testing and Materials, 1995). The plasticity index was measured by difference between the liquid limit and plastic limit and can be calculated by following formula, using LL as liquid limit and PL as plastic limit.

$$PI = LL - PL$$

Determination of COLE: To measure the coefficient of linear extensibility (COLE) of soil samples, 100 g of air dried soil (<2 mm) was used to make paste (not fully saturated) and left for 24 hours to achieve equilibrium. Ground remolded samples were used to determine COLE and for this purpose paste was loaded into a syringe and rods of varying length (5-10 cm) were extruded on glass plate. The resulting rods were trimmed at both sides and length was measured (Schafer and Singer, 1976). Rods were air dried and length was measured again to calculate COLE by following formula:

$$COLE = (L_m - L_d) / L_d$$

Where:

L_m and L_d = length of moist and dry soils, respectively.

Determination of tensile strength and shear strength: Tensile strength (TS) of samples was measured by crushing method. Remolded soil cores were saturated under capillary action for 24 hours. The saturated cores were put into pressure plate for 12 hours and then were dried at 105 °C up to constant weight. The dried cores samples were adjusted between two parallel plates of a digital unconfined compression apparatus (YYW-2, Nanjing Soil Instrument Factory Co. Ltd.). Pressure was applied on soil cores through plates by a motor at constant speed of 2 mm min^{-1}. The maximum reading was noted prior to core fracture under the pressure.

Direct shear tests (DST) were applied to determine shear strength (SS) of soil samples by a quadruplex strain controlled direct shear apparatus (Nanjing Soil Instrument Factory Co. Ltd.). The uniform soil cores of 6.18 cm diameter and 2 cm height were saturated for 24 hours. A 300 hPa matric potential was used to bring soil cores at equilibrium for 12 hours. The equilibrated cores were mounted on shear testing device consisting of a soil shear box, a loading head, a weight hanger, and weights of different loads. Loads of 50, 100, 200 and 400 kPa were applied and sheared to measure the shear strength of vertic soil (Lu et al., 2014). A lateral displacement at a speed of 0.8 mm min^{-1} was applied until failure occurred and the maximum shear force was recorded. The cohesion (c) and the angle of internal friction (φ) were obtained by the Mohr–Coulomb theory.

Statistical analysis

Statistix 8.1 Statistical Package was used to perform statistical analysis. Data are expressed as mean± S.D and were compared by least significant difference (LSD) at $p \leq 0.05$ level. The pearson correlation was used for inter-soil parameters correlations in problem soil samples.

Results and Discussion

Consistency limits

Soil consistency is a soil physical property defined as the action of a soil under applied pressure. It is directly responsible for the measurement of soil mechanical behavior. It includes soil properties like compressibility, sheer strength, plasticity, friability and stickiness. It has direct relation to soil moisture contents. Results (Table 1) showed that PL of the soil decreased with SB treatments and at $p \leq 0.05$, significant decrease (31.45% and 22.44%) was found at 6% and 4% addition of SB compared to control respectively. The re-

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duction of about25.74% in PL were also observed for WSB at 4% level which was higher than 6% level of FA treatment (20.2%),whereas, a significant increase (17.2%) in PL value was occurred at 6% level of WCB treatment as compared to control. The LL values of vertic soil decreased (23.2% and 20.6%) with the addition of SB and FA amendments at 6% level respectively which was more significant than the decrease (12% and 17%) due to addition of 6% level of WCB and WSB respectively. The decreased values of LL indicated the positive effect of amendments on the consistency limit of soil. The PI of the soil under different treatments decreased for all the amendments but the effect of WCB at 4% and 6% was more pronounced. A decrease in the PI of 45.59% and 58.13% was recorded for WCB treatments at 4% and 6% treatments compared to control. Positive effect of amendments on the behavior of soil was observed by decreasing the values of PL, LL and PI as depicted by Table 1. Highly significant effect of WCB was observed on PI whereas PL and LL were reduced significantly with the application of SB. The consistency limit of soil played important role in the management of water transportation and conservation and tillage practices (Lu et al., 2014).

