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The role of biochar on the desiccation cracking behavior of a clayey soil

Le rôle du biochar sur le comportement de fissuration de dessiccation un sol argileux

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ABSTRACT: In recent years, biochar has attracted increasing attention in environmental and geotechnical engineering. However, the effect of biochar on the desiccation cracking behavior of clayey soil is unclear. In this study, the effect of a wood biochar on a clayey soil (namely XS) desiccation cracking behavior under dry-wet cycles was investigated. Slurry samples with different dosages of biochar (0, 0.5, 2, 4, 5, 6, 10%, w/w) were prepared. The dynamic formation of cracks was recorded and the cracking characteristics were quantitatively analyzed using image processing techniques. The results indicated that biochar can reduce surface crack ratio and average crack width while increasing the number of crack segments and the total crack length. Simultaneously, biochar can affect the development position of desiccation cracking and reduce all the quantitative parameters of desiccation cracking with multiplied dry-wet cycles. We conclude that biochar affects the desiccation cracking behavior of soils by occupying shrinkage spaces and weakening the bonding between soil particles. In addition, biochar influences the development of desiccation cracking under dry-wet cycles by altering the pore structure and the contact between soil aggregates.

RÉSUMÉ: Ces dernières années, le biochar a attiré une attention croissante dans l'ingénierie environnementale et géotechnique. Cependant, l'effet du biochar sur le comportement de fissuration de dessiccation des sols argileux n'est pas clair. Dans cette étude, l'effet d'un biochar de bois sur le comportement de fissuration par dessiccation d'un sol argileux (à savoir XS) sous des cycles sec-humide a été étudié. Des échantillons de lisier avec différents dosages de biochar (0, 0,5, 2, 4, 5, 6, 10 %, p/p) ont été préparés. La formation dynamique des fissures a été enregistrée et les caractéristiques des fissures ont été analysées quantitativement à l'aide de techniques de traitement d'images. Les résultats ont indiqué que le biochar peut réduire le taux de fissure de surface et la largeur moyenne des fissures tout en augmentant le nombre de segments de fissures et la longueur totale des fissures. Simultanément, le biochar peut affecter la position de développement de la fissuration par dessiccation et réduire tous les paramètres quantitatifs de la fissuration par dessiccation avec des cycles sec-humide multipliés. Nous concluons que le biochar affecte le comportement de fissuration par dessiccation des sols en occupant des espaces de retrait et en affaiblissant la liaison entre les particules de sol. De plus, le biochar influence le développement de la fissuration de dessiccation sous les cycles sec-humide en modifiant la structure des pores et le contact entre les agrégats du sol.

KEYWORDS: biochar, desiccation cracking, dry-wet cycles, quantitative analysis

1 INTRODUCTION

Biochar is a carbon-rich solid material obtained by pyrolyzing biomass materials, and has a broad application prospect as soil amendment (IBI, 2015). Biochar can effectively increase soil water retention capacity, alleviate soil erosion, improve nutrient utilization, sequester carbon (effectively mitigating climate change), and immobilize pollutants, etc. as soil amendment (Clurman et al., 2020; Grunwald et al., 2018; Wong et al., 2019; Yang et al., 2020). Biochar can enhance the activity of methane-oxidizing bacteria when applied in landfills, effectively reducing the emission of methane gas (Reddy et al., 2020). Biochar is also extensively applied in agricultural engineering for the enhancement of crop production and environmental engineering for the remediation of contaminated soil. Limited studies have investigated the influence of biochar on the engineering properties of soil from the perspective of soil mechanics, such as soil desiccation cracking.

Soil desiccation cracking is a very common phenomenon due to the mutual proximity shrinkage of soil particles during water evaporation. Due to the extreme weather caused by climate change (e.g., long-term drought) and the urban heat island effect, soil desiccation cracking has become more serious (Cheng et al., 2020). Soil desiccation cracking is a complex process, and its existence has a tremendous impact on the growth of vegetation and the migration of water and solutes in soil. The hydraulic and mechanical properties of soil are greatly affected by the desiccation cracking patterns, which may lead to various geoengineering problems and disasters (Bordoloi et al., 2020). In landfills, the generation of desiccation cracking may cause structural failures and release of toxic gases. Cracking may also reduce the mechanical strength and provide channels for rainwater infiltration, damaging slope stability. In the remediation of contaminated sites, the generation of cracks provides channels for the migration of pollutants and weakens the remediation efficiency (Huang et al., 2019; Tang et al., 2020).

