



Influence of biochar particle size on the hydraulic conductivity of two different compacted engineered soils

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Abstract

Biochar is a recalcitrant material obtained after pyrolysis of labile biomass under oxygen-limited condition. The conversion of biomass into biochar is considered to be a sustainable way of generating bioenergy, minimizing the emission of greenhouse gases and managing the waste. Recently, the amendment of biochar in soil gained attention due to its multiple soil ameliorating features. Many studies have investigated the effect of biochar particle size on the physicochemical and hydraulic properties of relatively loose agricultural soil. However, such study is rarely conducted for compacted soil suitable for bioengineered structures. The objective of the current study is to investigate the effect of biochar particle size on the hydraulic conductivity of compacted soil for bioengineered structures. Saturated hydraulic conductivity (K_{sat}) of different compacted soils amended with biochar of different particle sizes ranging from 0.075 to 4.75 mm has been investigated. The results showed that the amendment of 5% to 15% (w/w) biochar of different particle sizes led to the change in K_{sat} of the silty sand. When compared with bare soil, a higher K_{sat} with biochar of particle size larger than 0.425 mm and a lower K_{sat} with particles of size smaller than 0.425 mm was observed. However, in pure sand, a lower K_{sat} irrespective of particle size of biochar was observed and the lowest K_{sat} was noted with biochar of particle size smaller than 150 μm . These changes in the K_{sat} after biochar amendment were attributed to the alteration of pore structure mainly, inter-pores of the soil, which is controlled by the particle size of the biochar. The findings of the present study could be useful for the field application i.e. in bioengineered structures.

Keywords Biochar · Particle size · Saturated hydraulic conductivity · Compacted soil · Bioengineered structures

1 Introduction

Biochar is a carbon-rich product obtained after pyrolysis or gasification of biomass at high temperature ($>200\text{ }^{\circ}\text{C}$) under oxygen deficit condition [1]. Biochar-amended soil is suggested as sustainable material for bioengineered structures, such as landfill cover, green roof, vegetated slope and mining sites in the recent past [2–7]. Biochar amendment in soil could

remain for a longer duration compared to raw biomass [8], while it could improve the performance of these structures by affecting the soil properties, especially hydraulic properties such as hydraulic conductivity [9–15]. Saturated hydraulic conductivity (K_{sat}) represents the upper limit of water migration rate for any soil i.e. the critical case of hydraulic conductivity. The K_{sat} is one of the crucial hydraulic properties of soil that helps in understanding the water movement and retention pathways through soil [16–18]. It governs the infiltration and seepage through dams, landfill system and agricultural land, percolation loss through a water storage system and flow through wells [19].

The impact of biochar on the K_{sat} of soil was studied in the past where variable outcomes have been reported [17, 20–22]. Lei and Zhang [20] reported an increase in K_{sat} of silty sand when biochar was amended, while Igalavithana et al. [22] reported a decreased K_{sat} of the same type of soil with biochar amendment. Similarly, Reddy et al. [3] and Wong et al. [14] reported an increased K_{sat} of clayey soil amended with 5% and

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20% (w/w) biochar compared to that of unamended clay, whereas Castellini et al. [23] documented a no change in K_{sat} of clayey soil after biochar amendment. These variable outcomes could be due to the variable particle size of the biochar. The difference in particle size of biochar could cause the variation in pore size distribution and porosity of the biochar-amended soil, consisting mainly inter-pores (pores between soil or biochar particles) and intra-pores (pores within biochar skeleton). The number and size of inter-pores and intra-pores depend on the particle size of biochar and the soil i.e. any change in the biochar particle size directly affects the intra and inter-pores [10, 24, 25]. As a consequence, there could be changes in the hydraulic conductivity. Although the alteration in K_{sat} of soil is caused by many factors, the change in pore size distribution or porosity is highly regarded as the main responsible factor [3, 26]. Furthermore, various bioengineered structures have criteria on hydraulic conductivity or infiltration e.g. landfill cover has the criteria of lower hydraulic conductivity to minimize the formation of leachate [14]. The amendment of specific particle size biochar could control the hydraulic conductivity of the soil. Therefore, the study of the impact of different particle sizes of biochar on the K_{sat} of soil is crucial and could be useful for bioengineered structures.

The influence of biochar particle size on the physicochemical and hydraulic properties of relatively loose soil suitable for agricultural application was reported in the literature [27–30]. However, such systematic study was rarely [31, 32] conducted for compacted soil suitable for bioengineered structures. Ghavanloughajar et al. [31] investigated the particles breaking (biochar) and hydraulic conductivity of biochar-amended sand under compacted and loose state for potential application as biofilters. Similarly, Le et al. [32] investigated the hydraulic conductivity of biochar-amended sand while identifying the initial biochar particle size subjected to higher breaking under compaction. However, these studies have not considered a specific degree of compaction (i.e. randomly compacted only to show the difference between compacted and loose state) which is very important for bioengineered structures as soil in these structures often compacted at 90 to 95% of maximum dry density for ensuring structural stability [5, 33]. The difference in degree of compaction of soil could lead to the variation in pores structure and soil-biochar-water interaction, hence the hydraulic conductivity [34]. Furthermore, the density of soil changes with the amendment rate and particle size of the biochar amended [35] which was not taken into consideration. A recent study [36] showed that the amendment of 15% (w/w) biochar could decrease the soil density by 18%. Therefore, the objective of the present study is to investigate the effect of biochar particle size on the saturated hydraulic conductivity (K_{sat}) of different type of compacted soil for potential application in bioengineered structures. We hypothesised that the amendment of biochar

with larger particle size would change the pore size distribution or K_{sat} of the soil distinctly compared to another biochar of smaller particle size as highlighted schematically in Fig. 1 and would be useful in controlling the hydraulic conductivity of bioengineered structures. To probe the hypothesis, soil columns were prepared by compacting soil amended with 5%, 10% and 15% (w/w) mesquite biochar of different particle sizes and the corresponding K_{sat} was measured.

