International Journal of Geosynthetics and Ground Engineering (2020) 6:22
https://doi.org/10.1007/s40891-020-00206-1

ORIGINAL PAPER

Effects of Biochar on the Compression and Swelling Characteristics of Clayey Soils

Yuping Zhang[1] · **Kai Gu**[1] · **Chaosheng Tang**[1] · **Zhengtao Shen**[2] · **Gangadhara Reddy Narala**[3] · **Bin Shi**[1]

Received: 15 February 2020 / Accepted: 18 May 2020

Abstract

In recent years, biochar has been widely used in environmental and geotechnical engineering applications, but minimal studies have been done on its influence on soil engineering properties. In this study, the effect of biochar on the compression and swelling characteristics of two clayey soils, namely PKE and XS, was studied by conducting standard consolidation tests and no-load swelling tests. The compression curves and swelling parameters of modified clays with different biochar content (0, 0.5, 1, 2%, w/w) and biochar particle sizes (<0.15, 1–2 mm) were obtained. The microstructure of the biochar-clay mixture was analyzed by scanning electron microscopy (SEM) test. The results showed that: (1) the compressibility of clayey soils can be effectively reduced by adding biochar, and this effect is more significant with the increase biochar percentage; (2) the effect of reducing soil compressibility by fine biochar was better than coarse biochar; (3) under the same pressure, the settlement rate of soil increased with the increase of biochar content; (4) the incorporation of biochar had no obvious influence on the no-load swelling behaviour of PKE while it has significantly increased the swelling of XS (low expansive soil). Additionally, the fine-grained biochar has a significant effect than the coarse-grained biochar on clayey soils.

Keywords Biochar · Clayey soils · Compression behaviour · Swelling behaviour

Introduction

Biochar refers to the solid materials which can be produced by biomass through thermochemical conversion in an oxygen-limited or anoxic environment under a certain temperature [1]. The primary sources of biomass are agricultural and forestry residues, wood processing waste, animal manure, and municipal sewage sludge [2]. Due to the favourable properties of biochar, including high porosity, high specific surface area, low density and others, it is widely used in agriculture, remediation of contaminated sites, and carbon sequestration [3]. Biochar can change the physical and chemical properties of soils, improve not only soil fertility [4] but also adsorb heavy metal ions [5]. Therefore, the use of biochar can improve soil structure, increase crop yield, and decontamination of polluted sites. At present, there are many studies on the effects of biochar on the physical and chemical properties of soil [6]. For example, biochar can reduce soil bulk density, increase soil pH, increase soil CEC, improve the water-holding capacity of the soil, and fix heavy metal ions [7–10]. In general, there are relatively few studies on the effects of biochar on soil engineering properties.

It was found that the incorporation of different biochar in desert soil can slightly enhance the formation of soil macroaggregates, but the effect will gradually weaken with time [11]. Pardo et al. [12] reported that biochar could form a complex network by interacting with water through active chemicals on the surface and in the pores of biochar particles. It also reduced the increase of excess hydrostatic pressure, provide partial shear resistance, and improve the liquefaction resistance of pure sand. The effect of biochar on different kinds of soil is distinct; generally, biochar can reduce the saturated hydraulic conductivity of coarse-textured soils, but increase the saturated hydraulic conductivity of fine-textured soils [13]. Three kinds of biochar (wheat straw, woodchips, and wastewater sludge) on the mechanical properties of clayey soil were studied, biochar reduced the

---

✉ Kai Gu
gukai@nju.edu.cn

[1] School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, Jiangsu, China

[2] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton T6G 2E3, Canada

[3] Department of Civil and Environmental Engineering, Shantou University, Guangdong 515063, China

tensile strength, cohesive of soil, and increased the angle of internal friction [14]. The sludge biochar can increase CEC in acidic soil because the oxygen-containing functional groups on the surface of biochar can provide more exchange sites [15]. Reddy et al. [16] and Wong et al. [17] found that biochar addition to the soil can increase the bacterial populations and increase the methane oxidation capacity of the soil. 10% biochar can effectively remove methane, and improve the water retention of soil [18]. However, compacted clay, such as a landfill cover undergoing cycles of drying and wetting is prone to failure due to shrinkage and cracking, thus disturb the integrity of cover layers. It has been found that biochar can increase the water holding capacity of the soil and effectively inhibit the development of soil cracks [19–22].

The compressibility and swelling behaviours are critical geotechnical properties of landfill cover systems. Excessive deformation will cause the infrastructure to shrink, produce an uneven settlement, and in severe cases, cause failure. Similarly, the addition of biochar influences the swelling properties of the soil, which influences the stability of the landfill and the slope. The swelling of soil can cause the slip of slope and the distortion failure for the landfill cover system. But minimal research has been done on the deformation characteristics of the biochar-modified soil. Therefore, it is necessary to study the effect of biochar on the compressibility and swelling behaviours of clayey soils. In this study, two soils namely Pukou expansive soil (PKE) and the Xiashu soil (XS) were used for conducting standard consolidation and no-load swelling tests. Combined with the observation of microstructure, the effects of different amounts of biochar and particle sizes on the compressibility and swelling of two clayey soils were investigated.

