Gas permeability in soil amended with biochar at different compaction states

He Huang¹, Wei-Ling Cai¹, Qian Zheng¹, Pei-Nan Chen¹, Chun-Rui Huang¹, Qing-Jie Zeng¹, Himanshu Kumar¹,², Hong-Hu Zhu*³, Ankit Garg¹, Kulenbekov Zheenbek, Vinod Kushvaha⁵

¹Shantou University, China
²Indian Institute of Technology Guwahati, India
³Nanjing University, China
⁴American University of Central Asia, Kyrgyzstan
⁵Department of Civil Engineering, Indian Institute of Technology Jammu, India

E-mail: zhh@nju.edu.cn

Abstract. Biochar amended soil (BAS) is widely studied to apply in green infrastructure, such as landfills and slopes. Presence of biochar improved soil hydraulic properties (e.g. water retention ability) in previous studies, while influence of biochar on gas permeability ($k_g$) under different compaction states is not clear yet. The main objective of this study is to investigate the $k_g$ of BAS under different soil compaction conditions. The soil selected for investigation was poorly graded sand. BAS was compacted in an in-house built 1-D column set up under three different soil density (65%, 80% and 95% degree of compaction) were considered in mixtures with 0% and 10% biochar content. The tests were carried out in a greenhouse at Shantou University. In tests, soil column was designed and subjected to drying-wetting cycles, during which soil suction, moisture content and $k_g$ were measured. Results showed that BAS (i.e. minimum water content 37.2% and 22.1%) had better water retention performance than bare soil (i.e. minimum water content 20.2% and 19.5%) at compaction conditions (65% and 80% degree of compaction). However, when the degree of compaction increased to 95%, bare soil and BAS shows similar water retention characteristic (i.e. minimum water content 15.7% and 15.9% respectively). The addition of biochar could decrease $k_g$ as compared with that of the bare soil, meanwhile, in the lower suction range, $k_g$ decreased with an increase of compaction (i.e. $k_g$65% > $k_g$80% > $k_g$95%).

1. Introduction

Biochar is a carbon-rich material produced from biomass at the condition high temperature and lacking oxygen [1-2]. Recent studies have focused on applying biochar to fields of agriculture.
[3] and engineering [4-5]. In agriculture, the compacted rate of soil is around 65% (i.e., loose state), which makes the soil have higher permeability to facilitate nutrients and gas exchange. Addition of biochar can improve soil fertility and water retention [6], which can boost agricultural yields. On the other hand, in geotechnical application, addition of biochar can improve soil water retention of dense soil [7]. Thus, BAS was often suggested to be used on engineering slopes to reduce soil erosion [8], and landfill cover to promote methane oxidation and odor reduction [9].

As far as authors are aware, a systematic research to investigate the influence of degree of compaction on $k_g$ and water retention properties of BAS is hardly conducted. The main objective of this study is to investigate the influence of different compaction treatment of BAS on its $k_g$ and water retention properties.

A group of soil containing 10% biochar and a control group of bare soil (BS) were studied in current research. All soil samples were compacted in an in-house built 1-D column set up under three different soil density (65%, 80% and 95% degree of compaction). Each column was subjected to a 49-day monitoring period, consisting of a 42-day drying period and a 7-day continuous wetting period, during which soil suction, moisture content and $k_g$ were measured.

2. Materials and method

2.1. Materials
The properties of the materials used in this study are summarized in table 1. Biochar adopted in current study was made from water hyacinth (a kind of invasive plant), which was collected from a local pond in Shantou, China. The particle size of biochar less than 2 mm, with specific gravity of 2.26. Soil selected for investigation was obtained from the campus of Shantou University, China. The soil is categorized as SP (poorly graded sand) according to unified soil classification system [10]. As is shown in table 1, the soil is dominated by coarse sand, with the main particle size distribution of 29.7% medium sand (1.18~2.36 mm), 50% coarse sand (2.36~4.75 mm), and the rest of soil is fine soil. As for the Atterberg limits of selected soil, plastic limit and liquid limit are determined to be 18.3% and 29.2% respectively. The maximum dry unit weight (MDUW) and optimum moisture content (OMC) from the compaction tests of BS and BAS (10%) are found to be 16.9 kN/m$^3$ and 18.8%, 16.5 kN/m$^3$ and 19.8%, respectively.