2 Materials and methods

2.1 Soil

Two different types of soil were collected from inside the campus of Indian Institute of Technology (IIT) Guwahati and the river bed of Brahmaputra River located in the North-eastern province of India (26.19° N, 91.69° E). Dead roots, large stones and any other impurity present in the soils were manually removed. The basic and index properties of the soils were determined according to ASTM standard referral [37–43]. The images of the soils are highlighted in Fig. 2a.

2.2 Biochar

Biochar for the present study was produced by Greenfield Eco. Pvt. Ltd. using hardwood of mesquite (*Prosopis juliflora*) as feedstock and pyrolysed at 500 °C. Table 1 highlights the feedstock and pyrolysis condition of the biochar. The biochar obtained from the vendor was crushed into smaller sizes using a mechanical grinder. Thereafter, biochar of different particle sizes, such as 4.75–2 mm, 2–0.425 mm, 0.425–0.075 mm and 0.15–0.075 mm, were separated using sieves and sieve shaker. These biochar fractions were chosen uniformly from the parent biochar of size range 0.075–4.75 mm to obtain trend of any effect. However, the particle size range 0.15–0.075 mm was chosen intentionally so that it is smaller than the particle size of sand (>0.150 mm). The physicochemical properties of the parent biochar, such as specific gravity, water absorption capacity, pH and electrical conductivity (EC), were measured according to the standard procedure described in ASTM standard [37, 40, 43]. The measurement of pH and EC was taken using a pH meter and electrical conductivity meter equipped with an electrode with a material: water ratio of 1:10 [44]. The elemental composition of the biochar was determined by combustion technique using an elemental analyser as described in Bird et al. [45]. Cation exchange capacity (CEC) and ash content were measured by ammonium acetate method [46] and the method described in ASTM E1755–01 [47]. The contact angle of wetting was measured by sessile drop method described in Jeffery et al. [48]. The images of the biochar with different particle sizes are highlighted in Fig. 2a.

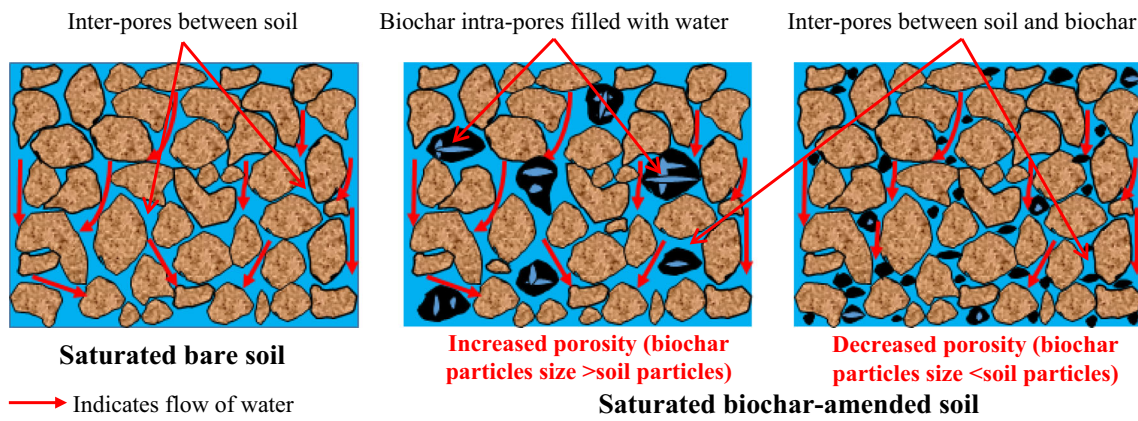


Fig. 1 Conceptual diagram showing the effect of biochar on porosity or water permeability in soil

2.3 Test procedure

2.3.1 Preparation of soil column

The soil column used for the experimental study is shown in Fig. 3. PVC moulds of size 50 mm diameter and 160 mm length were fabricated in the laboratory using PVC pipe and caps. Hollow plastic buffer was placed inside the cap for

accommodating a uniform distribution of water over the porous stone (Fig. 3). Five percent, 10% and 15% (w/w) biochar of each particle size fraction were dry mixed with the soil in an aluminium pan. Thereafter, for silty sand, deionized water corresponding to 90% of the maximum dry density (i.e. 0.9MDD) was added and mixed uniformly. The water-mixed samples were kept in an air-tight desiccator or incubated for a duration of 24 h for moisture equilibration. The soil-