Table 1: *Consistency limits (PL, LL and PI) as affected by amendments in vertic soil*

Treatments	Plastic Limits (PL) (%)	Liquid limits (LL) (%)	Plasticity index (PI) (%)
CK	26.96±3.1bc	44.11±1.5a	17.15±3.7abc
SB2%	22.98±2.2de	38.74±1.7bc	15.75±2.8abcd
SB4%	20.91±2.0def	34.71±1.9d	13.80±3.5abcde
SB6%	18.48±1.1f	33.85±4.2d	15.37±5.3abcd
LSD Value of SB	4.5415	7.1424	10.095
WCB2%	28.88±1.4ab	40.07±1.7b	11.19±2.0def
WCB4%	31.35±3.8a	40.68±2.3ab	9.33±6.1ef
WCB6%	31.60±1.5a	38.78±2.5bc	7.18±2.4f
LSD Value of WCB	6.3015	5.5159	9.9631
WSB2%	22.54±2.0de	41.87±1.3ab	19.32±2.8a
WSB4%	20.02±1.6ef	39.01±2.2bc	18.99±0.8ab
WSB6%	20.35±0.5bc	36.60±1.1cd	16.24±1.5abcd
LSD Value of WSB	3.7925	4.0677	4.7802
FA2%	24.04±0.6cd	36.49±2.2cd	12.45±0.6cdef
FA4%	21.84±1.0def	35.98±1.1cd	14.14±2.0abcde
FA6%	21.51±3.5def	35.03±0.6d	13.53±1.6bcde
LSD Value of FA	15.833	3.6305	6.8096
LSD Value	10.576	6.1243	9.8422

Means with different letter in the same column are significantly different ($p\leq 0.05$)

Coefficient of linear extensibility (COLE)

The coefficient of linear extensibility (COLE) indicates soil shrinkage and swelling capacity. The COLE values of studied soil and with different amendments are indicated in the Figure 2. It is obvious that COLE values decreased significantly ($p\leq$ 0.05) for all the amendments at different rates. A significant decrease in the COLE was observed for WSB and FA amendments, whereas effect of FA was more pronounced compared to control. A decrease of 64%, 60% and 78% was observed for 2%, 4% and 6% of FA amendment, respectively. Among different amendments and treatments FA (6%) and WSB (4%) had more pronounced effect on the reduction of COLE compared to SB and WCB treatments. It shows that WSB and FA imposed more effect on the COLE compared to biochar amendments (straw biochar and wood biochar) and control. The high value of COLE presented by studied soil indicating the shrinkage and swelling hazard. The introduction of amendments reduced the shrinkage and swelling hazard by altering the clay minerals responsible for the shrinkage and swelling properties of soil (Lu et al., 2014).

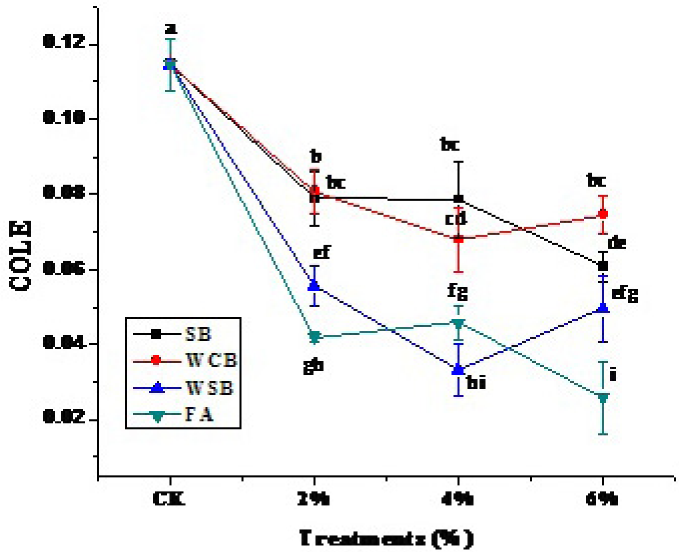

Figure 2: *Effect of biochar (SB, WCB and WSB) and fly ash (FA) at 2%, 4% and 6% rates on the COLE values of vertic soil.*

Tensile and Shear Strength

Results (Figure 3) revealed that tensile strength (TS) of soil decreased significantly with the addition of higher rates of amendments. Reduction of the tensile strength was; 29%, 32%, and 49% for WCB, 32%, 25% and 60% for WSB and 28%, 33% and 48% for FA, respectively. The effect of SB on the decrease (37.0%, 44.0% and 61.3%) of TS was more profound as compared to control and other treatments (WCB, WSB and FA) at 2%, 4% and 6%, respectively.