Materials and Methods

Soils and Biochar

The clayey soils used in this study were obtained from Nanjing, China. Pukou expansive soil (PKE, Clay with high plasticity) obtained from a depth of 0.1–0.5 m. According to previous studies, it is a moderate to high expansive soil. Xiashu soil (XS, Clay with low plasticity) is a typical soil in the middle and lower reaches of the Yangtze River. Main clay minerals are illite in XS, followed by montmorillonite, and the swelling potential of XS is lower than that of PKE. The basic physical properties of the two clayey soils were shown in Table 1.

Table 1 Basic physical properties of the clayey soils

Soil properties	PKE	XS
Specific gravity	2.71	2.73
Liquid limit (%)	76.0	34.5
Plastic limit (%)	29.0	17.0
Plasticity index	47.0	17.5
Max dry density (g/cm^3)	1.67	1.70
Optimal moisture content (%)	18.3	15.7
Clay content (%)	42	24
Air-drying moisture content (%)	11.83	5.83

The biochar used in this study is procured from Qingdao Biochar Environmental Bioengineering Co. Ltd., China. It was prepared from wood waste materials by pyrolysis at 500 °C for a period of 5 h. The relevant physical and chemical parameters are tabulated in Table 2.

Table 2 Basic physicochemical properties of biochar

Physicochemical property	Value
Pyrolysis temperature (°C)	500
Pyrolysis time (h)	5
Ash content (%)	28.26
pH	10.28
Specific surface area (m^2/g)	51.7
Bulk density (g/cm^3)	0.47

Methodology

The collected PKE and XS were air-dried, ground and sieved to obtain soil samples with a particle size of 0.25–0.5 mm. The dried biochar was sieved to obtain coarse-grained (1–2 mm) and fine-grained (< 0.15 mm) biochar. Clay-biochar mixed soil samples were prepared by mixing biochar with two-particle sizes into PKE and XS at dry state. The content of biochar added to soils was designed at four application rates (0, 0.5, 1, 2%, w/w). The samples were named based on the type of the soil, amount, and particle size of biochar. For example, the coarse biochar (1–2 mm) was added to PKE soil at four different biochar content (0, 0.5, 1, 2% dry weight), represents PKEC0, PKEC0.5, PKEC1, and PKEC2. The mechanical mixing device was used to uniformly mix the biochar and clay particles (in a dry state) for 5 min. A certain amount of water was uniformly added to the soil by spraying, and the initial water content of the sample was controlled to 15%. Then the samples were stored in a sealed container for 24 h, the samples with a diameter of 61.8 mm, and a height of 20 mm were prepared. The dry density was considered as 1.5 g·cm^{-3} by controlling the quantity of the required sample. For the standard consolidation tests and no-load swelling tests, four and two parallel samples were required, respectively. The combinations used for the testing are tabulated in Table 3.

Table 3 Samples combinations and density parameters of the samples

Soil	Sample no	Biochar content (%)	Dry density (g·cm^{-3})	Initial water content (%)
PKE	PKEC0, PKEF0	0	1.5	15
	PKEC0.5, PKEF0.5	0.5		
	PKEC1, PKEF1	1		
	PKEC2, PKEF2	2		
XS	XSC0, XSF0	0	1.5	15
	XSC0.5, XSF0.5	0.5		
	XSC1, XSF1	1		
	XSC2, XSF2	2		

The samples were named based on the soil type, particle sizes, and the content of biochar. For example, PKEC1 and PKEF1 represent 1% of coarse-grained biochar and fine-grained biochar added to PKE, respectively

(a) Standard consolidation test: The standard consolidation tests were performed using the consolidation apparatus, samples were saturated by vacuuming. The applied pressures were 100, 200, 400, 800, 1600, and 3200 kPa. After the test, sucked off the water from the container and quickly dismantle the parts of the instrument. Taken out the entire sample, a part of the sample was carefully cut off to determine the water content and sealed the rest portion of the specimen in an aluminum box.

(b) No-load swelling test: Placed the prepared sample in the dilatometer according to SSPRC [23] standard specifications, and added water to keep the water surface 5 mm higher than the sample. After the water injection was completed, measured the dial indicator according to 5 min, 10 min, 20 min, 30 min, 1 h, 2 h, 3 h, 6 h, and 12 h. The test was ended when the deformation not more than 0.01 mm within 6 h.

For microstructure analysis, each sample was cut into a block size of ~ 0.5 × 0.5 × 2 cm and then dried using a liquid nitrogen freeze dryer (SCIENTZ-18 N, Xinzhi, China). The microstructural analysis was performed with the help of a scanning electron microscope (SU3500, Hitachi, Japan).

Results and Discussion

Effect of Biochar Content on the Compressibility of Clayey Soils

Figure 1 shows the compression curves of two clayey soils under different particle sizes and varying amounts of biochar content. It can be seen that under the same pressure, the void ratio (e) of the sample increases with the increase of the biochar content, that is, the compressibility of the soil decreases with the increase of the amount of biochar. Figure 2 shows the variation of the compression coefficient (α) with pressure, $\alpha_{1\text{-}2}$ represents the compression coefficient in the pressure range of 100 ~ 200 kPa, and so on. As Fig. 2 shows that: (1) For PKE, when the pressure is less than 800 kPa, the compression coefficient of the soil decreases with the increase of the amount of biochar. For instance, the compression coefficient of PKE decreased by 24.26% and 20.10%, respectively, in the pressure range of 200 ~ 400 kPa after the addition of 2% coarse and fine grain biochar. When the pressure was higher than 800 kPa, the biochar had no significant effect on the compression coefficient of the soil; (2) For XS, the amount of biochar and the particle size has no significant impact on the soil compression coefficient. Reddy et al. [24] reported that the compressibility of the soil decreases with an increment of biochar, which in line with our results.