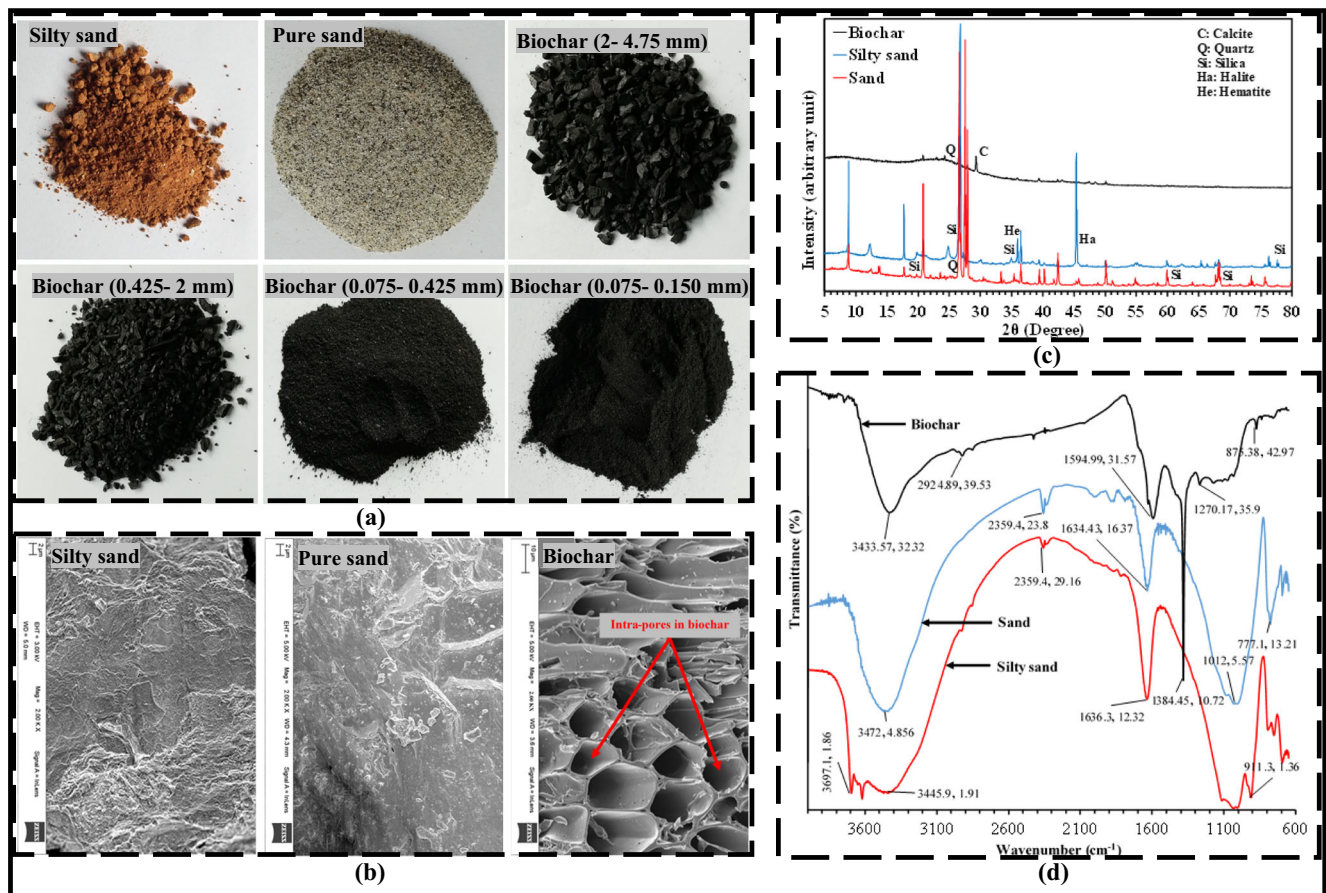


Fig. 2 a Raw images of the silty sand, pure sand and biochar of different particle size, b FESEM images of the soils and biochar, c XRD patterns and d FTIR spectra of the soils and biochar

Table 1 Properties of the soils and biochar tested

Properties	Biochar	Silty sand	Sand
Feedstock	Hard wood of mesquite (<i>Prosopis juliflora</i>)	-	-
Pyrolysis process	Slow pyrolysis	-	-
Pyrolysis temperature (°C)	500	-	-
Elemental composition (%)			
Carbon (C)	72		
Oxygen (O)	-		
Hydrogen (H)	-	-	-
Nitrogen (N)	0.26		
Phosphorus (P)	0.2		
Potassium (K)	2.6		
Molar ratios			
H:C	-	-	-
C:N	382	-	-
Ash content (%)	2	-	-
CEC (cmol kg ⁻¹)	19	2.5	-
Specific gravity	1 ± 0.1	2.7 ± 0.06	2.65 ± 0.05
pH	8.5 ± 0.22	4.5 ± 0.08	7.95 ± 0.05
Specific surface area (SSA, m ² /g)	137	23	6.8
Water absorption capacity (%)	200 ± 12.73	36 ± 1.4	-
Contact angle of wetting (°)	67 ± 3	-	-
EC (dSm ⁻¹)	1.6	0.0425	0.0343
Particle size distribution (%)			
Coarse sand (4.75–2 mm)	32	6	0.6
Medium sand (2–0.425 mm)	43	20	1
Fine sand (0.425–0.075 mm)	12	25	96.8
Silt (0.075–0.002 mm)	13	29	1.6
Clay (< 0.002 mm)		20	
Uniformity coefficient (Cu)			1.35
Coefficient of gradation (Cc)	-	-	0.87
Atterberg limits (%)			
Liquid limit	-	37	-
Plastic limit	-	26	-
Shrinkage limit	-	15	-
Compaction properties			
Optimum moisture content (%)	-	17	-
Maximum dry density (kg/m ³)	452	1730	1554
Minimum dry density (kg/m ³)	388	-	1375
Classification			
USCS	-	Silty sand (SM)	Poorly graded sand
USDA		Sandy clay loam	Sand
Taxonomy		Ultisols	Aridisols