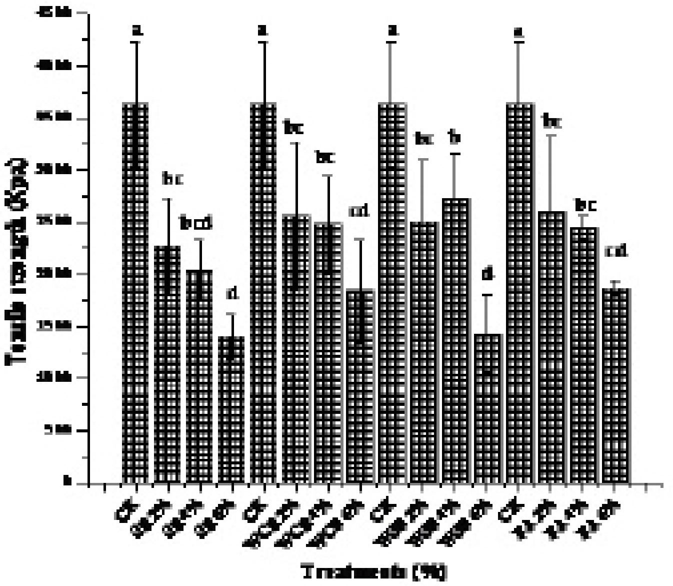

Figure 3: *Effect of biochar (SB, WCB and WSB) and fly ash (FA) at 2%, 4% and 6% rates on the tensile strength of vertic soil.*

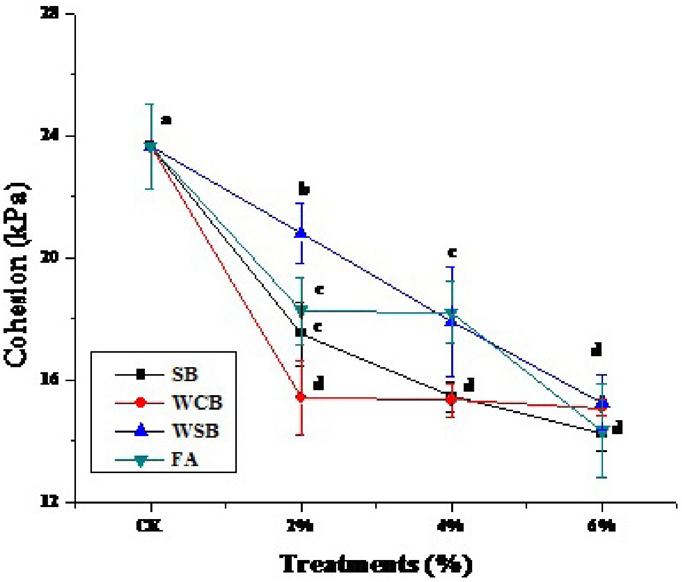

Figure 4: *Effect of biochar (SB, WCB and WSB) and fly ash (FA) at 2%, 4% and 6% rates on the cohesion (C) of vertic soil.*

The shear strength is expressed as cohesion (*C*) and angle of internal fraction (φ). The Figure 4 showed that *C* values decreased significantly ($p \leq 0.05$) for higher rates of amendments as compared to control. Overall, the cohesion values decreased from 23.62 kPa (CK) to 17.52, 15.45 and 14.26 kPa (SB), 15.40, 15.33 and 15.07 kPa (WCB), 20.81, 17.71 and 15.26 kPa (WSB) and 18.27, 18.21 and 14.34 kPa (FA) at 2%, 4% and 6% treatment rates, respectively. Hence these values suggested that positive effect on the reduction of *C* values was more pronounced for biochar treatments (SB and WCB). In contrast to *C*, no regular trend was found for φ values for all the treatments. Mostly the amended soil showed higher φ values at 2% rate compared to control. A small reduction in the amended soils was observed at 4% rate whereas at higher rate of SB (6%) treated soil exhibited a significant reduction than all other treatments. It is evident from Figure 5 that a minute effect was noted except highest level of SB amendment on the angle of internal friction (φ). An improvement in the soil strength (tensile and shear strength) in case of vertic soils is optimum requirement in agriculture and application of straw biochar than all other amendments had significantly improved the soil strength status of studied soil as depicted from Figures 3, 4 and 5.