Biochar can significantly change the pore structure of the soil, thereby affecting soil permeability, water retention and desiccation cracking of soil. According to previous studies, biochar can significantly increase the water holding capacity of silt clay and sand, mitigate water evaporation, and minimize desiccation cracking (Wang et al., 2020; Zhang et al., 2020; Zong et al., 2014). However, there are still few studies on the desiccation cracking characteristics of biochar-amended clayey soil. The present study carried out laboratory experiments to explore the effect of biochar on the desiccation cracking of a clayey soil under dry-wet cycles. Microstructure analysis was also conducted to help reveal the mechanisms.

2 MATERIALS AND METHODS

2.1 *Tested soil and biochar*

The soil, named Xiashu (XS), was collected from the middlelower reaches of the Yangtze River Plain in Nanjing, Jiangsu Province, China. According to the USCS classification, it is a lean clay (CL) (ASTM, 2017). The biochar was obtained from the Qingdao Belka Environmental Biological Engineering Co., Ltd, China. It was pyrolyzed from wood in an oxygen-limited environment at 500°C for 5 hours. XS soil and biochar were respectively dried and crushed, passed through a 0.25 mm sieve before sealing for further tests. The basic physical and chemical properties of the soil and biochar are shown in Table 1.

Table 1 Basic properties of XS soil and biochar

XS soil		Biochar	
Soil properties	Value	Physicochemical property	Value
Specific gravity	2.73	Pyrolysis temperature (°C)	500
Atterberg limit		Pyrolysis time (h)	5
Liquid limit (%)	34.5	Ash content (%)	28.3
Plastic limit (%)	17.0	pH	10.3
Plastic index	17.5	Specific surface area (m^2/g)	51.7
USCS classification	CL	Bulk density (g/cm^3)	0.47
Standard compaction test			
Max dry density (*Mg/m^3*)	1.70		
Optimum moisture content (%)	16.2		

2.2 *Preparation of samples*

The application rates of biochar were set at a mass ratio of 0, 0.5, 2, 4, 6, and 10 %. A total of 6 sets of experiments were carried out, each with a parallel sample. During experiment, the XS soil and biochar were mixed at a certain mass ratio in dry state. Water was then added to prepare a slurry sample with a water content of 80%. A mechanical mixer was used to ensure an even mixture of water-soil-biochar. The mixture was then sealed in a container for 48 hours. The detailed procedure of sample preparation can be found in Zhang et al., (2020).

2.3 *Experimental procedure*

All samples were placed in an air-conditioned room with a constant temperature of 25°C for drying, a camera and an electronic balance with an accuracy of 0.01 g were used to take pictures and weigh the sample at designed intervals, respectively. Therefore, the development process of the surface cracks and the weight change of the sample can be monitored.

The slurry samples with 0, 5, and 10% biochar content and 80% initial water content were prepared in the dry-wet cycle test, numbered D-WB0, D-WB5, and D-WB10, respectively. The samples were drying at a constant temperature of 25°C. After the weight of the sample being stable (change less than 0.01 g) for 2 hours, water was gradually added to wet the sample. When the weight of the sample reaches its initial value (i.e., the water content is 80%), the sample was sealed for 72 hours for homogenization. A total of 3 cycles of wetting and drying for each sample were applied.

2.4 *Image processing and quantitative analysis of cracks*

Quantization processing of the crack image using the NJU-CIAS developed by Nanjing University is illustrated in Figure 1. The process includes four steps: to convert the color image to grey (Figure 1a), binarization (Figure 1b), skeletonization (Figure 1c), and identification of the number of crack segments (Figure 1d). The quantitative parameters of cracks, such as surface crack ratio, number of crack segments, average crack width, and the total crack length, can be obtained. Details of the image processing can refer to Tang et al., (2008).