CEC cation exchange capacity, EC electric conductivity. Value in table represents the average value ± standard deviation

biochar mixtures were then statically compacted at a density equivalent to 0.9MDD and up to a thickness of 80 mm. Similarly, the compaction of biochar-amended sand was carried out at 0.9MDD and natural moisture content (air-dry state) obtained from the relative density test. The initial

compaction condition and the quantity of soil and biochar for each samples are highlighted in Table 2. The selection of compaction density of 0.9MDD and the corresponding water content were based on the standard proctor test [39] and relative density test [49] conducted before the permeability test,

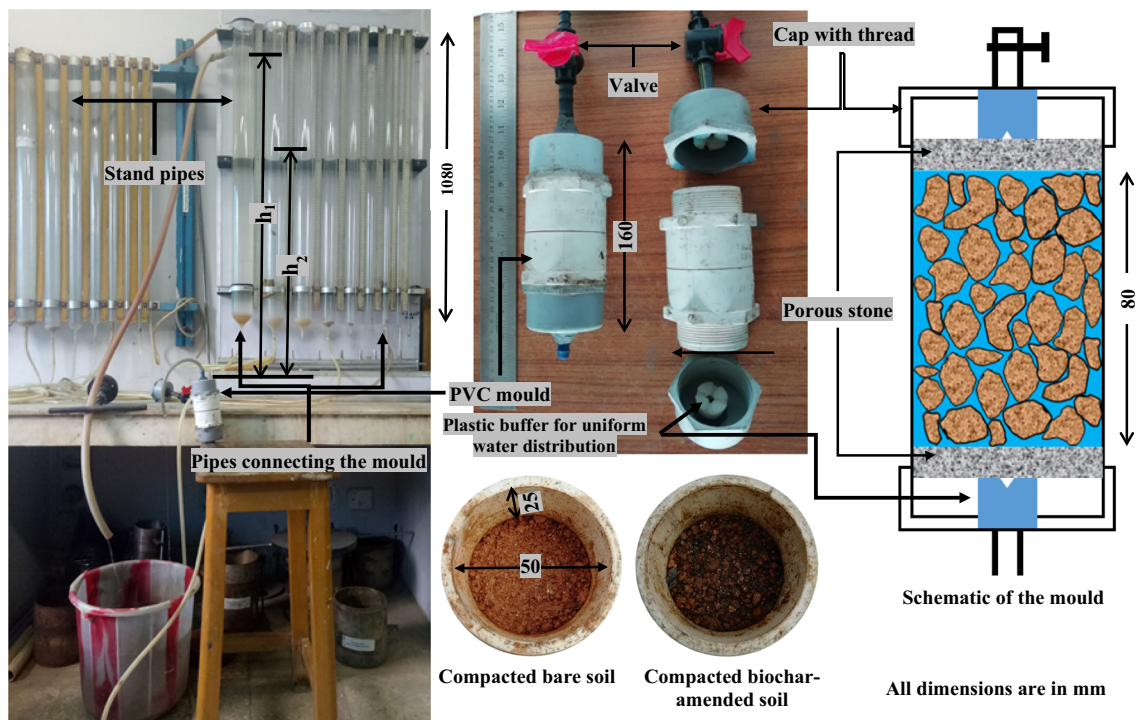


Fig. 3 Experimental setup adopted for the measurement of permeability

and to represent the compaction criteria adopted for bioengineered structures reported in the literature [33, 50]. Three independent replicates of soil column for each biochar amendment rate and particle size were prepared.

2.3.2 Measurement of K_{sat}

The K_{sat} of the compacted soil columns was measured using conventional rigid-wall permeameter in accordance with the standard testing procedure described in ASTM D5856 [51]. All the samples were saturated by allowing deionized and de-aired water ($\text{EC} = 0.0003 \text{ dSm}^{-1}$ and $\text{pH} = 6.8$) from bottom to the top on an average for 4 days. Deionized water was used to avoid any chemical interaction between biochar and the impurities present in normal tap water, and to avoid the formation of scum on the soil pore spaces that could alter the flow rate. Full degree of saturation or minimum air entrapment was ensured by observing minimum variation in the outflow volume measured by several times (at least seven times). After saturation, the hydraulic conductivity of the bare silty sand and the biochar-amended silty sand was determined by measuring the flow rate under falling head condition. Similarly, for bare sand and the biochar-amended sand, the flow rate was measured under constant head condition due to a higher rate of flow. All the tests were carried out in a laboratory at temperature of $25 \pm 1 \text{ }^\circ\text{C}$ and the necessary correction in K_{sat} due to temperature change was taken care of. The

K_{sat} of the silty sand was calculated using the following equation [19]:

$$k = \left(\frac{a \times L}{A \times t} \right) \ln \left(\frac{h_1}{h_2} \right) \quad (1)$$

where k is the hydraulic conductivity (m/s), a is the cross-sectional area of the standpipe (m^2), L is the length of the sample (m), A is the cross-sectional area of the sample (m^2), h_1 and h_2 are the initial and final water head with respect to the outflow (m) and t is the time for the hydraulic head difference to decrease from h_1 to h_2 .

Similarly, for the sand, the K_{sat} was calculated as follows:

$$k = \frac{V \times L}{A \times \Delta h \times t} \quad (2)$$

where V (m^3) is the volume of water flows through the sample in a known time t (s) and Δh is the hydraulic head difference (m). Measurement was repeated for seven times and the average value with standard deviation is reported.

2.3.3 Determination of porosity and theoretical K_{sat}

The porosity of the bare and biochar-amended soil corresponding to different biochar particle size was determined from the initial compaction dry density of the soil columns. The porosity of the compacted samples was calculated from the relationship given below [52].

$$n = \left(1 - \frac{\gamma_d}{G \times \gamma_w}\right) \times 100 \quad (3)$$

where n is the porosity (%), γ_d is the dry density or unit weight of the compacted samples (kN/m^3), G (–) is the specific gravity of the samples corresponding to the different particle sizes of biochar and γ_w is the unit weight of water (kN/m^3). The theoretical K_{sat} was estimated from the porosity or void ratio using a modified Kozeny-Carman equation. The details of the equation could be found in Ren et al. [18].

