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Soil-water retention behavior of compacted biochar-amended clay: a novel landfill final cover material

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Abstract

Purpose Biochar has long been proposed for amending agricultural soils to increase soil-water retention capacity and therefore promotes crop growth. Recent studies revealed the potential use of biochar-amended soil in landfill final covers to promote methane oxidation and odor reduction. However, the effects of biochar application ratio, compaction water content (CWC), and degree of compaction (DOC) on soil-water retention characteristics of biochar-amended clay (BAC) at high soil suction (dry condition) are not well understood. The present study aims to overcome this knowledge gap.

Materials and methods Soil suction was induced using vapor equilibrium technique by a temperature- and humidity-controlled chamber, and the water desorption (drying) and adsorption (wetting) water retention curves (WRCs) of compacted pure kaolin clay and peanut shell BAC with different biochar application ratios (0, 5, and 20 %, *w*/*w*), DOCs (80, 90, and 100 %), and CWCs (30 and 35 %) were measured. The correlations between these factors and the gravimetric water content were analyzed by three-way ANOVA followed by the Tukey HSD test. The soil microstructure was studied by scanning electronic microscope with energy-dispersive X-ray spectroscopy.

Results and discussion Measured WRCs of BAC suggest that the soil-water retention capacity at high suction range (48.49–124.56 MPa) was in general increased, upon biochar application. The BAC compacted with CWC of 35 % at low (80 %) and high (100 %) DOCs for the 5 % BAC were increased by 7.30 and 9.77 %, when compared with clay, while the increases of 20 % BAC were 39.89 and 59.20 %, respectively. This is attributed to the embedded effects of clay particles in biochar pores, which reduce the total pore space of BAC. The soil-water retention capacity of BAC was also increased with CWC and decreased with DOC. The results of three-way ANOVA analysis show that the effects of DOC and biochar ratio on soil gravimetric water content was significant ($p < 0.05$) only at 48.49 MPa on drying path. For other induced suctions, only effects of CWC were significant ($p < 0.05$).

Conclusions Biochar application increases soil-water retention capacity of the BAC at high soil suction (48.49–124.56 MPa) (dry condition) at both low (80 %) and high DOC (100 %). The soil-water retention capacity of 20 % BAC was much higher than that of 5 % BAC. BAC is a potential alternative landfill final cover soil with a higher soil-water retention capacity to be used in dry areas or regions with a long period of evaporation event.

Keywords Biochar-amended clay · Compacted soil · Landfill final cover · Soil suction · Soil-water characteristic · Water retention capacity

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1 Introduction

Closed sanitary landfills are equipped with final cover system in order to reduce rain water infiltration into the waste layer which may lead to leachate generation and minimize landfill gas migration to the atmosphere. Compacted biochar-amended clay (BAC) has been used as an alternative landfill final cover soil, and its gas permeability was investigated in our early study (Wong et al. 2015). Compacted clay liner has been commonly used as a barrier layer in landfill final covers because of its low permeability (US EPA 1989). To further investigate the potential applications of compacted BAC, its soil-water retention characteristics were investigated in the present study.

Biochar is a carbon-rich black solid substance derived from biomass (such as peanut shell, wheat straw, and wood chips), by heating at low-oxygen environment (Lehmann and Joseph 2009). It has long been proposed as a soil amendment for improving soil fertility in agriculture and for removing environmental contaminants, such as heavy metals and polycyclic aromatic hydrocarbons in soil remediation (Lehmann and Joseph 2009; Ahmad et al. 2014; Mohan et al. 2014; Waqas et al. 2015). Several recent studies revealed the potential applications of biochar in landfill final cover soils, including removal of odorous compounds in landfill gas (i.e., hydrogen sulfide) by absorption (Shang et al. 2012; Shang et al. 2013; Xu et al. 2014) and reduction of methane emission by promoting microbial methane oxidation (Yu et al. 2013; Reddy et al. 2014; Sadasivam and Reddy 2015). Because of the highly porous and large specific surface area properties (Lehmann and Joseph 2009), biochar will alter the physical properties, such as pore size distribution, soil-water retention capacity, and hydraulic conductivity of the biochar-amended soils (Downie et al. 2009; Lei and Zhang 2013). More comprehensive studies on the biochar-amended soils are required before it can be used as an alternative landfill final cover material.