The effect of biochar on the compressibility of PKE and XS is mainly related to its high CEC and low-density characteristics of biochar. When the soil particles are in contact with water, the negative charges on the surface of the soil particles attract hydrated ions and water molecules due to the electrostatic effect, thus forming adsorbed water on the particle surface. Biochar generally has a high CEC and has a large number of negative charges and oxygen-containing functional groups on the surface [25, 26]. It has a strong water absorption capacity and can absorb more than ten times its weight of water [27]. The addition of biochar can significantly increase the CEC of the soil, enhance the negative charge on the surface of the soil particles and the cation concentration in the pore water so that the thickness of the water absorbed on the surface of the soil particles increases.

The thickness of adsorbed water around the biochar modified soil particles is thicker, and the soil particles have a larger spacing. Compared with the reference sample, it is difficult to compress under the low-pressure. With the increase of pressure, the adsorption of soil particles on the water is not enough to resist the discharge of pore water, the thickness of the absorbed water becomes thin. The soil particles in PKE are more closely connected compared with XS. Therefore the dissipation of pore water is more difficult under the same pressure. Thus, the compression coefficient of PKE is significantly smaller than that of XS. Additionally, the effect of biochar on the compressibility of soil is also related to its low density and porous structure. Under the same dry density conditions, the relative compactness of the sample is more significant with the higher amounts of biochar due to the low-density of biochar. Although biochar has high porosity, it has high particle strength [28], and it is not easy for structural damage to occur during compression.