2.2. Test plan
The designed BAS sample were mixed with 10% biochar and 90% soil by weight percentage, meanwhile, BS (100% soil) was set as the control group. Each sample was compacted in a PVC pot with a diameter of 300mm and a height of 250 mm, as shown in figure 1. All composites were statically compacted in three layers up to 150 mm at 0.65, 0.8, 0.95 MDUW under the OMC condition, respectively. The MDUW and OMC of BS and BAS were shown in table 1. Test soil columns are shown in figure 1, the bottom of the soil column was provided with a permeable screen, which allowed to drain water but prevents the loss of soil particles.

All compacted soil columns were placed in a greenhouse at Shantou University, China. A sprinkler device was used to irrigate samples to make all samples achieve initial condition. In current study, all soil columns were subjected to a 49-day monitoring period, consisting of a 42-day drying period and a 7-day continuous wetting period. Soil suction and volumetric moisture content were measured by a measurement system, as shown in figure 1. A suction
sensor (MPS-6 with range from 10 to 100,000 kPa; [11]) and a volumetric water content sensor (EC-5 [11]) were inserted 100mm into the soil from the top of the column. The two sensors were spaced 100mm apart to eliminate interaction. All sensors were connected to a Pro-check data logger system [11].

\[ \frac{kg}{\mu q L} \]

where \( \mu \) is the absolute viscosity of the gas flow \((14.8 \times 10^{-6} \text{N} \cdot \text{s/m}^2)\), \( q \) is the gas flow rate, \( L \) is the length of the soil layer, \( A \) is the soil cross-sectional area and \( \Delta p \) is the gas pressure difference. The measurement system of \( kg \) is shown in figure 1, the \( q \) could measure by the flow meter and the \( \Delta p \) could measure by the pressure sensor.

| Properties                        | Standard       | Soil  | BC  | BAS10% |
|-----------------------------------|----------------|-------|-----|--------|
| Particle-size distribution        | ASTM D 422     | 50.0  | -   | -      |
| 2~4.75 mm                         | 29.7           | -     |
| 0.85~2 mm                         | 18.11          | -     |
| 0.425~0.8 mm                      | 1.16           | -     |
| 0.15~0.425 mm                     | 0.81           | -     |
| 0.075~0.15 mm                     | 0.22           | -     |
| Atterberg limits                  | ASTM D 4318    | 29.2  | -   |
| Liquid limit (LL/%)               | 18.3           | -     |
| Plastic limit (PL/%)              | 10.9           | -     |
| Plastic index (PI/%)              | 16.9           | 16.5  |
| MDUW (kN/m³)                      | ASTM D 698     | 18.8  | 19.8 |
| OMC (%)                           | ASTM D 854     | 2.59  | 2.26 |
| Specific gravity                  |                | 2.55  |

### 3. Results and discussion

#### 3.1. Soil water characteristic curves (SWCC)

SWCC are usually used to characterize the hydraulic properties of soil, which is of great significance in agriculture and engineering applications. It is an essential and important parameter to study soil hydrodynamics properties [5, 15-16]. As shown in figure 2, in loose soil (i.e. 65% and 80% degree of compaction soils), biochar can significantly improve soil water retention ability. In the dense soil (i.e. 95% degree of compaction), however, the variation of SWCC of BAS is almost the same as that of BS. From figure 2 (a) to (c), the soil water retention ability gradually decreases in both BAS and BS samples. This is likely because low-compacted
state can provide more pore space for water storage, while biochar has a strong water retention capacity due to its porous structure and large specific surface.

Figure 1. Test column in greenhouse at Shantou University, China.