Previous studies revealed the effects of biochar on soil physiochemical properties and also hydraulic characteristics of biochar-amended soils (Chen et al. 2010; Major et al. 2010). It has been commonly reported that biochar application would increase the soil-water holding/retention capacity, which would vary with biochar feedstock, pyrolysis temperature, pyrolysis duration, and soil types (Lei and Zhang 2013). However, most studies regarding the soil-water retention curve (WRC) of biochar-amended soils were only focused on the low suction range (0 to 1.5 MPa) (Or et al. 2007; Hardie et al. 2014; Ojeda et al. 2015). More recently, Arthur et al. (2015) investigated the effects of biochar amendments on soil-water retention at a high suction range (10 to 480 MPa) in a non-compacted sandy loam soil, and results show that biochar application would increase soil-water holding capacity. It is well-understood that degree of compaction (i.e., soil density), which is used for determining the soil compaction, has profound effects on water retention behavior (Ng and Pang 2000; Ng and Menzies 2007). The effects of degree of compaction (DOC) on soil-water retention may be different between non-compacted and compacted soils since water retention depends on soil pore space and soil compaction could greatly reduce soil pore space among BAC aggregates (Coulon and Bruand 1989). Besides, soil aggregates are often formed when the soil is compacted at a certain compaction water contents (CWCs) and DOC, resulting in different soil-water retention characteristics (Wong et al. 2015). Effects of biochar application in different soil types such as sandy loam soil and clay on soil-water retention behavior are different, resulting in different WRCs (Ng and Menzies 2007). Interestingly, a recent field study on sandy soil suggested that biochar application will not always increase soil-water retention capacity of the amended soils, and no significant effects of biochar application on soil-water retention capacity were observed (Jeffery et al. 2015). It shows the knowledge gap in the effects of biochar application on soil-water retention characteristics, considering different biochar application ratio, DOCs, and (gravimetric) CWCs.

In the present study, soil-water retention behavior of BAC was investigated by determining drying (water desorption) and wetting (water adsorption) of WRCs. The total suction of soil specimens used in this study was controlled by the vapor equilibrium technique. Traditionally, different relative humidities (RHs) were generated by a series of saturated salt solution in a closed experimental environment (Delage et al. 1998). However, soil specimens would be easily disturbed during drying and wetting cycle, as salt solutions used are temperature-sensitive. In addition, a long period of vapor equilibrium time is needed (Likos and Lu 2003; Leung and Ng 2010). Therefore, the RHs adopted in this study was controlled by a well-calibrated automatic humidity chamber, which can shorten the experimental period, and handle a large amount of samples at a time, with more accurate temperature control (Likos and Lu 2003). This study aims to measure the WRCs of the compacted BAC and kaolin clay under a high suction range (48.49–124.56 MPa), with different application ratios of biochar (0, 5, and 20 %, *w/w*), DOCs (80, 90, and 100 %), and CWCs (30 and 35 %). The BAC microstructures were analyzed by scanning electron microscopy (SEM) (JEOL JSM 6390) with energy dispersive X-ray spectroscopy (EDX) to investigate underlying mechanisms of the effects of biochar application on WRCs, at different conditions (i.e., biochar content, DOC, and CWC). The surface hydrophobicity of the clay, biochar, and BAC was also determined by the water drop penetration time (WDPT) test.

2 Materials and methods

2.1 Preparation of biochar

Peanut shell biochar used in this study was produced by slow pyrolysis of heating peanut shell biomass at 5–10 °C min^{-1} until 500 °C and retained for 30–40 min. Water cooling system and continuous nitrogen gas supply were adopted during the cooling period, in order to maintain an inert environment. Biochar was passed through a 425-μm sieve to homogenize the biochar used before mixing with kaolin clay (Wong et al. 2015).

2.2 Characterization of materials and preparation of BAC specimens

The moisture content (%), pH, organic matter (%), electrical conductivity (EC) (ds m^{-1}), ash content (%), and particle size distribution (%) of the kaolin clay, 5-mm-sieved and 425-μm-sieved peanut shell biochar used were analyzed and reported in Wong et al. (2015) (A1, Electronic Supplementary Material). In brief, moisture content was determined by oven-drying; organic matter and ash content were analyzed by loss on ignition; pH and EC were measured by pH and EC meters, respectively; and the particle size distribution was analyzed in accordance with the ASTM standard D422 (ASTM 2007). All soil physiochemical properties were analyzed with three replicates ($n = 3$) (except the particle size distribution). The surface hydrophobicity of clay, biochar, and biochar-amended clay (5 and 20 %) was measured by the WDPT test (Kinney et al. 2012; Letey 1969). The air-dried soil was placed into a petri dish and a smooth soil surface was made. A 50-μl deionized water droplet was applied onto the soil surface using a pipette, and the penetration time of the water droplet was recorded by a stop watch. The soil surface was covered by a transparent plastic cover after the release of the water droplets to minimize evaporation. The WDPT of each soil was conducted with ten replicates ($n = 10$). The hydrophobicity of the soil and the biochar-amended soils was classified into seven categories (A2, Electronic Supplementary Material) according to the WDPT, ranging from "very hydrophilic" (WDPT <5 s) to "extremely hydrophobic" (WDPT >5 h) (Doerr 1998).

BAC specimens were prepared by mixing the air-dried kaolin clay and peanut shell biochar, containing three different proportions of biochar (0, 5, and 20 %, *w/w*). The biochar was air-dried for 7 days and sieved through a 425-μm sieve before use. The dry BAC was mixed with deionized water to different targeted CWCs (30 and 35 %), and then, the wet soil was gently sieved through a 2-mm sieve to break down clods which can significantly affect soil hydraulic properties (Benson and Daniel 1990). The sieved soils were stored in an air-tight plastic bag for 2 days for water equilibration. The equilibrated soils were compacted into a specimen of 70 mm in diameter and 10 mm in height with three different proportions of DOCs (80, 90, and 100 %). There were three replicates ($n = 3$) for all BAC specimens with different proportions of biochar, CWCs, and DOCs produced.