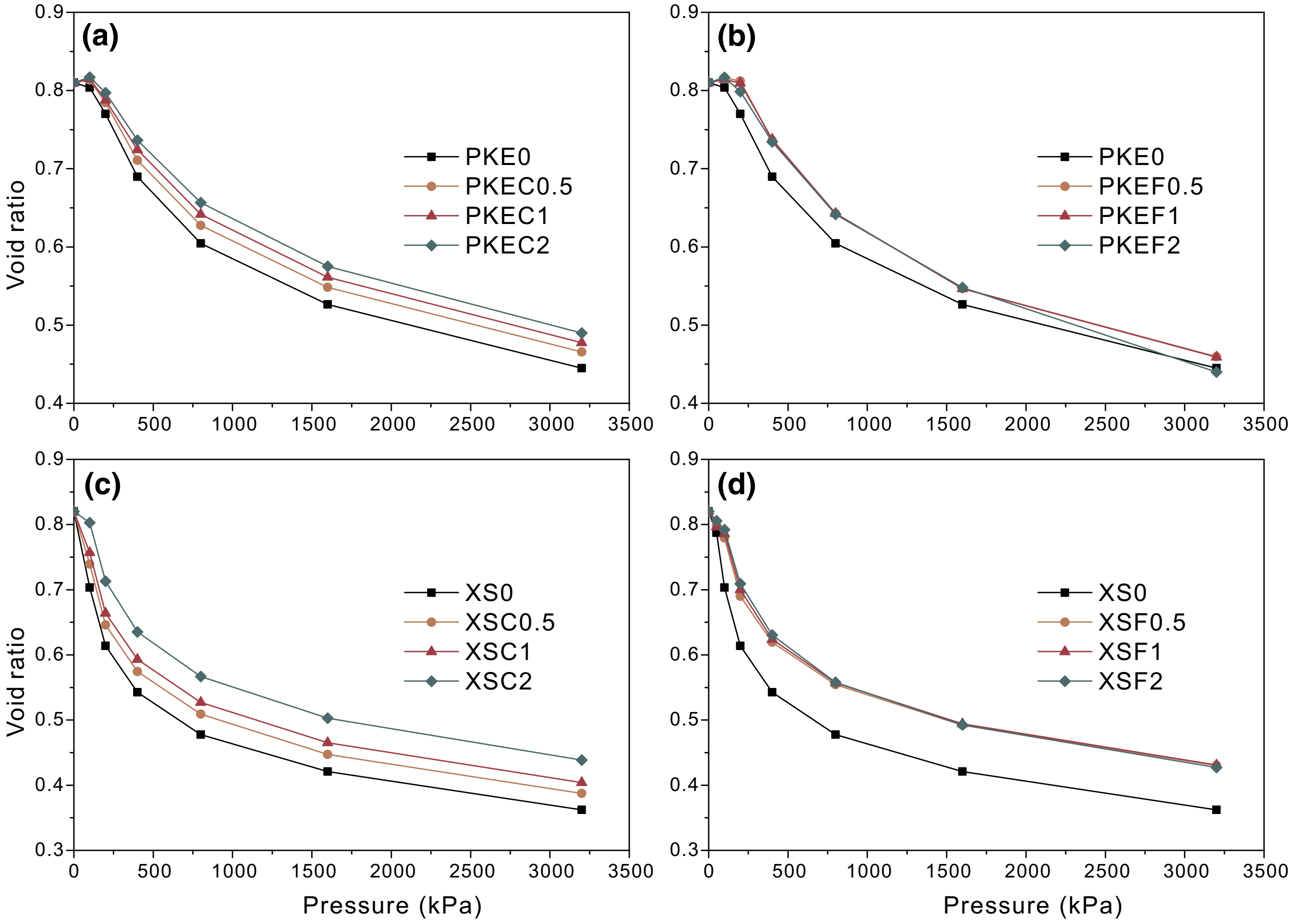

Fig. 1 Compression curves of samples: **a** PKE with coarse biochar; **b** PKE with fine biochar; **c** XS with coarse biochar; **d** XS with fine biochar

Therefore, the more the biochar is added, the lower the compressibility of the sample.

Effect of Biochar Particle Size on the Compressibility of Clayey Soils

Figure 2 shows the α-p relationship curve of PKE and XS soils amended with coarse and fine biochar particles. For PKE, the compression coefficient α shows a trend of first increase and then decrease with the increment of the pressure. The effect of rearrangement of soil particles is not apparent with low pressure, thus, its compression coefficient value is small. As the pressure increases, the soil particles undergo a significant rearrangement, and the large pores undergo more compression, which increases the compression coefficient. However, with the further increase of pressure, the small pores in the soil were not easily compressed. The lubrication effect of the water film on the surface of the soil particles is almost invalid, and the smaller biochar particles improve the microstructure, consequently, the compression coefficient becomes smaller. With the same amount of biochar and pressure, the compression coefficient of fine-grained biochar was lower than that of coarse-grained biochar. For PKE, the compression coefficient of the samples with coarse-grained biochar is > 0.2 MPa^{-1}, and that of fine-grained biochar is < 0.2 MPa^{-1} in the pressure range of 100 ~ 200 kPa. However, the compression coefficient of XS shows a downward trend with the increase of pressure, mainly because of the structure of XS is relatively loose, and high macropores than PKE. The water in macropores is more easily discharged at low pressures, thus its pore structure can be compacted at lower pressures.

Figure 3 shows the SEM images of biochar-modified clay. It can be seen (Fig. 3a, b) that the biochar particles are filled between or within the aggregates of the soil [29], which changes the pore structure of the soil. Compared with coarse-grained biochar, fine-grained biochar (< 0.15 mm) easily filled the pores of two clayey soils (0.25–0.5 mm), making more small pores in the soil. The coarse-grained biochar (1–2 mm) has a larger particle size, and the filling effect is not as good as that of fine-grained biochar. Moreover, when biochar is filled between soil aggregates, there will be

