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Effects of biochar on hydraulic conductivity of compacted kaolin clay ☆

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ABSTRACT

Compacted clay is widely used as capillary barriers in landfill final cover system. Recently, biochar amended clay (BAC) has been proposed as a sustainable alternative cover material. However, the effects of biochar on saturated hydraulic conductivity (k_{sat}) of clay with high degree of compaction is not yet understood. The present study aims to investigate the effects of biochar on k_{sat} of compacted kaolin clay. Soil specimens were prepared by amending kaolin clay with biochar derived from peanut-shell at 0, 5 and 20% (w/w). The k_{sat} of soil specimens was measured using a flexible water permeameter. The effects of biochar on the microstructure of the compacted clay was also investigated using MIP. Adding 5% and 20% of biochar increased the k_{sat} of compacted kaolin clay from 1.2×10^{-9} to 2.1×10^{-9} and 1.3×10^{-8} ms^{-1}, respectively. The increase in k_{sat} of clay was due to the shift in pore size distribution of compacted biochar-amended clay (BAC). MIP results revealed that adding 20% of biochar shifted the dominant pore diameter of clay from 0.01–0.1 μm (meso– and macropores) to 0.1–4 μm (macropores). Results reported in this communication revealed that biochar application increased the k_{sat} of compacted clay, and the increment was positively correlated to the biochar percentage.

1. Introduction

Compacted clay has been widely adopted as capillary barriers in landfill final cover system to reduce rainwater infiltration into the waste layer, and landfill gas migration into the atmosphere. However, desiccation–induced cracks and the subsequent leakage through the liner in cool and wet climate regions were often reported (Albright et al., 2006; Melchior, 1997). To minimise the crack formation in compacted clay, applications of different amendments, such as nanoparticles, cement, peat ash and silica sand, were proposed (Mousavi and Wong, 2015; Ng and Coo, 2016). Recently, biochar has been proposed as a sustainable and environmentally-friendly landfill final cover amendment (Wong et al., 2016, 2017). Biochar is a carbon-rich material derived from biomass by pyrolysis (Lehmann and Joseph, 2009), a physiochemical process under oxygen deficient and high temperature (200–700 °C) conditions.

Biochar addition alters the physicochemical properties of amended soil (Lehmann and Joseph, 2009; Wong et al., 2016; Wong et al., 2017) and the subsequence hydraulic properties, for instance, the water permeability that related to the rainwater infiltration through the cover system. However, the knowledge of the effects of biochar on saturated hydraulic conductivity (water permeability) (K_{sat}) is not yet conclusive. It has been shown that biochar may increase (Asai et al., 2009; Lei and Zhang, 2013; Oguntunde et al., 2008), decrease (Devereux et al., 2012; Ibrahim et al., 2013), or have no significant effects (Laird et al., 2010) on the soil hydraulic conductivity (K). Recently, Barnes et al. (2014) reported that biochar decreased K of sandy soil by 92% but increased K more than 300% in clay soil. However, the bulk density (commonly expressed as the degree of compaction in geotechnical engineering) of different soil types in these tests were not the same, meaning the results are not really comparable. Previous studies on hydraulic conductivity have been reported by agricultural scientists and soil scientists, on soils with a low degree of compaction to facilitate crop growth (Asai

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et al., 2009; Barnes et al., 2014; Devereux et al., 2012; Ibrahim et al., 2013; Laird et al., 2010; Lei and Zhang, 2013). This contrast with engineering practice (e.g. slopes of restored landfills) in which soils are frequently highly compacted to increase slope stability. The effects of biochar on saturated hydraulic conductivity of compacted biochar–amended soil are still not well understood. One of the factors that biochar application alters soil hydraulic conductivity is by changing the soil pore size distribution. However, studies on the effects of biochar on porosity of biochar amended soil with relatively high degree of compaction is scarce (Wong, 2017).

In field, soil water content varies with different weather conditions, such as rainfall. The objective of the present study is to investigate the effects of biochar on the saturated hydraulic conductivity of compacted clay, which is the most extreme and critical condition. Kaolin clay was amended with 0 (control), 5, and 20% of peanut-shell biochar and compacted at 90% degree of compaction (DOC) (Wong, 2017). In engineering practice, the relationship between dry density and gravimetric water content of a soil was commonly reported as compaction curve. Designated DOC can therefore be calculated based on the maximum dry density (MDD) of the soil. For instance, 90% DOC is the value of MDD times 0.9 (ASTM D698-12e2, 2012). The saturated hydraulic conductivity of compacted specimens was determined by a flexible wall permeameter. The effects of biochar on the pore size distribution of the compacted clay was further measured using Mercury Intrusion Porosimetry (MIP).