2.3 Establishment of the WRCs

Vapor equilibrium technique (VET) was adopted to induce soil total suction by controlling the temperature and relative humidity surrounding the soil specimens in a closed environment (humidity chamber) (Ng et al. 2015). The relationship between suction and soil moisture content can be described by the WRC (Ng and Menzies 2007), which can be seen as a measure of water-holding capacity at a given soil suction. Soil suction (ψ) is a key parameter to illustrate hydraulic behavior of unsaturated soils controlling soil-water retention capacity (Leung and Ng 2010). Soil suction (ψ), or total soil suction (ψ_T), is composed of matric suction (ψ_M) and osmotic suction (ψ_O). Their relationships can be expressed by the following equation:

$$\psi_T = \psi_M + \psi_O \tag{1}$$

The relationship between soil total suction and the relative humidity (RH) (%) can be illustrated by the Kelvin's equation (Edlefsen and Anderson 1943; Richards 1965):

$$\psi_T = -\frac{RT}{\upsilon_{wo}\varpi_v}\ln(RH) \tag{2}$$

where ψ_T is the soil total suction (kPa), R is the universal gas constant (8.31432 J Mol^{-1} K^{-1}), T is the absolute temperature (K), υ_{wo} is the specific volume of water (0.001 m^3 kg^{-1}), and ϖ_v is the molecular mass of water vapor (18.016 kg kmol^{-1}).

The compacted soil specimens were put into a petri dish (with cover removed) and then into an automatic humidity control chamber (MHU-150 L). The chamber was well calibrated by a humidity-temperature probe before use. The accuracy of the VET adopted in this study depended on RH and temperature control of the humidity chamber. The relative humidity and temperature inside the chamber were automatically controlled with an error of 2.5 and 0.5 %, respectively. The humidity chamber was calibrated and set at 22 °C since it is a standard room temperature for soil testing. The error in the total suction measurement caused by the 0.5 °C fluctuation of the humidity chamber was less than 2 kPa for the induced total suction larger than 30 MPa (Agus and Schanz 2007). The temperature within the chamber was set at 22 ± 0.5 °C throughout the experiment and RH set according to the designated total suction to be induced. The soil specimens were subjected to drying (water desorption) path followed by wetting (water adsorption) path. For soil drying path, the RH was set at 70, 60, 50, and 40 %. According to Eq. (2), the corresponding induced total suctions were 48.49, 69.44, 94.23, and 124.56 MPa, respectively. For soil wetting path, the RH was set at 40, 50, 60, and 70 %, and the corresponding induced soil total suctions were the same as those mentioned in drying path. The weight of the soil specimens were measured at every 12 h using a 0.001-g resolution electronic balance. An equilibrium of water vapor between the soil specimen and the surrounding environment in the chamber was assumed, when the weight change of specimen was less than 0.05 g within 12 h (Hoffmann et al. 2005). At the beginning of drying and wetting cycle, the RH of the chamber was set at 70 %, until the weight change of all soil specimens were less than 0.05 g over 12 h. After that, the RH of the chamber was subjected to 10 % stepped decrement or 10 % of stepped increment during drying and wetting paths, respectively, when the equilibrium was reached. After 1 cycle of drying and wetting was completed, the soil specimens were oven-dried at 105 °C for 24 h to determine the soil dry weight. The gravimetric water contents at each RH (40, 50, 60, and 70 %) during drying and wetting period were then obtained according to the measured dry soil weight.

The averaged gravimetric water content ($n = 3$) at different induced total suctions (ψ_T) were calculated based on the dry soil weight and determined by following equation:

$$GWC = \frac{M_{water}}{M_{soil}} \tag{3}$$

where M_{water} is the mass of water and M_{soil} is the mass of dry soil.

2.4 Statistical analyses

Three-way analysis of variance (ANOVA) (at a probability level of 5 %) was used to analyze the gravimetric water content of soil specimens with the following factors: biochar ratios (0, 5, and 20 % by weight), compaction water contents (30 and 35 %), and degree of compactions (80, 90, and 100 %) at all induced suctions on both drying and wetting paths. Effects of biochar ratios and degree of compactions on gravimetric water content of biochar-amended clay were further analyzed by Tukey HSD test. Percentage change in gravimetric water content of the biochar-amended clay was also calculated by comparing with clay for biochar ratio and 80 % for degree of compaction. All statistical analyses were conducted using SPSS (version 17.0).

2.5 Microstructure analyses by SEM with EDX

The SEM (JEOL JSM 6390) with energy-dispersive EDX was used to interpret the WRCs by analyzing the microstructure of the BAC. After measuring the WRCs, cubic soil samples with the size of about 0.5 cm^3 were removed from each BAC specimen (with three replicates). The samples were immersed in liquid nitrogen (–195 °C) for 5 min and the frozen samples were freeze-dried using a freeze drier (Gallé 2001; ASTM 2004). The processed specimens were coated with a thin gold layer before SEM and EDX analyses.