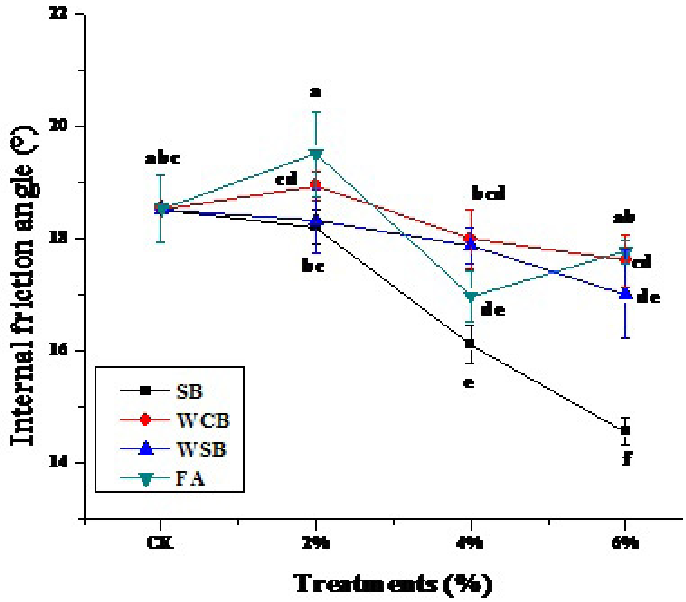

Figure 5: *Effect of biochar (SB, WCB and WSB) and fly ash (FA) at 2%, 4% and 6% rates on the internal friction angle (φ) of vertic soil.*

Correlation among the physical parameters

Pearson correlation was used to find the correlation existed between different physical parameters of studied soil as shown in the Table 2. Pearson correlation was used to see the correlation among different soil parameters. The correlation results revealed that PL was positively correlated with LL (r=0.58) and negatively correlated with PI (r=-0.72). LL was positively correlated with φ (r=0.50) and TS (r=0.58). COLE and φ showed significant positive correlation (p=0.05) with *C* and TS, respectively. *C* indicated positive correlation with TS (r=0.91).

Improvement in consistency limit and COLE

Soil consistency is specified with reference to mois

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Table 2: *Pearson correlation among the different parameters*

	PL	LL	PI	COLE	AIF	C	TS
PL	1						
LL	.588*	1					
PI	-.723**	.135	1				
COLE	.286	.495	.073	1			
AIF	.270	.504*	.099	.917**	1		
C	.204	.467	.149	.947**	.811**	1	
TS	.362	.588*	.059	.985**	.919**	.919**	1

**Correlation is significant at the 0.05 level (2-tailed).*
*** Correlation is significant at the 0.01 level (2-tailed).*
PL: plastic limit; LL: liquid limit; PI: plasticity index; AIF: angle of internal friction (φ); C: cohesion; TS: tensile strength

ture contents of soil and has great importance for agriculture (plant root penetration and behavior under cultivation (Hemmat et al., 2010a; Aksakal et al., 2013). Soil consistency limits are helpful to determine the optimum water contents for tillage operation in agricultural soils. It appears that no specific trends were observed for the consistency limits after the addition of amendments. However, values of PL, LL and PI decreased as compared to control. It is well documented that addition of organic amendments improved the physical properties as well as consistency limits of soils (Lu et al., 2014). Overall, a decrease in the PI was observed for all the amendments used and effect of WB was more pronounced. Consistency limit of soil under amendments showed no correlation with other soil physical parameters, however LL showed significant ($P \leq 0.05$) correlation with φ and TS. Generally smaller PI showed better workability in engineering applications and agricultural practices and decreased values of PI under the effect of different amendments were also reported by many authors (Puppala et al., 2007; Lin et al., 2007a; Lu et al., 2014).

The higher values of COLE in the control soil indicated a typical shrink and swell behavior of vertic soils. The presence of significant proportions of montmorillonite were responsible for high COLE values in vertic soil as depicted in the XRD pattern of Figure 1 (Grossman et al., 1968; Moustakas, 2012). The reduction in the COLE after the addition of amendments represented the reduction of shrinkage and swelling in the vertic soil and was probably due to two processes after the addition of amendments as described by Lu et al., (2014). First process included the interchanging of swelling clay with non-swelling amendments and the second process involved resistance in the swelling which depends on the clay-carbon contact and effective clay-carbon particles contact. The positive effect of amendments (fly ash) was also found in the study of Kumar and Sharma (2004). The organic amendments increased the soil hydrophobicity, which reduced the clay swelling. The amount and mineralogy of clay and high values of CEC increased the COLE of soil. The amendments like biochar, fly ash and wastewater sludge biochar, used to alter the texture of soil, decreased the CEC values of soils and interfering in the amount and type of clay minerals (Fernandez-Galvez et al., 2012; Tejasvi and Kumar, 2012; Ram and Masto, 2014). The reduction of soil COLE values under the effect of amendments is a required property in case of Vertisols to avoid formation of bigger cracks which affect the root formation leading to erosion and high water evaporation.