Figure 2. SWCC of bare soil (BS) and BC amended soil (BAS) under different compaction states (a) 65%, (b) 80% and (c) 95% degree of compaction.

In general, in curves suction values of BS were found to less than BAS per water content value. This can be attributed to the addition of biochar changed the pore structure and chemical composition of soil. On the one hand, biochar addition can increase void ratio of soil composite. Thus, soil suction increases due to high capillary effects without change of external pore
structure under the same compaction state. On the other hand, soil-biochar composites subject to extra osmotic effect and short-range adsorption effects due to biochar addition. Which can be attributed to biochar is abundant in exchangeable ions and surface functional groups which are hydrophilic [13, 17]. These hydrophilic chemical composition of biochar in pore water can enhance osmotic suction, electrical fields to improve short-range adsorption effects and hence, increase suction. On the contrary, from figure 2 (a) to (c), it is obvious that compaction shortens the distance between BAS and BS curves. For 80% degree of compaction soils, peak suction values for BAS is 2755 kPa as compared to 553 kPa for BS. However, for highly compacted soils (i.e. 95% degree of compaction), the peak suction for BAS and BS are 2953 kPa and 2425 kPa respectively. Compaction treatment and BC addition can both influence void ratio of samples [13, 18]. On the one hand, void ratio decreases with degree of compaction increases; on the other hand, biochar addition achieves the higher void ratio. In loose soil (i.e. 65% and 80% compaction state), there are larger number of large voids which are not likely to lead high capillary effects. Thus, the effect of compaction is much lower than that of biochar addition. However, in 95% degree of compaction soils, capillary effects are enhanced a lot with the reducing of internal pore structure of soils.

![Figure 3](image)

**Figure 3.** Variation of $k_g$ with suction of bare soil (BS) and BC amended soil (BAS) under different compaction states (a) 65%, (b) 80% and (c) 95% degree of compaction.

3.2. Gas permeability

The relationship of $k_g$-suction is shown in figure 3. It is obvious that $k_g$ increased with soil suction, regardless compaction state and biochar addition. According to SWCC model, high suction means lower water content and more pore space with air, which provide more feasible flow paths for air transference. Comparisons among figure 3 (a) to (c), $k_g$ of 65% degree of compaction is more than that of 80% and 95% degree of compaction ($k_g$ 65% > $k_g$ 80% > $k_g$ 95%). This is likely because there are more pores in the loose soil and hence, more available paths for air flow. However, $k_g$ of 95% compaction is high than that of 80% and 65% degree of
compacted samples in high suction range (i.e. about > 1000 kPa). Furthermore, it clearly shows that for both BS and BAS, the slope gradient of curves (suction versus $k_g$) change according compaction degrees: slope of 95% > slope of 65% > slope of 80%. Brooks and Corey [19] suggest that the slopes of these curves are related with the pore structure characteristics. This means that compaction state effect the pore structure and hence, $k_g$ changed.

Comparisons among each curve, $k_g$ decreases due to biochar amendment, regardless compaction state. Garg et al. [13] suggest that $k_g$ of BAS reduced because biochar mixed in soil can retain water due to its intra-pores. In addition, a study conducted by Bordoloi et al. [5] founded that BC could reduce soil shrinkage limit. Over their study, BAS with 10% biochar was found to reduce cracks by more than 50% compared to BS. This could be the reason for the $k_g$ reduction, as it impedes the gas transport path. Overall, $k_g$ is related to pore structure and pore size. Both compaction state and biochar addition could change the pore structure and pore size and hence, alter $k_g$ in soil.

4. Conclusion
The outcomes of this study show that compaction reduced the $k_g$ of soil and helped soils achieve high suction, especially 95% degree of compaction. Highly compacted (95%) soils have the potential application in engineering stability of soil body. Furthermore, compacted BAS can provide considerably low $k_g$ in field to make soil layer impermeable. Thus, highly compacted (95%) BAS is suggested for engineering applications. In loose soil (65% compaction), BAS should be suggested in cultivation land to achieve high water retention ability, as well as enhance fertility of land.

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