3 Results and discussion

3.1 WRCs of BAC with different degrees of compaction and biochar contents

Figure 1 shows the WRCs of the BAC (5 and 20 %, *w*/*w*) and kaolin clay with 35 % compaction water content at low (80 %) (Fig. 1a) and high (100 %) (Fig. 1b) DOCs. Discussion would only focus on the two compaction extremes investigated (i.e., 80 and 100 %). WRC results of the BAC with 90 % DOC were provided in the Electronic Supplementary Material (A3). Within the studied total suction range (48.49 to 124.56 MPa), the soil-water content of all soil specimens decreased with increasing total suction for both DOCs on the drying and wetting paths. Furthermore, soil water retention capacity increases with increasing biochar content for both DOCs. However, the increment of soil water retention capacity at different DOCs was observed. At low DOC (80 %), almost similar water retention capacity of BAC was recognized when biochar content increases from 0 to 5 %. However, when biochar content increases from 5 to 20 %, increase in water retention capacity of BAC was observed. Comparatively, at high DOC (100 %) and low biochar content (5 %), larger increment of water retention capacity of BAC was observed as compared to that of kaolin clay at low DOC (80 %) and low biochar content (5 %). However, there is only slight increase when biochar content was further increased to 20 %. This is because the mechanisms governing the biochar effects on the water retention capacity of BAC at low DOC (80 %) with 5 % biochar and high DOC (100 %) with 20 % biochar were different.

At low DOC (80 %), 5 % of biochar was not enough to fill up all macro-pores inside clay aggregates. Therefore, less water can be retained (i.e., low water retention capacity). However, more pores of clay aggregates was filled when 20 % biochar was added (Figs. 3a, 4a). Thus, at the given suction, more water was retained at low DOC (80 %) and high biochar content (i.e., 20 %) (Fig. 6a). Conversely, when DOC was increased to 100 %, both pores in biochar and clay were suppressed under high degree of compaction, resulting in a

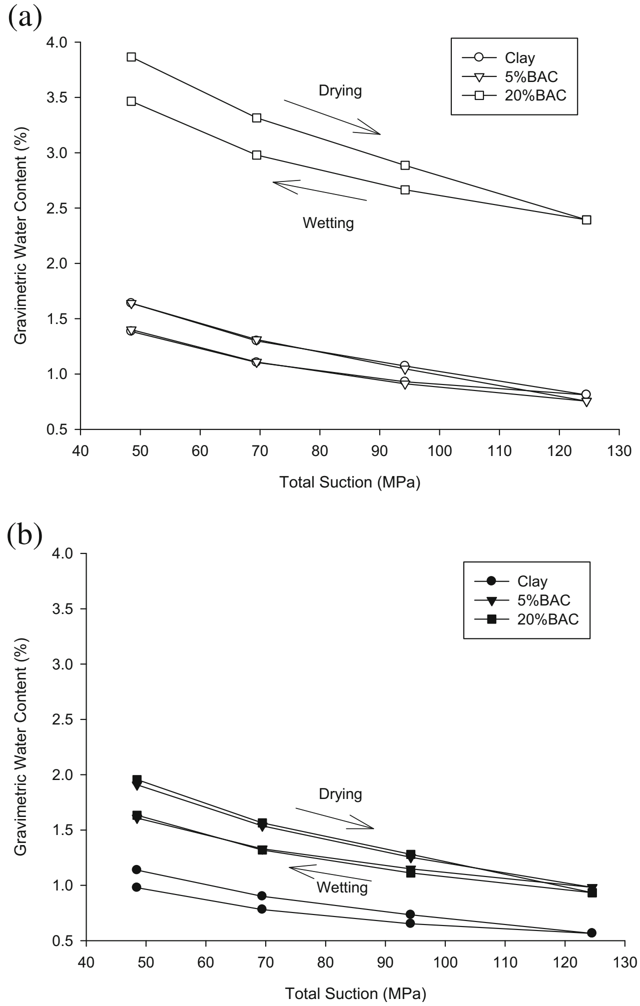

Fig. 1 Drying and wetting soil-water retention curves (WRCs) of clay and biochar-amended clay (BAC) with 35 % compaction water content (CWC) at **a** 80 % and **b** 100 % degree of compaction (DOC)

similar increment of water retention capacity for 5 and 20 % biochar content as compared with kaolin clay (Fig. 6b).

Results of the three-way ANOVA analysis show that the effects of DOC on gravimetric water content of clay and biochar-amended clay were significant ($p < 0.05$) only at 48.49 MPa on drying path ($F = 161.878$, $p = 0.000$) (Table 1). The effects of biochar content on gravimetric water content (GWC) were also significant ($p < 0.05$) only at 48.49 MPa on drying ($F = 29.524$, $p = 0.000$) path ($F = 23.967$, $p = 0.000$). The effects of compaction water content on GWC were significant at all induced suction except for 48.49 MPa on drying path. However, the combined effects of DOC and biochar content were insignificant ($p > 0.05$) at all induced suctions. Mean gravimetric water content of biochar-amended clay samples with different biochar ratios (BR) and DOCs at suction 48.49 MPa were further analyzed by Tukey HSD test and summarized in Table 2. It should be noticed that the factors BR and DOC were considered separately in the Tukey HSD test, and the effects of compaction water content was not conducted as there are only two groups ($n = 2$, 30 and 35 %) in CWC. Tukey HSD test results show that adding 5 % biochar would only slightly increase GWC of the BAC by 0.36 %, while adding 20 % of biochar would greatly increase the GWC by 8.81 %. The GWC of the BAC was decreased by 11.11 and 17.69 % when the DOC was increased from 80 to 90 and 100 %, respectively. Fig. 2 shows the effects of biochar content (0, 5, and 20 %) and degree of compaction (80, 90, and 100 %) on the soil gravimetric water content (%) at 48.49 MPa (drying path).