2.3.4 BET, XRD, FTIR and FESEM analyses

The specific surface area (SSA) of the biochar and soils was determined by using Brunauer-Emmett-Teller (BET) analyser (Autosorb IQ MP, Quantachrome, Florida). The minerals present in the biochar and soils were determined by X-ray diffractometer (28 Bruker AXS D8 model, Billerica, MA). The surface functional groups present in the biochar and the soils were identified by using a Fourier transform infrared (FTIR) spectrophotometer (IRAffinity-1, Shimadzu, Japan) according to Hussain et al. [15]. The morphology of the soils and biochar was studied by capturing FESEM images ($\times 500$ to $\times 25\text{K}$) using a Field emission scanning electron microscope (sigma-300, Zeiss).

2.3.5 Statistical analysis

The two-way analysis of variance (ANOVA) was used to determine whether there were any significant differences between the means of the K_{sat} with respect to the different

amendment rate and particle size of biochar. The difference is considered statistically significant when the observed p value was less than 0.05 (pre-set, 95% significance level). Analysis was carried out in the Origin Pro (Origin 9) software.

3 Results and discussion

3.1 Properties of the soil and biochar

The properties obtained after characterization of the soils and the biochar are presented in Table 1. The soils are classified as silty sand (SM) and poorly graded sand (Table 1, [41]). The microstructural analyses, such as FESEM, XRD, BET and FTIR, were conducted only to characterize the materials i.e. the soils and the biochar. The FESEM images of the biochar and the soils are shown in Fig. 2b. Intra-pores or pores within biochar skeleton are clearly visible from Fig. 2b, whereas intra-pores could not be observed in the soils. The BET results obtained for the soils and biochar are presented in Table 1. Biochar showed a relatively higher SSA compared to the soils and this is attributed to the intra-pores in biochar that make the biochar a porous media. The XRD patterns of the soils and biochar are shown in Fig. 2c. The peaks at $2\theta = 24.3^\circ$, 29.3° and 26.5° in the biochar were attributed to the formation of turbostratic carbon crystallites, calcite and quartz minerals respectively [53]. Similarly, the silty sand and pure sand mainly consist of silica and quartz minerals. The FTIR peaks observed in the soils and the biochar are highlighted in Fig. 2d. The broad peaks at wavenumber 3433 , 3472 , 3445 cm^{-1} in

Table 2 Initial compaction condition and theoretical estimated K_{sat} of the samples tested

Soil type		0% (Bare)	5% BAS	10% BAS	15% BAS
Silty sand	Density, 0.9MDD (kg/m^3)	1548	1440	1320	1287
	Moisture content (%)	8	10.1	10.5	12.5
	Soil quantity (kg)	0.280	0.248	0.217	0.202
	Biochar quantity, w/w (kg)	0	0.012	0.022	0.030
	Biochar quantity, v/v (%)	0	12	25	38
	K_{tsat} (cm/s), (4.75–2 mm)	5.95×10^{-5}	6.56×10^{-5}	9.35×10^{-5}	1.09×10^{-4}
	K_{tsat} (cm/s), (2–0.425 mm)		6.10×10^{-5}	9.05×10^{-5}	9.66×10^{-5}
K_{tsat} (cm/s), (0.425–0.075 mm)		4.86×10^{-5}	5.02×10^{-5}	5.72×10^{-5}	
Sand	Density, 0.9MDD (kg/m^3)	1399	1279	1207	1138
	Moisture content (%)	0.2*	0.67*	0.96*	1.32*
	Soil quantity (kg)	0.253	0.220	0.198	0.179
	Biochar quantity, w/w (kg)	0	0.011	0.020	0.026
	Biochar quantity, v/v (%)	0	17	35	50
	K_{tsat} (cm/s), (4.75–2 mm)	3.2×10^{-3}	4.3×10^{-3}	4.5×10^{-3}	5.7×10^{-3}
	K_{tsat} (cm/s), (2–0.425 mm)		3.8×10^{-3}	4.1×10^{-3}	5.4×10^{-3}
K_{tsat} (cm/s), (0.425–0.075 mm)		2.7×10^{-3}	2.9×10^{-3}	4.0×10^{-3}	
K_{tsat} (cm/s), (0.150–0.075 mm)		2.9×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	

BAS biochar-amended soil, 0.9MDD 90% of maximum dry density, v/v volume of biochar with respect to soil volume. *Moisture content at air-dry state. K_{tsat} , theoretical saturated hydraulic conductivity

biochar and the soils are due to the hydroxyl (OH) group which is responsible for the attraction of water molecules through hydrogen bonding i.e. hydrophilicity [54]. The peak at 1594 cm^{-1} in biochar is attributed to the stretching of aromatic ring (C=C) [55], whereas peaks at 1384 , 1270 and 875 cm^{-1} are due to CH_3 (alkanes), C-O stretch (carboxylic acid) and asymmetric bending of calcite groups respectively [56]. Comparatively, the peak at 2924 cm^{-1} in the biochar is due to the aliphatic C–H bond of alkanes and responsible for hydrophobicity [57]. However, the hydrophobic action of biochar due to aliphatic C–H bond of alkanes diminishes upon flushing of water with time [57]. Peak at 2359 cm^{-1} in the soils is due to C=O (symmetric) group, while peaks at 1634 , 1636 cm^{-1} represents the C=O stretching (ionisable carboxyl groups) and associated with hydrophilicity [58]. Peaks at 1012 , 911 and 777 cm^{-1} are confirming the Si–O (quartz) stretching and Si–O bending in the soils [59]. The biochar was found to be hydrophilic in nature from the measured contact angle (Table 1).