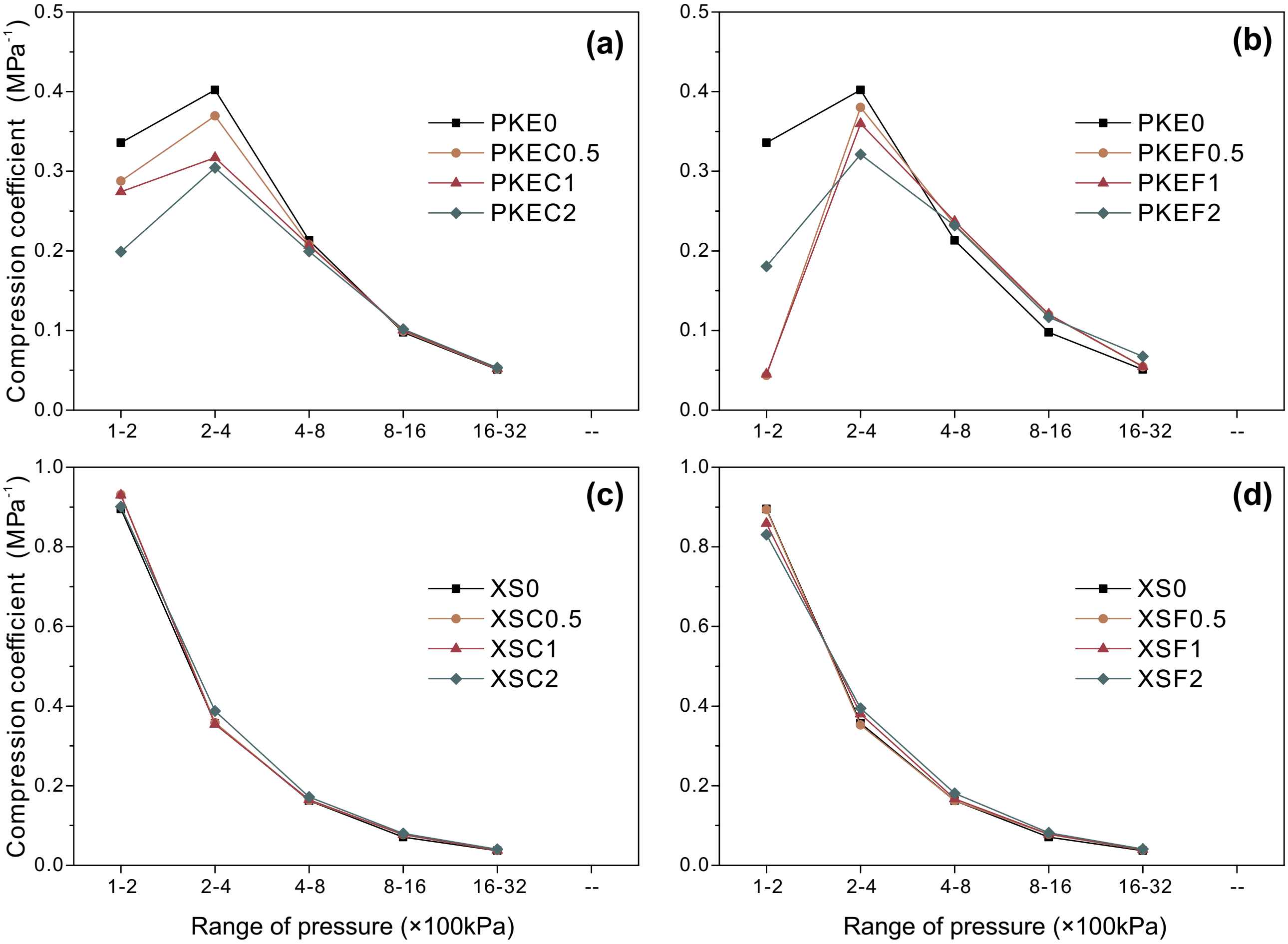

Fig. 2 Relation between compression coefficient and pressure: **a** PKE with coarse biochar; **b** PKE with fine biochar; **c** XS with coarse biochar; **d** XS with fine biochar

a certain spatial distance between the biochar particles and the aggregates (Fig. 3c). The effect of "spreading" obvious with the large particle size of biochar, there is a large pore between the aggregates and the biochar. Therefore, under the same pressure conditions, the pore structure of clay samples treated with coarse-grained biochar is more easily compressed. Compared with the addition of coarse-grained biochar to clay, the compression coefficient of fine-grained biochar is low at low pressure.

Effect of Biochar on the Settlement Rate of Clayey Soils

Figure 4 shows the settlement rate of samples with different biochar content (particle size < 0.15 mm) under the same pressure (400 kPa). It can be found that the addition of biochar can increase the settlement rate of clayey soil, and has a positive correlation with the amount of biochar.

In the microstructure image of biochar modified soil (Fig. 5), it can be seen that biochar embedded into soil particles, and connected the soil particles in PKE. Due to the porous structure of biochar, effective drainage channels can be formed in the soil. The interface between biochar and soil particles accelerates the drainage process of the soil. The high content of biochar leads to more developed hydrophobic channels between soil particles and biochar, and the faster the drainage process, therefore, the addition of biochar promotes the drainage of soil water.

Effect of Biochar on the Swelling of Clayey Soils

The addition of biochar increases the cation exchange capacity and negative charge density of the soil enlarges the thickness of the electric double layer around the soil particles. Moreover, C–H and C–OH on the surface of biochar can form bonds with water molecules and adsorb water molecules [30]. Furthermore, the large number of hydrophilic oxygen-containing groups on the surface of biochar (reflecting higher cation exchange capacity) can enhance the binding of H_2O molecules. Therefore, high