In addition, it should be noted that hysteresis between the water desorption (drying) and adsorption (wetting) loops were observed for all soil specimens, with more soil-water retained during drying path when compared with the wetting path. It was due to the non-uniform pore size distribution in soils, especially for soils amended with porous medium (i.e., biochar).

These results imply that biochar application would increase soil-water retention capacity of the amended soils, regardless

Table 1 *F* and *P* values of the three-way ANOVA for the effects of biochar ratio (BR), compaction water content (CWC), degree of compaction (DOC), and their interactions on the gravimetric water content of clay and biochar-amended clay at different suctions

	Drying path								Wetting path					
Induced suction (MPa)	48.49		69.44		94.23		124.56		94.23		69.44		48.49	
Factor(s)	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
BR	29.524	**0.000**	9.188	22.629	7.054	17.889	4.776	12.252	6.029	15.125	7.560	18.962	9.823	23.967
CWC	0.001	0.974	0.001	**0.003**	0.001	**0.002**	0.002	**0.004**	0.003	**0.008**	0.013	**0.034**	0.100	**0.024**
DOC	161.878	**0.000**	65.861	162.197	66.135	167.714	65.615	168.317	65.173	163.505	65.196	163.534	65.435	159.655
BR*CWC	2.361	0.111	0.915	2.254	0.918	2.329	0.857	2.198	0.887	2.226	0.872	2.187	0.868	2.118
BR*DOC	0.351	0.842	0.142	0.350	0.138	0.351	0.164	0.420	0.712	0.431	0.167	0.419	0.170	0.416
CWC*DOC	0.634	0.537	0.265	0.652	0.273	0.693	0.296	0.760	0.295	0.741	0.298	0.747	0.316	0.770
BR*CWC*DOC	1.508	0.223	0.573	1.410	0.568	1.440	0.571	1.464	0.566	1.421	0.561	1.406	0.581	1.417

Values in bold represent statistical significance at probability level 0.05

Table 2 Tukey analyses on gravimetric water content of clay and biochar-amended clay with different biochar ratios (BR) and degree of compaction (DOC) at 48.49 MPa (drying path)

Biochar ratio (BR)	
0 %	19.30
5 %	19.37 (0.36 %)
20 %	21.00 (8.81 %)
Degree of compaction (DOC)	
80 %	21.88
90 %	19.45 (−11.11 %)
100 %	17.93 (−17.69 %)

Values in bracket are percentage difference compared with 0 % biochar for BR and 80 % for DOC

of the biochar application rate at high DOC (100 %), but only with higher application rates at low DOC (80 %). It shows that the DOC would affect the soil-water holding capacity of the BAC. The beneficial effects of biochar amendment on soil-water retention of agricultural soils were reported by previous studies (Abel et al. 2013; Herath et al. 2013; Sun and Lu 2014). This is due to the fact that biochar possesses inherently high porosity and specific surface area (Lehmann and Joseph 2009; Downie et al. 2009; Lei and Zhang 2013); more water was adsorbed in the small pores of biochar and clay (Verheijen et al. 2010). According to a previous study, the Brunauer-Emmett-Teller (BET) N_2 surface area of the biochar used in this study (peanut shell biochar) was 43.5 $m^2\ g^{-1}$ (Zhao et al. 2013).

Figure 3a shows the micro-pore distributed on the surface of peanut shell biochar by SEM. The SEM-EDX element mapping (Fig. 4a–f) of the 20 % BAC specimen further proved that biochar pores were partially filled up by clay particles, showing the elemental distribution of the BAC with porous biochar particles, and clay was entered in those pores. The distribution of different elements shown in Fig. 4a was visualized by dots with different colors (Fig. 4a–f). The presence of carbon (C) (Fig. 4b) revealed the existence of biochar, while the presence of aluminum (Al), silicon (Si), and oxygen (O) indicated the existence of kaolin clay ($Al_2Si_2O_5(OH)_4$). There was a high abundance of Al, Si, and O surrounded by C, showing some clay particles were inside the biochar pores (Figs. 3a, 4a).