3.2 Effect of biochar on the grain size distribution of the soils

The grain size distribution (GSD) curves of the soils amended with 5% biochar of different particle sizes are shown in Fig. 4a and b. The biochar had considerably lower fine content (13%) compared to the silty sand (49%). The GSD curve of the silty sand (Fig. 4a) shifted downward when biochar of particle size larger than 0.425 mm was amended and this is due to the increase of larger size particles in the GSD of amended soil compared to the bare soil. Similarly, the amendment of biochar of particle size smaller than 0.425 mm shifted the GSD curve upward and this is attributed to the increase of smaller size particles in GSD of amended soil compared to the bare soil. In Fig. 4b, for pure sand (particle size mostly around 0.150 mm), the amendment of biochar of particle size larger than 0.425 mm added some larger size particles in the GSD as the GSD curve shifted downward. However, the amendment of biochar of particle size smaller than 0.150 mm increased

some finer particles in the GSD as the GSD curve shifted upward (near toe of the curve).

3.3 Effect of biochar particle size on K_{sat} of the silty sand

Figure 5a and b shows the saturated hydraulic conductivity (K_{sat}) and porosity of the biochar-amended soil with biochar particle size of 0.075 – 0.425 mm , 0.425 – 2 mm and 2 – 4.75 mm , and amendment rate of 5%, 10% and 15% (w/w) respectively. The bare soil showed a K_{sat} value of $8.2 \times 10^{-5}\text{ cm/s}$. It increased to $14.5 \times 10^{-5}\text{ cm/s}$ and $17.7 \times 10^{-5}\text{ cm/s}$ in particle size 0.425 – 2 mm and 2 – 4.75 mm and decreased to $5.9 \times 10^{-5}\text{ cm/s}$ in particle size 0.075 – 0.425 mm when biochar amendment rate was increased to 15%. Considering the biochar particle size, the amendment of biochar with larger size particles of 0.425 – 2 mm and 2 – 4.75 mm showed a higher K_{sat} ($P < 0.05$) compared to the K_{sat} of bare soil. However, the change was observed negligible in the case of 5% biochar amendment rate. This higher K_{sat} was attributed to the increased total porosity or pore volume of the biochar-amended soil with larger biochar particles, which is evident from the porosity results presented in Fig. 5b. The bare soil exhibits a porosity of 41.8% and it increased to 45% and 45.9% in 15% biochar-amended soil with larger biochar particles. The bare soil consists of 6% particles within the size range of 2 – 4.75 mm , 20% within 0.425 – 2 mm and remaining 74% below these size ranges (i.e. $< 0.425\text{ mm}$, Table 1). Therefore, the amendment of biochar of particle size 0.425 – 2 mm and 2 – 4.75 mm increased the numbers of larger size particles ($> 0.425\text{ mm}$) in the GSD as seen from Fig. 4a that possibly increased the porosity by forming larger size inter-pores (biochar-biochar or soil-biochar) i.e. by increasing the size and numbers of inter-pores. Furthermore, the increased porosity could also be contributed by the intra-pores (mostly $\sim 0.010\text{ mm}$, Fig. 2b) present in biochar, while the soil consists of 20% fine content (clay, $< 0.002\text{ mm}$) that could settle inside or block the biochar intra-pores as observed for pure clay in Wong et al. [60]. However, the tendency of settlement is

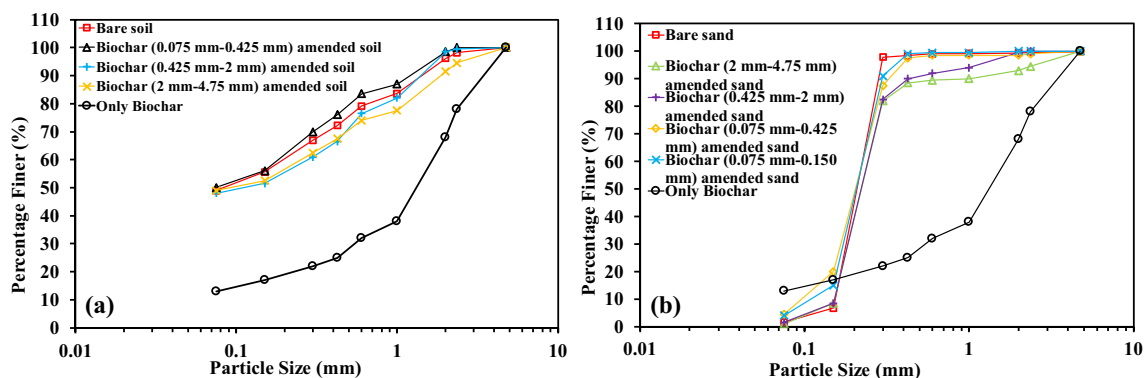


Fig. 4 Grain size distribution curve for a silty sand and b pure sand amended with biochar of different particle size

expected to be negligible in the present study, as the clay content was far lower than the content in pure clay (100%). The alteration of porosity i.e. inter-pores or intra-pores was observed to become more prominent when the amendment rate of biochar was increased from 5 to 15% (Fig. 5b), resulted in higher K_{sat} .