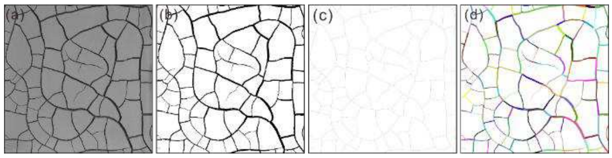

Figure 1. Procedures of image processing, (a) grey crack image; (b) binary crack image; (c) crack skeleton; (d) crack segments.

2.5 *Microstructural analysis*

To study the effects of biochar on the microstructure of XS soil, samples after evaporation with a size of 0.5×0.5×2 cm were prepared by the freeze-drying method for scanning electron microscope (SEM) test.

3 RESULTS

3.1 *Evaporation characteristic of biochar modified soil*

The evaporation process of soil water can be divided into a constant rate evaporation stage, deceleration rate evaporation stage, and residual stage. The evaporation rate is invariable at the constant rate evaporation stage. Therefore, the average evaporation rate of the first 60 hours of biochar-amended soil was selected as the reference value, and the first crack generation time was recorded.

With the increase of the amount of biochar, the evaporation rate of the amended soil tends to decrease first and then increase; the evaporation rate was lowest at 1.65 g/h with 0.5% biochar addition, 8.7% lower than the reference sample (Figure 2). A reduced evaporation rate was observed with the amount of biochar less than 4%. With 10% biochar addition, the evaporation rate reached 2.54 g/h, which was 41.1% higher than that of the sample without biochar. The time to generate the initial crack in amended clayey soil showed a trend of first increasing and then decreasing with the increment of the amount of biochar. The initial crack formation time of the 0.5 % biochar sample was 6 hours later than that of the reference sample. When biochar content reached 10%, the initial crack was formed at 46 hours, which is 28 hours earlier than the reference sample (74 hours). The initial crack development time has a negative correlation with the evaporation rate, high evaporation rate corresponds to less time of initial crack generation, and vice versa.

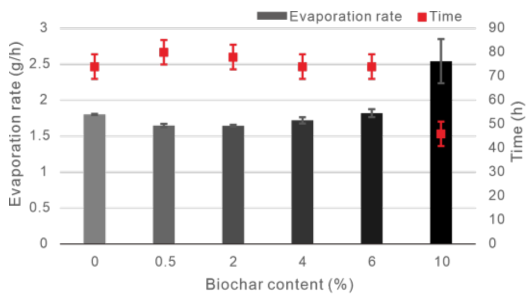

Figure 2. The evaporation rate and the time when the initial crack generated of biochar amended soil.

3.2 *Quantitative analysis of desiccation cracking*

Figure 3 shows the quantification results of desiccation cracking characteristics of biochar amended soil. Biochar reduced the area of desiccation cracking, promoted the generation of crack segments, and increased the total crack length. Due to the decrease of desiccation cracking area and the increase of total crack length, the average crack width becomes smaller.

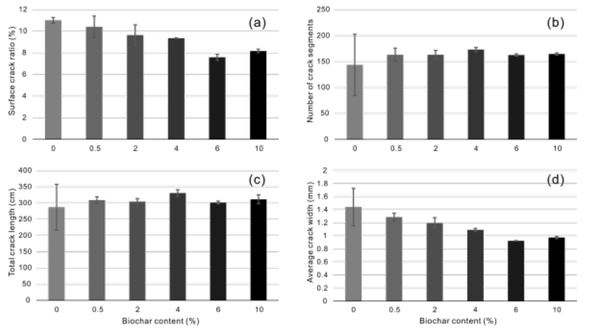

Figure 3. Quantitative parameters of biochar amended soil cracks with biochar application rates of 0, 0.5, 2, 4, 6 and 10%: (a) surface crack ratio; (b) number of crack segments; (c) total crack length; (d) average crack width.

3.3 *Effects of dry-wet cycles on cracks*

Figure 4 shows the desiccation cracking pattern of the samples that experienced 0 and 3 dry-wet cycles. There are wide cracks and narrow cracks on the surface of the 0-cycle sample, and the width difference between the two is obvious. After three dry-wet cycles, the number of crack segments increased significantly. The soil was divided into more small pieces, and the crack connectivity increased, which is in line with Tang et al., (2011). Compared with the reference sample, the crack development position of the biochar amended soil is still along with the crack position of the 0-cycle, and the biochar weakens the "healing" ability of XS soil.