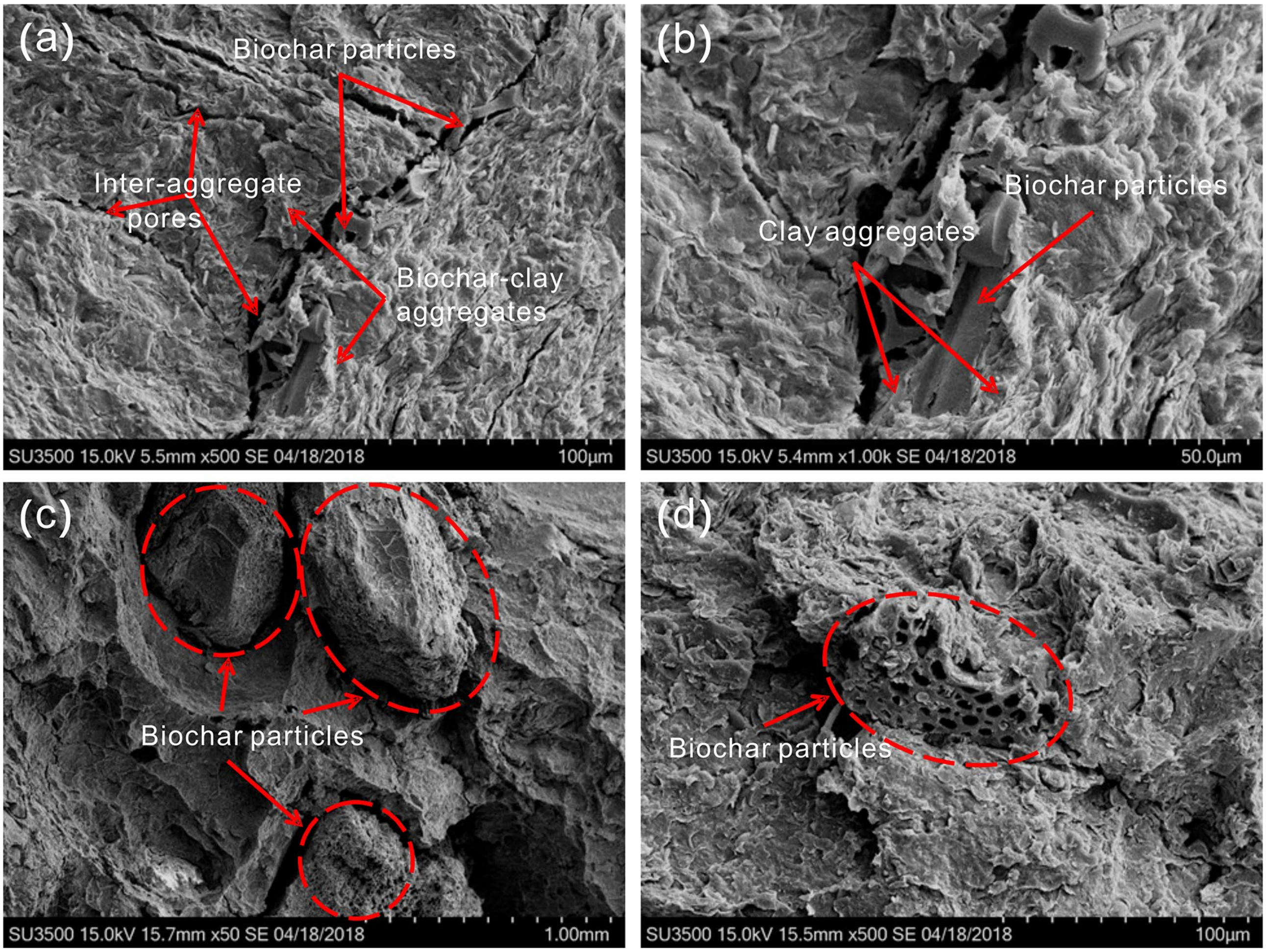

Fig. 3 SEM images of biochar-amended soil from different samples: **a**, **b** No.PKEF2, **c** No.PKEC2, **d** No. PKEF0.5

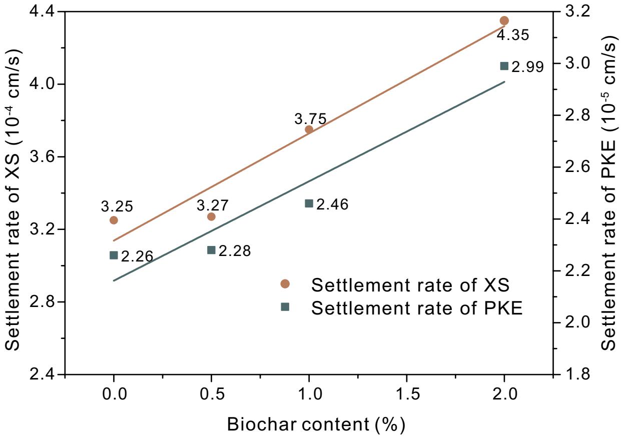

Fig. 4 Settlement rate curves of the samples with fine-grained biochar at 400 kPa pressure

cation exchange biochar can affect the overall swelling of the soil. PKE contains 42% of clay content, which is mainly composed of highly hydrophilic clay minerals montmorillonite and illite, has a strong water absorption capacity [31]. The impact of biochar on swelling is small due to the high swelling potential of PKE (Fig. 6). For XS, the water absorption capacity is weak because of the lower mineral contents. Therefore, the effect of biochar on XS is more obvious than that of PKE. For XS, the swelling percentage of the biochar mixed soil increases with the increase of biochar content. The results were consistent with the studies of Jačka et al. [30], who demonstrated that biochar could increase the swelling of sandy loam soil, and the highest swelling was measured to be 13.2% with 5% biochar. The effect of fine-grained biochar is significant than that of coarse-grained biochar at the same biochar content. The specific surface area of fine-grained biochar is higher than that of coarse-grained biochar at the same biochar content, more water molecules are adsorbed on the surface of particles, and the soil is more prone to swelling.