2. Materials and methods

2.1. Testing materials

Kaolin clay was used in this study, which is classified as CH by the Unified Soil Classification System (USCS). The basic properties of the clay, such as specific gravity and index properties were reported in Ng et al. (2016). Biochar used in this study was derived from peanut-shell, produced by pyrolysis at 500 °C for 30 min. The impurities and incompletely pyrolyzed biomass were removed by sieving through a 5-mm sieve. The biochar was further sieved through a 425-μm sieve to obtain a more homogeneous specimen, thus preventing any possible preferential flow of water during the permeability test. The physicochemical properties of the biochar, such as pH, organic matter and particle size distribution, were reported in Wong et al. (2016).

2.2. Preparation of soil specimen

Biochar-amended clay (BAC) was prepared by mixing 0 (control), 5 and 20% (by dry weight) of air-dried peanut-shell biochar with kaolin clay. The BACs were added with de-ionized water to optimum gravimetric water content. The optimum gravimetric water content of clay, 5% BAC and 20% BAC were 36, 39, and 41%, respectively (Wong, 2017). The wet BACs were then sieved through a 2 mm sieve to break down clay clods that can significantly affect soil hydraulic properties (Benson and Daniel, 1990). Sieved BACs were stored in zip-lock bag for 2 days for moisture equalization (Ng and Yung, 2008). The BACs were compacted into soil column with 70 mm in diameter and height at 90% degree of compaction. The compacted columns were covered with an elastic membrane (flexible wall) and located in the flexible wall water permeameter (Ng and Coo, 2016).

2.3. Measurement of hydraulic conductivity

The saturated hydraulic conductivities (k_{sat}) of BAC were determined in accordance with the "Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter" (ASTM D5084, 2016). Constant pressure at the top and base of the soil specimen was set for back-saturation, the pore-pressure was measured and monitored using apore-pressure transducer. The transducer was attached to the drainage valves (top and bottom) of the permeameter. The soil specimen was subjected to a bottom-up saturation on average 12 days. A gradual back-saturation pressure was applied up to 200 kPa for 4 days. The confining pressure was set at 20 kPa. The waterflow across the specimen was controlled by pressure controller and monitored using the burettes (accuracy: 0.02 mL) of permeameter (Ng and Coo, 2016). According to ASTM D5084 (2016), the hydraulic conductivity was calculated based on the last three measurements with variation less than 10%. The hydraulic conductivity (k) of compacted soil specimen was calculated using the following equation:

$$\mathrm{k} = \frac{\Delta Q \cdot L}{A \cdot \Delta h \cdot \Delta t}$$

where k is the hydraulic conductivity (m/s), ΔQ is the quantity of flow for a given time interval Δt (m^3), L is the length of the specimen (m), A is the cross-sectional area of specimen (m^2), Δh is the average head loss across the specimen $((\Delta h_1 + \Delta h_2)/2)$ (mass of water), Δt is the interval of time (s), over which the flow ΔQ occurs $(t_2 - t_1)$, t_1 is the time at start of permeation trial, t_2 is the time at end of permeation trial, Δh_1 is the head loss across the specimen at t_1 (mass of water), Δh_2 is the head loss across the specimen at t_2 (mass of water).

2.4. Microstructure analyses

The pore size distribution of biochar-amended clay (20% w/w) was determined by a mercury intrusion porosimeter (Quantachrome, PoreMaster 60 GT), which is based on the theory of intruding a non–wetting fluid (mercury in MIP) into the voids of porous materials with open and interconnected structures under pressure (Ng and Coo, 2016). Compacted clay amended with 20% biochar was freeze–dried by immersing into liquid nitrogen (−195 °C) for 5 min (Gallé, 2001), and freeze–dried in a freeze dryer (Super Modulyo, Thermo Electron, MA, USA) at −80 °C for one week before the measurement.

3. Results and discussion

3.1. The effects of biochar on saturated hydraulic conductivity (k_{sat}) of compacted clay

Fig. 1 shows the effects of biochar on saturated hydraulic conductivity (k_{sat}) of compacted clay. The k_{sat} of kaolin clay was 1.2×10^{-9} m s^{-1}, adding 5 and 20% of biochar increased the k_{sat} to 2.1×10^{-9} and 1.3×10^{-8}, respectively. There was a linear relationship between the biochar application rate and k_{sat}, which shows the consistency and accuracy of measured experimental results. The experimental result implies that biochar application increased the k_{sat} of compacted clay. The increase in k_{sat} upon biochar addition was caused by the increase in pore size of the BAC. Fig. 2 shows the Cumulative Intrusion Pore Volume (CIV) of compacted kaolin clay and 20% biochar–amended clay. CIV refers to the total volume of mercury that intruded into the pores of the specimen with increasing pressure (Penumadu and Dean, 2000). In this study, micropores, mesopores, and macropores are defined as pores with sizes <10, 10–50, and >50 nm, accordingly (Moon et al., 2006). In general, the pore diameter of kaolin clay amended with 20% (w/w) 425 μm–sieved biochar was larger, when compared with kaolin