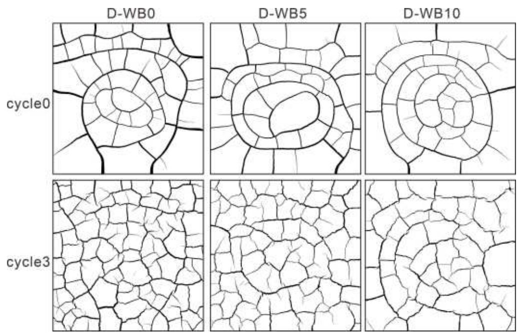

Figure 4. Desiccation cracking images for amended soil after 0 and 3 dry-wet cycles with the biochar addition of 0, 5, and 10% (D-WB0, D-WB5, and D-WB10 treatments, respectively).

To explore the influence of biochar on the development of desiccation cracking under dry-wet cycles, the contact relationship between the same volume of slurry droplets was used to simulate the soil aggregates on both sides of the crack after saturation, test results are shown in Figure 5. After the two droplets without biochar in contact, the surface was flat, and the contact surface with 5% biochar has a downward depression. The depression with 10% biochar was more significant. In the process of drying, the depression position becomes a stress concentration point and develops cracks. After the dry-wet cycle, the cracks with biochar were still in the original position, while the cracks of the sample without biochar developed randomly.

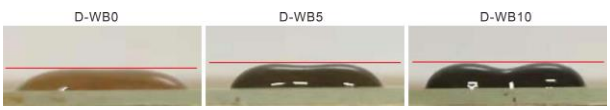

Figure 5. The contact surfaces of soil slurry droplets with different rate biochar application.

Figure 6 shows the crack quantification results of the samples that experienced 0 and 3 dry-wet cycles. At 0 cycles, biochar reduced the surface crack ratio and average crack width, increasing the number of crack segments and the total crack length. When the number of dry-wet cycles was 3, biochar reduced the surface crack ratio, the number of crack segments, total crack length, and the average crack width. The higher the amount of biochar, the more obvious the effect.

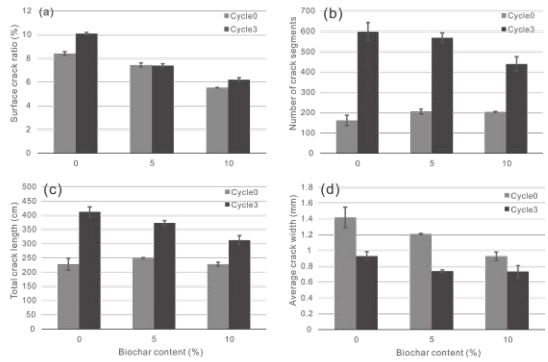

Figure 6. Crack quantitation results of amended soil experienced 0 and 3 dry-wet cycles with biochar addition of 0, 5, and 10%: (a) surface crack ratio; (b) number of crack segments; (c) total crack length; (d) average crack width.

3.4 *The microstructure of biochar amended soil*

Biochar-amended soil sample was subjected to SEM after evaporation experiment, and the results are shown in Figure 7. The structure of XS is loose and the surface has developed pores (Figure 7a & 7c). Biochar particles are embedded in soil aggregates (Figure 7b). The connection between biochar and soil particles is not tight, and biochar makes the soil structure looser and porous (Figure 7d). According to the results of Mercury Intrusion Porosimetry (MIP) test, the porosity of the reference sample was 18.86%, 34.31% with 6% biochar addition, which was 81.92% higher than the control, biochar significantly increased the porosity of the soil.