The amendment of biochar with smaller particle size (0.075–0.425 mm) caused a lower K_{sat} ($P < 0.05$) compared to that of bare soil. The lowest K_{sat} was observed in 5% biochar-amended soil and increased with an increase in amendment rate from 5 to 15%. This could be attributed to the decreased total porosity of the soil when biochar of particle size 0.075–0.425 mm was amended in the soil as shown in Fig. 5b. The decrease of the porosity could be due to the formation of smaller size inter-pores compared to the bare soil or clogging of inter-pores that have made the flow path more tortuous and reduced the flow velocity thereby, lower K_{sat} . However, this effect of reduced porosity or clogging pores was observed to decrease with an increase in biochar amendment rate from 5 to 15% and leading to an increase in K_{sat} . Therefore, the amendment of biochar in soil could have the possibilities of either increase or decrease the K_{sat} depending on the biochar particle size. The theoretically estimated K_{sat} (Table 2) also showed the similar trend with slightly lower values compared to the measured value. The estimation involved the specific surface area which was calculated from the liquid limit that has possibly caused the lower value [18]. In literature, Lim and Spokas [61] and de Jesus Duarte

et al. [29] reported variable response of biochar amendment on the K_{sat} of soil due to different particle sizes of biochar where amendment of biochar particle size smaller than the soil particles often reduced the K_{sat} . Thus, the results of the present study are found to be consistent with the literature. However, study by Laird et al. [62] and Ouyang et al. [63] found no influence of biochar amendment on the K_{sat} of loam and silty clay soil. Biochar was amended at 0.5–2% (w/w) which was very low compared to the amendment rate (5–20%) considered in other studies including the present study, and possibly caused no influence on the K_{sat} . Furthermore, the affinity or movement of water in soil or biochar-amended soil depends on many factors including wettability characteristics i.e. hydrophilic or hydrophobic [58]. The amendment of hydrophobic biochar which is characterised by aliphatic functional group could increase the hydrophobicity and decrease or not influence the K_{sat} of the soil due to prevention of water movement into the soil [34].

3.4 Effect of biochar particle size on K_{sat} of the pure sand

The variation of K_{sat} and porosity of bare sand and sand amended with biochar of different particle sizes of 0.075–0.15 mm, 0.075–0.425 mm, 0.425–2 mm and 2–4.75 mm and amendment rate of 5%, 10% and 15% (w/w) are depicted in Fig. 5c and d. The bare sand exhibited a K_{sat} of 3.3×10^{-3} cm/s and it is observed to decrease when biochar

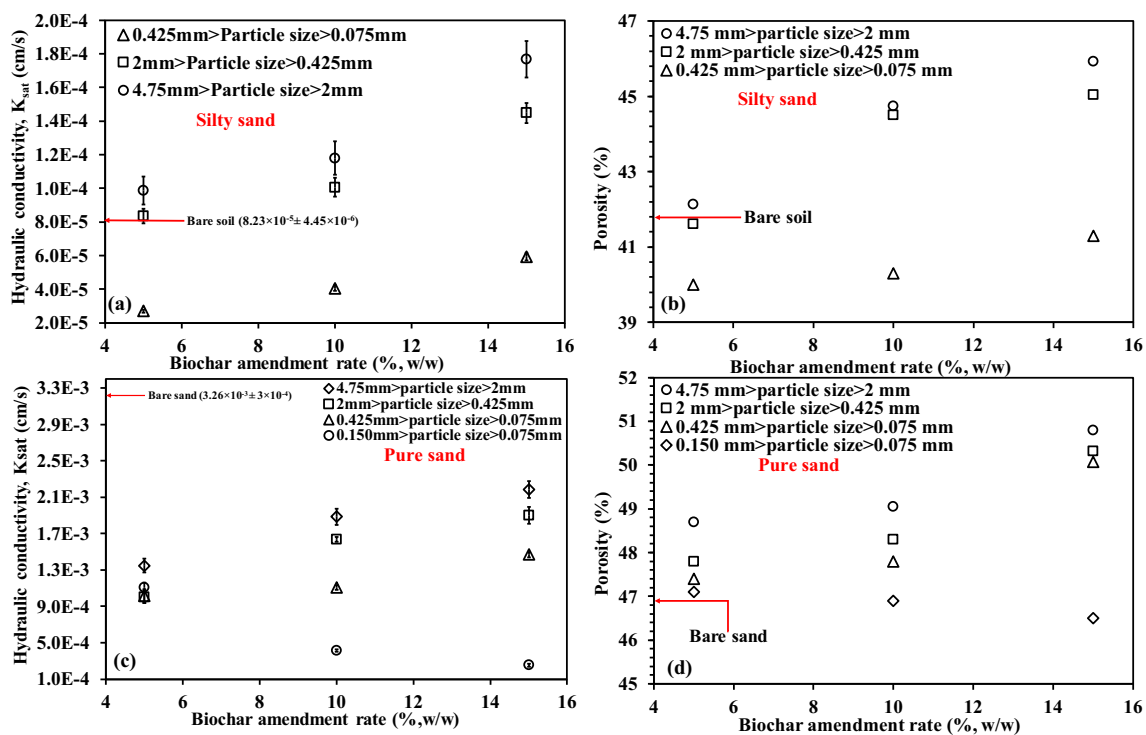


Fig. 5 Variation of saturated hydraulic conductivity (K_{sat}) and porosity of **a, b** silty sand, and **c, d** pure sand with biochar amendment rate (the error bar represents the standard error defined by standard deviation)