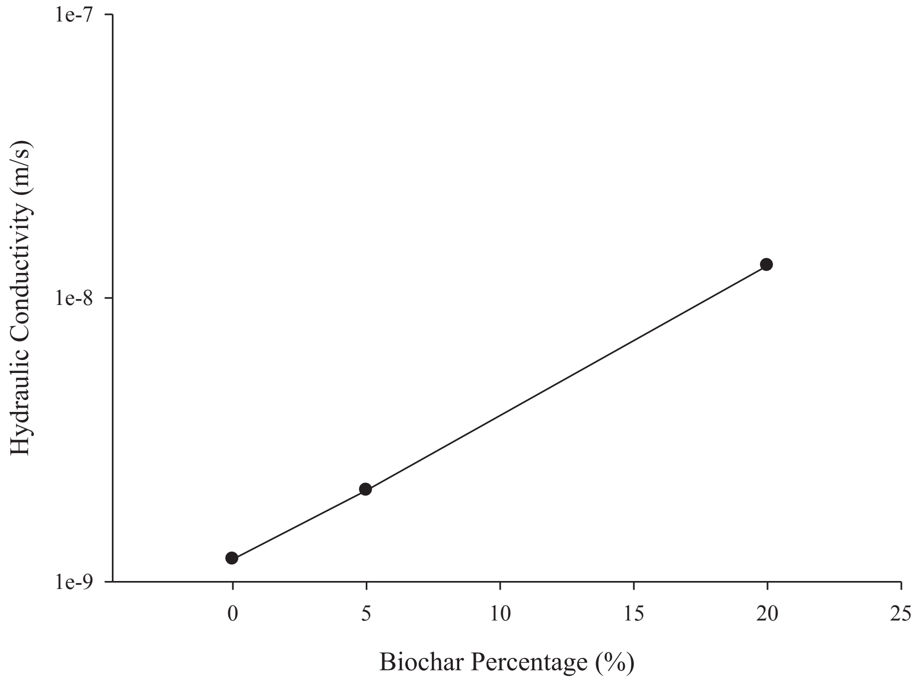

Fig. 1. The effects of biochar on hydraulic conductivity of compacted clay.

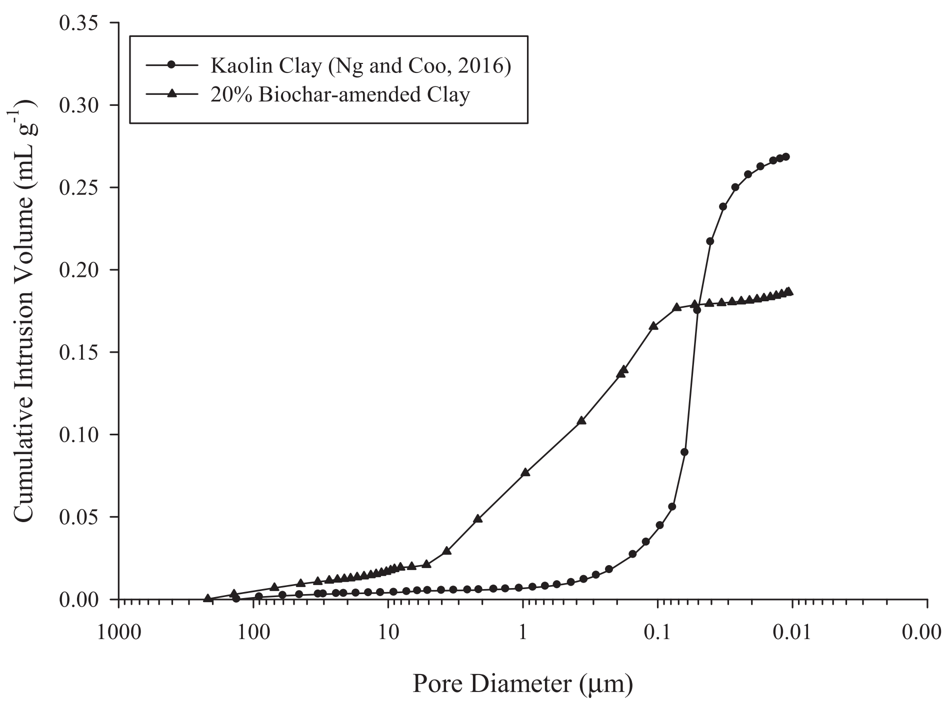

Fig. 2. Cumulative intrusion volume of kaolin clay and 20% biochar–amended clay.

clay. The dominant pore diameter of BAC was between 0.1 and 4 μm (macropores), while the dominant pore diameter of clay was between 0.01 and 0.1 μm (meso– and macropores). It implies that biochar was more porous compared with clay. However, adding 20% of biochar reduced the total pore volume of compacted kaolin clay from 0.27 to 0.18 mL g^{-1}. This may be due to the embedment effects of biochar pore by clay and particles as revealed from the SEM image reported by Wong (2017).