Arthur et al. (2015) reported the WRCs of sandy loam amended with 50 mg^{-1}ha^{-1} biochar (birch wood, pyrolysis temperature, 500 °C) in high suction range and showed that the GWCs of sandy loam and biochar-amended sandy loam at 48.49 MPa on the drying (water desorption) path were about 1.45 and 1.90 %, respectively. However, the present study showed that the GWCs of clay and 5 % biochar-amended clay with 80 % DOC and 30 % CWC were 1.78 % and 1.91 %, respectively. The discrepancy was due to the difference in pore size between sandy loam and clay, with sandy loam having a larger pore size than that of clay. Therefore, the possibility of sandy loam soil particles embedded in biochar pores was

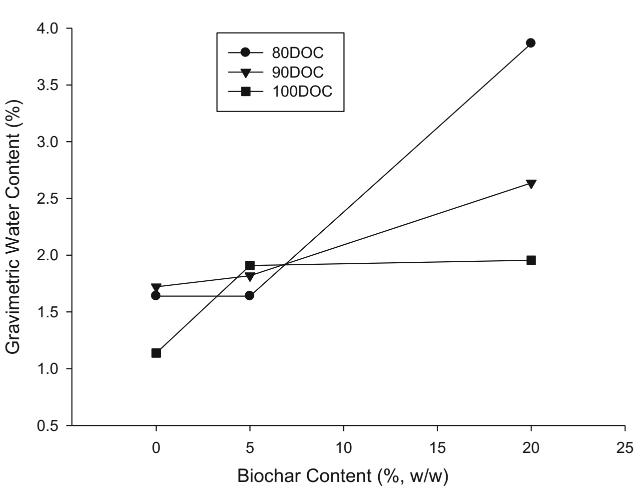

Fig. 2 Gravimetric water content (%) of biochar-amended clay (BAC) with different biochar content (%, *w/w*) and degree of compaction (DOC) with 35 % compaction water content (CWC) at 48.49 MPa (drying path)

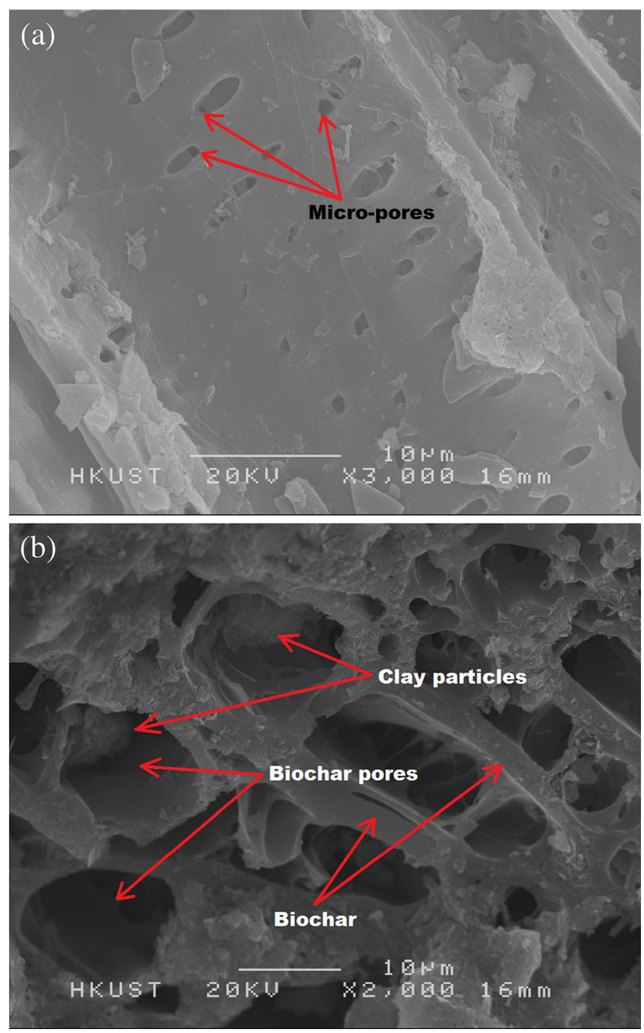

Fig. 3 **a** SEM image (×3000) shows the peanutshell biochar with micro-pores distributed on its surface and **b** SEM image (×2000) illustrates biochar pores partially filled with clay