irrespective of particle size was amended. The lowest K_{sat} of 2.5×10^{-4} cm/s ($P < 0.05$) was found in 15% biochar-amended sand with smaller particle size (0.075–0.150 mm). The lower K_{sat} in biochar-amended sand compared to the bare sand could be due to the decreased porosity of the biochar-amended sand upon wetting, since the samples of biochar-amended sand were compacted in air-dry state. Bare sand showed a porosity of 47.2% and it increased to 50% and 50.8% in 15% biochar-amended sand with larger biochar particle size (i.e. 0.425–2 mm and 2–4.75 mm). Even though the porosity in compacted samples increased due to the addition of biochar (Fig. 5d), the flow of water during test possibly reduced the pores size and hence the porosity by filling or clogging the pore spaces leading to a lower K_{sat} compared to the bare sand similar to the case reported for biochar-amended sand in Novak et al. [64]. The decrease of pores size, mainly inter-pores, could be either by filling of smaller soil or biochar particles. The bare sand mainly (97%) consists of particle size within 0.150–0.425 mm (Fig. 4b) and the addition of biochar of larger particle size (i.e. > 0.150 mm) reduced the pores space or porosity possibly by filling the inter-pores between larger biochar particles with the smaller sand particles. While in biochar-amended sand with smaller biochar particle size (< 0.150 mm), the decreased porosity could be attributed to the filling of inter-pores between sand particles by the smaller biochar particles. The decrease of porosity due to the amendment of biochar of different particle sizes makes the flow path tortuous and hinders the water flow path leading to a lower K_{sat} compared to the bare sand.

Considering the particle size of the biochar, the amendment of 5% biochar showed a minimal variation in K_{sat} ; however, with increase in amendment rate of biochar from 10 to 15%, the K_{sat} was changed significantly. The amendment of biochar of particle size larger than 0.150 mm increased the K_{sat} ($P < 0.05$) and particle size smaller than 0.150 mm decreased the K_{sat} ($P < 0.05$). The negligible effect of biochar particle size or the minimum variation of K_{sat} at 5% biochar amendment rate could be attributed to the low amendment rate, while the increased K_{sat} in 10% and 15% biochar-amended sand with larger biochar particle size (> 0.150 mm) was attributed to the increased porosity of the same compared to the porosity of 5% biochar-amended sand as shown in Fig. 5d. Similarly, the decreased K_{sat} with smaller biochar particle size (< 0.150 mm) was attributed to the decreased porosity in higher amendment rate (Fig. 5d). The increase of amendment rate (i.e. from 5 to 10% and 15%) of larger particle size biochar (> 0.150 mm) in the sand possibly caused a formation of larger size inter-pores compared to the inter-pores in 5% biochar-amended sand leading to an increase in porosity. However, in the case of amending smaller particle size biochar (< 0.150 mm), the higher amendment rate of biochar caused a filling or blocking of inter-pores at a higher extend compared to that of 5% amendment rate leading to a lower porosity. The

theoretical estimated K_{sat} (Table 2) was found to be higher than the measured K_{sat} , as it was estimated from the initial compacted porosity and the changed porosity after wetting caused the lower measured K_{sat} . The results of the present study are found to be consistent with the existing literature [28, 29, 61]. However, literature [48] also reported no influence of biochar amendment on the K_{sat} of sand. Biochar used was hydrophobic in nature (contact angle $> 90^\circ$) that could prevent the water movement in the soil and hence, no influence on the K_{sat} . However, in the present study, biochar was found to be hydrophilic in nature (contact angle $< 90^\circ$, Table 1).

The K_{sat} is the hydraulic conductivity of soil at full degree of saturation i.e. soil pores completely filled with water. However, when soil pores partially filled with water i.e. unsaturated state, then the hydraulic conductivity will be different and is the function of suction and water content [65]. The hydraulic conductivity of partially saturated biochar-amended soil could be lower than the saturated soil due to the discontinuous water flow path by the occluded air in the pores [23]. The intra-pore and different particle sizes of biochar modify the pores structure of the soil after amendment that could affect the suction and water content of the biochar-amended soil, and soil in field (like bioengineered structures) most often remains in unsaturated state [14, 15]. Therefore, the study of the unsaturated hydraulic conductivity and other properties at unsaturated state is crucial and need to be considered.

4 Conclusions

In this study, the effect of different particle sizes of biochar on the saturated hydraulic conductivity (K_{sat}) of two different compacted soil types has been reported. Rigid-wall permeability test was conducted on compacted silty sand and pure sand amended with biochar of different particle sizes and amendment rate. The K_{sat} of the pure sand was observed to be decreased when biochar of different particle sizes was amended and the highest decrease by 92% with respect to the bare sand was observed with biochar of particle size smaller than 0.150 mm. However, in silty sand, the amendment of larger particle size (> 0.425 mm) biochar increased the K_{sat} by 115%, and amendment of smaller particle size (< 0.425 mm) biochar decreased the K_{sat} by 30% compared to the bare silty sand. The change in the pore size distribution or porosity of the soil with different particle sizes of biochar was responsible for the variation in K_{sat} . Therefore, the results of the present study proved that the different particle sizes of biochar also alter the K_{sat} responses of compacted soil. Thus, the potential application of biochar-amended soil in bioengineered structures could consider the effect of biochar particle size for satisfying the design criteria on hydraulic conductivity. However, the present study considered silty sand and pure sand for testing

which are mainly limited to sand particles; thus, more studies are needed to consider wide range of soil particles, especially pure clayey soil. Furthermore, the hydraulic conductivity of soil changes with degree of compaction; therefore, the effect of biochar particle size on the hydraulic conductivity of soil needs to be further investigated under different degree of compaction density.

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