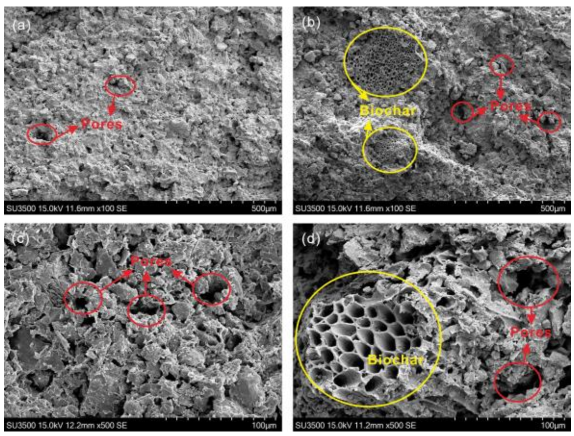

Figure 7. SEM image of biochar amended soil: (a) (c) without biochar, (b) with 2% biochar, (d) with 6% biochar.

4 DISCUSSION

The factors affecting soil water evaporation include internal factors and external factors. The test was carried out in a constant temperature and humidity environment, so the main factors are the internal factors related to the soil structural characteristics and hydraulic properties. At low dosage, biochar has little effect on the soil microstructure, and biochar particles are scattered in the soil aggregates. The loose and porous characteristics of biochar can store some water, thus mitigating the evaporation

(Yang et al., 2020). A higher dosage of biochar significantly increases the porosity of the soil and induces looser structure of amended soil. The water inside the soil can migrate to the evaporation surface more smoothly, increasing the evaporation rate. On the other hand, the addition of biochar promotes the development of crack segments, and the crack surface becomes a new evaporation surface, increasing the evaporation rate (Zhang et al., 2020). Biochar affects the evaporation rate of soil and thus the generation time of desiccation cracking.

The occurrence of desiccation cracking is closely related to the tensile stress and tensile strength of the soil. In the drying process, because of the loss of water due to evaporation, suction and tensile stress are developed. Once the tensile stress exceeds the tensile strength in the partial region, cracks developed. According to Zong et al., (2014), biochar reduces the density and the overall cohesion of soil, thereby weakening the binding force between particles and reducing the tensile strength of the soil. Therefore, biochar makes soil easy to generate cracks, increasing the number of crack segments and the total length of the cracks. As a non-plastic material (Sadasivam and Reddy, 2014), biochar is evenly embedded in soil aggregates. In the process of drying, biochar occupies the shrinkage space of soil particles, inhibiting the development of wide cracks, thereby reducing the area and width of the cracks.

Dry-wet cycles reduce the homogeneity of the soil structure, resulting in increased roughness of the desiccation cracking network (Tang et al., 2011). After 3 dry-wet cycles, the roughness of desiccation cracking is significantly stronger than 0 dry-wet cycles (Figure 4). Compared with the reference sample, biochar resulted in irregular pores (Figure 7), and the uniformity of soil was reduced. After multiple dry-wet cycles, the structural uniformity of the reference sample was reduced to a greater degree than biochar amended soil. In the process of saturation, cracks began to heal. Base on the contact of slurry droplets, the healing degree of the cracks in the biochar amended soil was significantly lower than that of the reference sample (Figure 5). With the loss of evaporative water, the tensile strength cannot be restored to the original level. The biochar amended soil is easier to develop cracks in the original crack healing position compared with the reference sample. Therefore, biochar changes the desiccation cracking network morphology of samples under the dry-wet cycles by affecting the pore structure of the soil, the contact condition of the aggregates, and the tensile strength.

5 CONCLUSIONS

In this study, the effect of biochar on the desiccation cracking behavior of XS experienced multiple dry-wet cycles was investigated. Biochar changes the evaporation rate of Xiashu soil. The evaporation rate shows a trend of first decreasing and then increasing with the increment of biochar addition. Repeated dry-wet cycles enhanced the heterogeneity of soil, thus reducing the smoothness of the desiccation cracking patterns. Biochar reduced the surface crack ratio and the average crack width by changing the pore structure and occupying shrinkage space, and this effect was more significant at higher biochar addition. Biochar can change the contact between soil aggregates and affect the healing ability of soil cracks. To date, only the effect of biochar on the desiccation cracking of clayey soil was studied indoor. In the future, it will be necessary to apply biochar on-site to explore its effect on the desiccation cracking characteristics in field conditions.

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