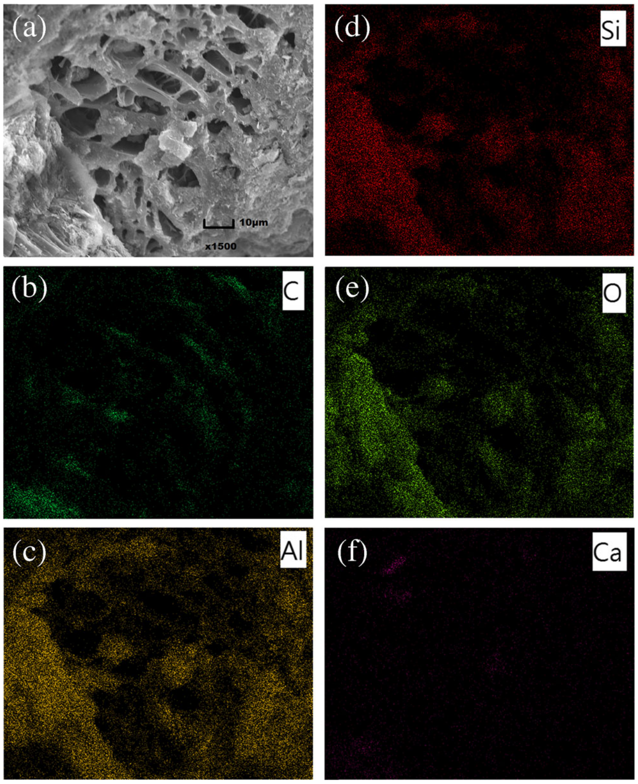

Fig. 4 **a** SEM image (×1500) of the 20 % biochar-amended clay (BAC) revealed that the biochar pores were partially filled with clay and **b–f** SEM-EDX elemental mapping analysis of the area in Fig. 4a. *C* carbon, *Al* aluminum, *Si* silicon, *O* oxygen, *Ca* calcium

expected to be lower when compared with clay. Thereby, less water can be retained by biochar amended sandy loam soil upon drying, when compared with the BAC investigated in this study.

3.2 Effects of CWCs on water retention curves

Figure 5 shows the WRCs of clay and BACs at 80 % (Fig. 5a) and 100 % (Fig. 5b) DOC with 30 % CWC for 69.44, 94.23, and 124,56 MPa suctions for both drying and wetting paths; 48.49 MPa suction is not included because it was not statistically significant ($p > 0.05$) (Table 1). The decreasing trend of GWC of soil specimens towards high suction end was observed as in the previous results (Fig. 1). The GWCs of clay, 5 % BAC, and 20 % BAC with 80 % DOC at the soil suction of 69.44 MPa on the drying path were 1.40, 1.54, and 1.95 %, respectively. When the DOC was increased to 100 %, the GWCs were 1.39, 1.54, and 2.23, respectively. Similar to the WRC results presented previously, biochar application would increase the soil-water holding capacity of the compacted clay. At a single suction value (48.49 MPa), adding 5 % of biochar at low DOC (80 %) did not increase GWC while adding 20 % biochar increased the GWC by 135.80 %, when compared with kaolin clay (0 % biochar). At high DOC (100 %), adding 5 and 20 % biochar increased the GWC by 67.80 and 71.86 %. This implies that, with 35 % CWC, adding 5 % biochar would increase soil-water retention capacity only at high DOC.

When the CWC was reduced to 30 %, at low DOC, the increases in GWC of 5 % BAC with 30 and 35 % CWC were 7.30 and 0 %, respectively. However, upon 20 % biochar addition, the increases of GWC were 39.89 and 135.98 %, respectively. While at high DOC, the increases of 5 % BAC with 30 and 35 % CWC were 9.77 and 67.54 %, respectively. When the biochar application rate was 20 %, the increases in GWC of 5 % BAC with 30 and 35 % CWC were 59.20 and 71.93 %, respectively. These results imply that the soil-water holding capacity of the compacted BAC was not only affected by the contents of biochar and DOC but also the CWC. It was further proven by the results of the three-way ANOVA. Results show that the effects of CWC on gravimetric water content of clay and biochar-amended clay were significant ($p < 0.05$) at almost all induced suctions (except at 48.49 MPa on drying path).

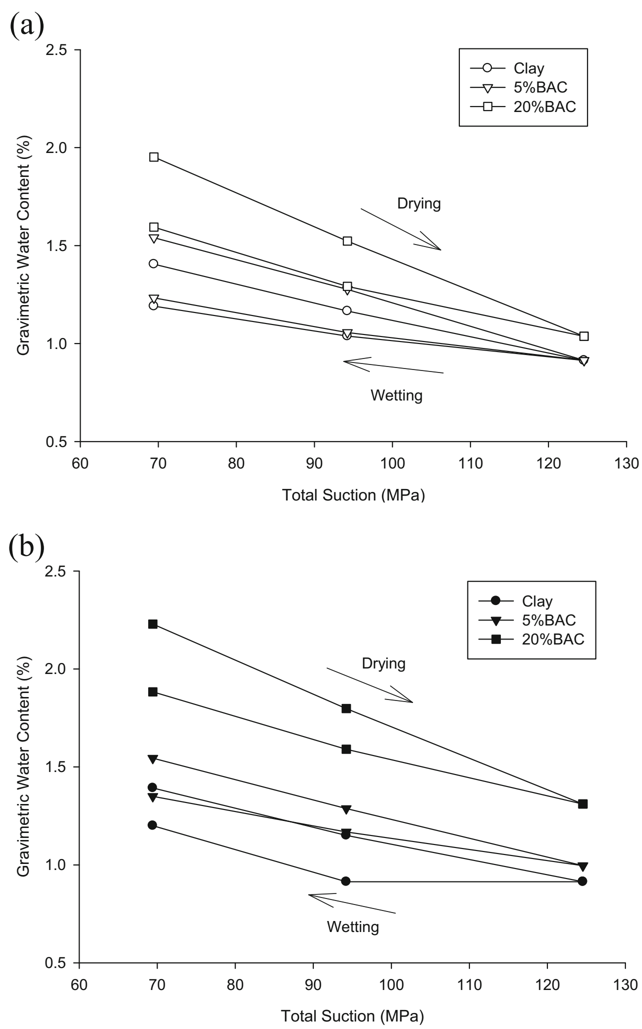

Fig. 5 Drying and wetting soil-water retention curves (WRCs) of clay and biochar-amended clay (BAC) with 30 % compaction water content (CWC) at **a** 80 % and **b** 100 % degree of compaction (DOC)