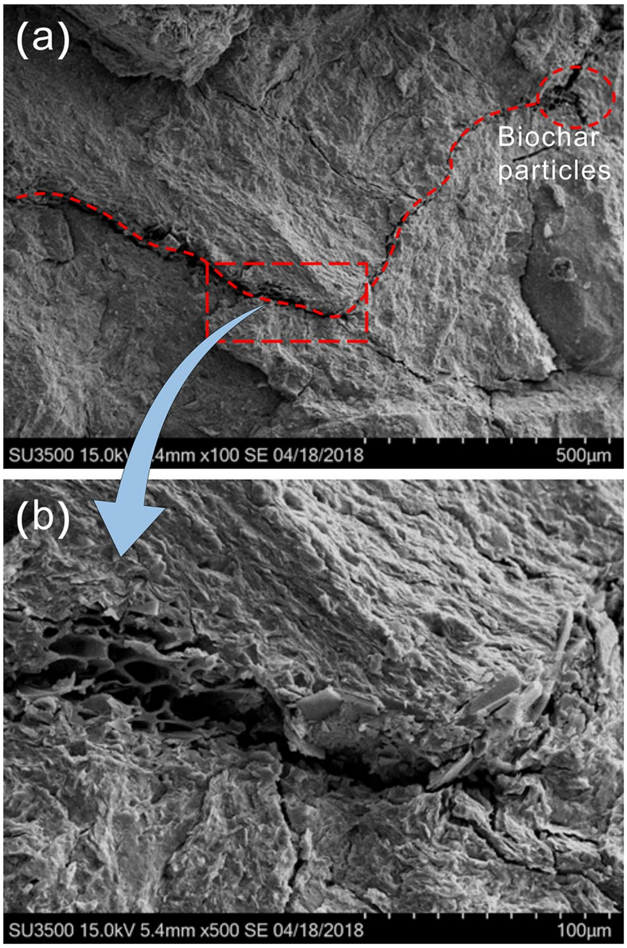

Fig. 5 Biochar forms “crack” drainage channels in soil: **a**, **b** No. PKEF2

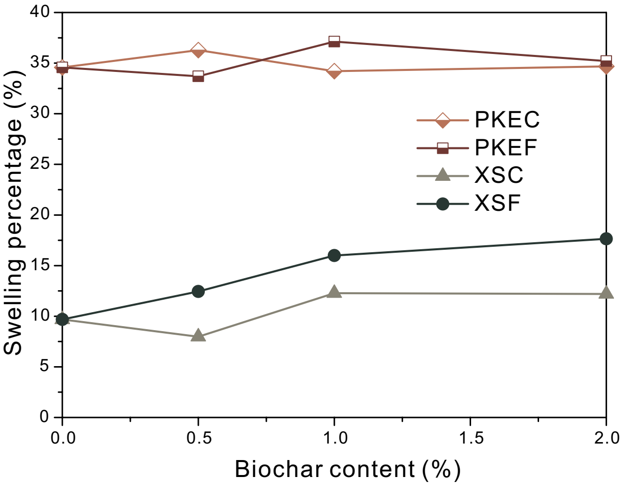

Fig. 6 Effect of biochar content on swelling properties of clayey soils

Subsequently, the swelling soil amended with fine-grained biochar is higher than that of coarse-grained biochar. It is necessary to avoid the damage caused by the change of swelling properties of the soil by biochar when using biochar to improve low expansive soil.

Conclusions

The effects of biochar on the compressibility and swelling properties of two clayey soils were studied by standard consolidation tests and no-load swelling tests. The following conclusions can be drawn:

(1) Biochar can effectively reduce the compressibility of clayey soils due to the high CEC and low-density characteristics of biochar. Higher biochar content has a significant on the compressibility of both clayey soils.
(2) The effect of fine-grained biochar on reducing the compressibility of PKE and XS soil is better than that of coarse-grained biochar because of the changed pores structure. The filling effect of fine-biochar is conducive to the formation of small pores. However, coarse-grained biochar and aggregates form larger pores and are easily compressed.
(3) During the compression process, biochar is filled in the pores of the aggregates, forming a connected drainage channel due to the porosity of biochar. Thereby, the compression process of the soil accelerates, and the compression rate increases with the increase of biochar content.
(4) The addition of biochar has no obvious effect on the swelling characteristics of PKE, but it can significantly increase the swelling characteristics of XS, and the effect of fine-grained biochar is better than that of coarse-grained biochar.

Acknowledgements This research was financially supported by the National Natural Science Foundation of China (41977217) and the Fundamental Research Funds for the Central Universities, China (020614380061).

References

1. International Biochar Initiative (IBI) (2012) Standardized product definition and product testing guidelines for biochar that is used in soil. International Biochar Initiative, New York
2. Duku MH, Gu S, Hagan EB (2011) Biochar production potential in Ghana—a review. Renew Sustain Energy Rev 15:3539–3551. https://doi.org/10.1016/j.rser.2011.05.010