Fig. 3 shows the Incremental Intrusion Pore Volume (IIV) of compacted kaolin clay and 20% BAC. The IIV is referred to the volume of mercury that intruded into the pores of the specimen between the incremental intrusion pressure (Ng and Coo, 2016). The dominant pore diameter of clay was 0.06 μm (macropores), followed by 0.05 μm (mesopores). Each composed of about 0.7 mL g^{-1} pore volume separately. On the other hand, a pore volume of 20% BAC was mainly composed of pore diameters between 0.1 and 4 μm

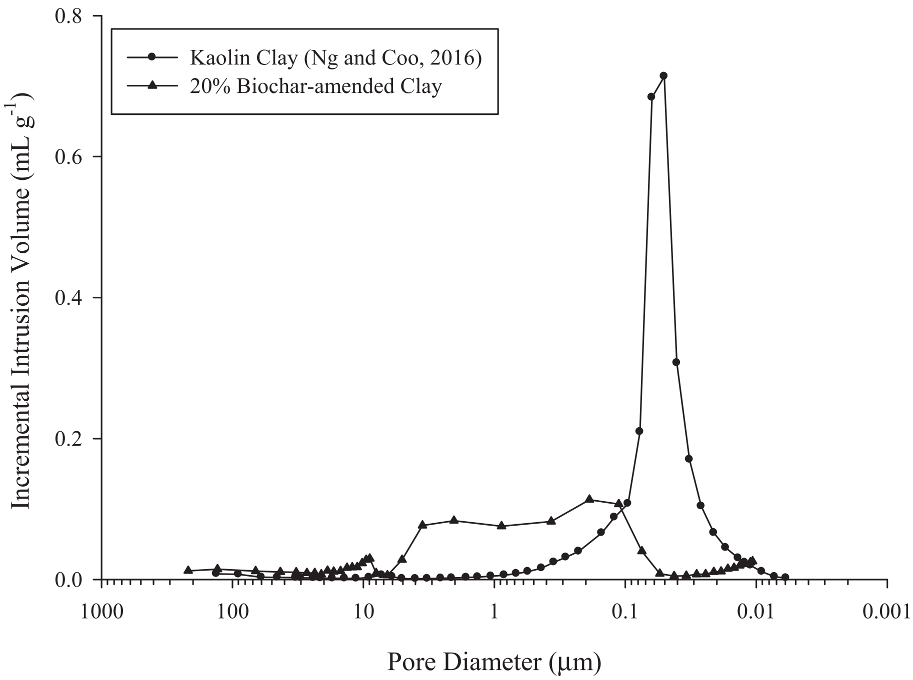

Fig. 3. Incremental intrusion volume of kaolin clay and 20% biochar–amended clay.

(macropores). This implies that the pore diameter of kaolin clay was mainly centralised and composed of both meso– and macropores, while the BAC was composed of a wide range of macro–pores.

Barnes et al. (2014) reported the effects of biochar application on k_{sat} of clayey soil. 10% (w/w) of biochar (<850 μm) derived from mesquite wood was added into clay-loam soil. The k_{sat} of soil was increased from 3.2×10^{-8} to 1.2×10^{-7} m s^{-1}. While in this study, by adding 10% of biochar, the k_{sat} of compacted clay was estimated to increase by less than half order of magnitude (Fig. 1). It implies that the effects of biochar addition on the increase in k_{sat} of clay is less significant if the clay was compacted at relatively high degree of compacted (e.g. landfill final cover).

4. Conclusions

The effects of biochar application on saturated hydraulic conductivity (k_{sat}) of compacted kaolin clay was investigated in this communication. Adding 5% and 20% of biochar increased the k_{sat} of compacted kaolin clay from 1.2×10^{-9} to 2.1×10^{-9} and 1.3×10^{-8}, respectively. The increase in k_{sat} of clay was due to the shift in pore size distribution of compacted biochar-amended clay (BAC). The MIP results revealed that the dominant pore diameter of clay was between 0.01 and 0.1 μm (meso– and macropores). Adding 20% of biochar shifted the dominant pore diameter to between 0.1 and 4 μm (macropores). However, the effects of biochar application on k_{sat} of clay in this study (compacted clay) was less significant when compared with some reported studies using agricultural clay-loam soil (lower degree of compaction). Therefore, compacted biochar-amended clay can be used as an alternative landfill final cover material without greatly increase the k_{sat} of clay.

Compliance with ethical standards

The authors would like to declare that they have no conflict of interest, and there were no human nor animal participants in this research.

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