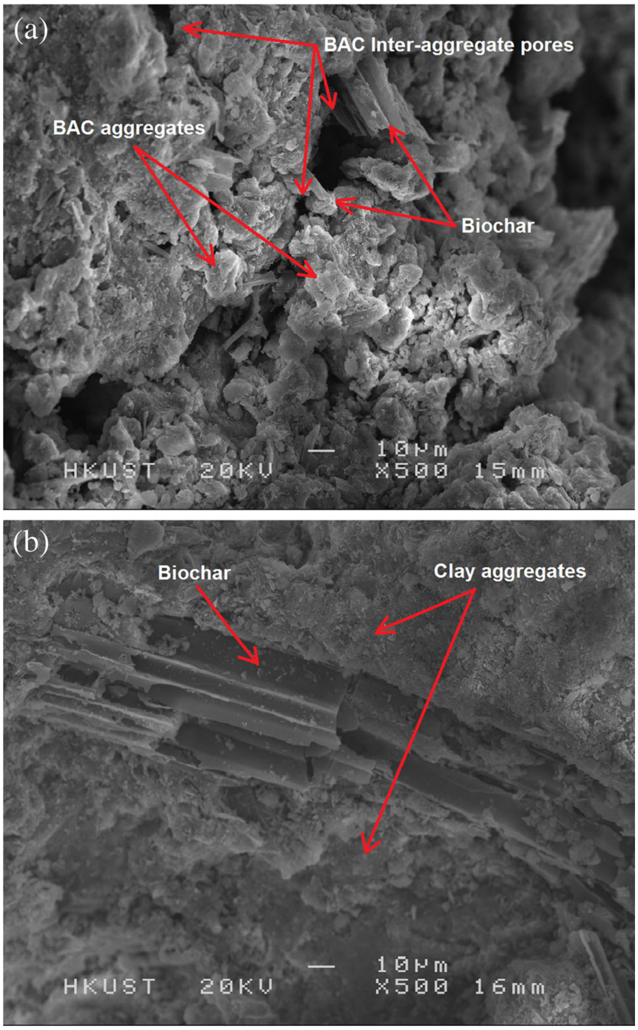

Fig. 6 SEM image (×500) of the 20 % biochar-amended clay (BAC) sample with **a** 80 % and **b** 100 % degree of compaction (DOC)

Clay aggregates were formed at low DOC (80 %), the inter-pores between BAC aggregates were filled by biochar particles and water was stored in the small pores within these biochar particles. As shown in Fig. 6a, some particles were embedded inside the inter-pores between BAC aggregates. This observation further confirms the beneficial effects of biochar application to soil for clogging soil pores with disintegrated biochar materials (Verheijen et al. 2010). The aggregation effects were reduced, according to the increase in DOC (Fig. 6b). It has been noted that water which was originally trapped inside the pores of inter-aggregate of BAC and the pores of biochar at the time of compaction was difficult to escape upon drying (Delage et al. 1996).

4 Conclusions

Soil-water retention curves of BAC with different degrees of compaction (80 and 100 %), compaction water contents (30 and 35 %), and biochar contents (0, 5, and 20 %) were obtained at high suction range (48.49–124.56 MPa) by vapor equilibrium technique. Water retention curves suggest that the soil-water retention capacity of the BAC at high suction range (48.49–124.56 MPa) were in general higher, when compared with pure clay. Upon 20 % (*w*/*w*) biochar application, the GWCs of BAC at low (80 %) and high (100 %) DOC were increased by 39.89 and 59.20 %, respectively, when compared with clay. SEM images suggested that the effects of biochar application on BAC soil-water retention capacity was mainly due to the embedded effects of clay particles in biochar pores at high DOC (100 %) and biochar particles in clay pores at low DOC (80 %) and thereby reduce the pore volume. The soil-water retention capacity of the BAC was also in general, increased with the CWC. When the CWC was 35 %, the increases in CWC of the 20 % BAC at low and high DOC were 135.97 and 71.93 %, respectively, when compared with clay. This is because BAC with low DOC has higher water retention capacity due to the biochar particle clogging effect in inter-pores between BAC aggregates. Results of the three-way ANOVA show that the effects of both DOC and biochar content on gravimetric water content of clay and biochar-amended clay were significant ($p < 0.05$) only at 48.49 MPa on drying path, and CWC was significant ($p < 0.05$) for other induced suctions. Results from the present study implies that biochar would retain more water at high soil suction range (e.g., during dry period or in arid areas), when compared with clay. The increase in soil-water retention of the BAC (20 % biochar) is still promising (71.93 %) when the DOC reaches 100 %, where high DOC is a criteria of landfill cover soil. Therefore, the BAC can be a potential alternative landfill final cover soil and even retained more water when compared with clay.

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