3. Wang J, Wang S (2019) Preparation, modification and environmental application of biochar: a review. J Clean Prod 227:1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282
4. Herrmann L, Lesueur D, Robin A, Robain H, Wiriyakitnateekul W, Bräu L (2019) Impact of biochar application dose on soil microbial communities associated with rubber trees in North East Thailand. Sci Total Environ 689:970–979. https://doi.org/10.1016/j.scitotenv.2019.06.441
5. Gong X et al (2019) Biochar facilitated the phytoremediation of cadmium contaminated sediments: metal behavior, plant toxicity, and microbial activity. Sci Total Environ 666:1126–1133. https://doi.org/10.1016/j.scitotenv.2019.02.215
6. Garg A et al (2020) Mechanism of biochar soil pore–gas–water interaction: gas properties of biochar-amended sandy soil at different degrees of compaction using KNN modeling. Acta Geophys 68:207–217. https://doi.org/10.1007/s11600-019-00387-y
7. O'Connor D et al (2018) Biochar application for the remediation of heavy metal polluted land: a review of in situ field trials. Sci Total Environ 619–620:815–826. https://doi.org/10.1016/j.scitotenv.2017.11.132
8. El-Naggar A et al (2019) Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma 337:536–554. https://doi.org/10.1016/j.geoderma.2018.09.034
9. Banitalebi G, Mosaddeghi MR, Shariatmadari H (2019) Feasibility of agricultural residues and their biochars for plant growing media: physical and hydraulic properties. Waste Manag 87:577–589. https://doi.org/10.1016/j.wasman.2019.02.034
10. Hailegnaw NS, Mercl F, Pračke K, Száková J, Tlustoš P (2019) Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. J Soil Sediment 19:2405–2416. https://doi.org/10.1007/s11368-019-02264-z
11. Zhang L, Jing Y, Chen G, Wang X, Zhang R (2019) Improvement of physical and hydraulic properties of desert soil with amendment of different biochars. J Soil Sediment 19:2984–2996. https://doi.org/10.1007/s11368-019-02293-8
12. Pardo GS, Sarmah AK, Orense RO (2018) Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. Géotechnique 69:471–480. https://doi.org/10.1680/jgeot.17.P.040
13. Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am 81:687–711. https://doi.org/10.2136/sssaj2017.01.0017
14. Zong Y, Chen D, Lu S (2014) Impact of biochars on swell-shrinkage behavior, mechanical strength, and surface cracking of clayey soil. J Plant Nutr Soil Sc 177:920–926. https://doi.org/10.1002/jpln.201300596
15. Hossain MK, Strezov V, Yin Chan K, Nelson PF (2010) Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (Lycopersicon esculentum). Chemosphere 78:1167–1171. https://doi.org/10.1016/j.chemosphere.2010.01.009
16. Reddy KR, Yargicoglu EN, Yue D, Yaghoubi P (2014) Enhanced microbial methane oxidation in landfill cover soil amended with biochar. J Geotech Geoenviron. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001148
17. Wong JTF, Chen X, Deng W, Chai Y, Ng CWW, Wong MH (2019) Effects of biochar on bacterial communities in a newly established landfill cover topsoil. J Environ Manag 236:667–673. https://doi.org/10.1016/j.jenvman.2019.02.010
18. Yargicoglu EN, Reddy KR (2018) Biochar-amended soil cover for microbial methane oxidation: effect of biochar amendment ratio and cover profile. J Geotech Geoenviron 144:4017123. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001845
19. Zhang Y, Gu K, Li J, Tang C, Shen Z, Shi B (2020) Effect of biochar on desiccation cracking characteristics of clayey soils. Geoderma 364:114182. https://doi.org/10.1016/j.geoderma.2020.114182
20. Prakash A, Bordoloi S, Hazra B, Garg A, Sreedeep S, Zhu H (2020) Modeling dependence among suction, moisture, and cracking of a novel biochar synthesized from weed species. Adv Civ Eng Mater 9:20180092. https://doi.org/10.1520/ACEM20180092
21. Wei C, Gao W, Whalley WR, Li B (2018) Shrinkage characteristics of lime concretion black soil as affected by biochar amendment. Pedosphere 28:713–725. https://doi.org/10.1016/S1002-0160(18)60041-4
22. Bordoloi S, Gopal P, Boddu R, Wang Q, Cheng Y, Garg A (2019) Soil-biochar-water interactions: role of biochar from Eichhornia crassipes in influencing crack propagation and suction in unsaturated soils. J Clean Prod 210:847–859. https://doi.org/10.1016/j.jclepro.2018.11.051
23. SSPRC(State Standard of the People's Republic of China) (2019) Standard for soil test method (GB/T50123–2019). People's Republic of China Ministry of Construction, Beijing
24. Reddy KR, Yaghoubi P, Yukselen-Aksoy Y (2015) Effects of biochar amendment on geotechnical properties of landfill cover soil. Waste Manag Res 33:524–532. https://doi.org/10.1177/0734242X15580192
25. Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol Fert Soils 48:271–284. https://doi.org/10.1007/s00374-011-0624-7
26. Zeng Z et al (2013) Sorption of ammonium and phosphate from aqueous solution by biochar derived from phytoremediation plants. J Zhejiang Univ Sci B 14:1152–1161. https://doi.org/10.1631/jzus.B1300102
27. Kinney TJ, Masiello CA, Dugan B, Hockaday WC, Dean MR, Zygourakis K, Barnes RT (2012) Hydrologic properties of biochars produced at different temperatures. Biomass Bioenerg 41:34–43. https://doi.org/10.1016/j.biombioe.2012.01.033
28. Sadasivam BY, Reddy KR (2014) Engineering properties of waste wood-derived biochars and biochar-amended soils. Int J Geotech Eng 9:521–535. https://doi.org/10.1179/1939787915Y.0000000004
29. Wong JTF, Chen Z, Chen X, Ng CWW, Wong MH (2017) Soil-water retention behavior of compacted biochar-amended clay: a novel landfill final cover material. J Soil Sediment 17:590–598. https://doi.org/10.1007/s11368-016-1401-x
30. Jačka L, Trakal L, Ouředníček P, Pohořelý M, Šípek V (2018) Biochar presence in soil significantly decreased saturated hydraulic conductivity due to swelling. Soil Tillage Res 184:181–185. https://doi.org/10.1016/j.still.2018.07.018
31. Gu K, Tang C, Shi B, Hong J, Jin F (2014) A study of the effect of temperature on the structural strength of a clayey soil using a micropenetrometer. B Eng Geol Environ 73:747–758. https://doi.org/10.1007/s10064-013-0543-y