Improvement in the tensile and shear strengths

Soil strength is associated with plant growth and high soil strength resulted in the poor crop growth. Tensile strength (TS) is the stress or force per unit area required to cause soil to fail in tension (Dexter and Watts, 2000). A reduced tensile strength in soil is required for plant roots to grow by crossing the zones of high mechanical stress. The TS of the soil is influenced by amount of clay, mineralogy and particle size of the clay. However, by the addition of organic amendments, the binding forces of clay particles reduced due to flocculation and aggregation, consequently reducing the TS through reduction of clay particles effect (Barzegar et al., 1995). The reduction in the TS under biochar amendments was probably due to biochar that had significantly reduced the bonding between clay minerals and increased the soil porosity. Brodowski et al. (2005) also reported that rapid oxidation of biochar promoted its interaction with mineral phases and enhanced aggregate formation. Moreover, biochar application had provided voids, having central and well pore structure, for clay particles' contact to reduce the cohesiveness among soil particles and ultimately reduced the soil strength. Similarly, Lu et al. (2014) reported that biochar and coal fly ash significantly reduced the soil strengths. Moreover, applications of amendments increase the aggregation and their stability. The formation of these aggregates considerably decreased the strength of soil and ultimately reduced the TS (Sahin et al., 2008; Ouyang et al., 2013; Hua et al., 2014; Lu et al., 2014; Sun and Lu, 2014).

Improvement in the soil organic matter and mechanical properties is fundamental aim for high crop production. Among the mechanical properties, shear strength is used to predict soil bearing capacity and a measure for soil erosion, difficulty in seedling emergence and plant root growth (Hemmat et al., 2010b). The results confirmed the positive effect of amendments (SB, WCB, WSB and FA) on the mechanical strength by reducing the shear strength values. Soil *C* values are due to function of soil particle surfaces interconnection and addition of biochar had reduced the connection of these particles by forming carbon coating around mineral particles. Another reason for low *C* values is the high water repellency by organic compound adsorbed around the mineral particles reducing the attraction between solid and liquid phases (Lu et al., 2014). Table 3 showed pearson correlation among the different physical parameters and shear strength (*C* and φ) that had significant relationship with COLE and TS. The decreases in the cohesion values are due to organic matter, which occupied the spaces particulars for soil particles which in turns reduce the particles interactions. Further, the application of amendments decreased the cohesion by forming moisture layers around clays and softening the cohesive bonds as found in plastic clays (Mitchell and Soga, 2005; Puppala et al., 2007). Lu et al. (2014) also described the possible reason in the reduction of *C* values as cohesion is assigned to lower surface tension force at the air/water interface between water films around the soil particles at higher degree of water saturation. Amendments exerted a positive effect on the TS by lowering the values and it was probably due to amendment's effect on the weakening of inter-particle bond strength among the soil clods. The amendments provided the lubricating effect and ultimately weaken the TS (Lu et al., 2014; Zong et al., 2016).

Conclusion

It was concluded that both fly ash and biochar significantly improved the physico-mechanical properties of vertisols. The amendments like biochar (SB, WCB and WSB) and fly ash (FA) improved the consistency limits and COLE. Highly significant effect of WCB was observed on PI. The effect of WSB and FA on the COLE was more significant ($P \leq 0.05$) in decreasing COLE values compared to control and other amendments. The WCB, WSB and FA showed significant reduction in the tensile strength. The cohesion (*C)* values were decreased significantly due to biochar (SB and WCB) application as compared to other amendments, whereas, no specific trends were observed for internal angle of friction (φ). Pearson correlation among different treatments sugest that COLE was significantly ($p \leq 0.01$) correlated with φ, *C* and TS. The physico-mechanical parameters of vertisols were improved by application of amendments. However, at higher doses (4% and 6%) of treatments were not different from lower doses *i.e.* 2% so it is suggested that 2% level of biochar and fly ash is more preferable according to feasibility and economic point of view.

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Author's Contribution

The first author has designed and performed the laboratory analysis and composed the manuscript while the co-authors contributed in data analysis, tabulations and critical review of the current study. All authors agreed to publish this final manuscript.

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