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Effect of Dry and Wet Cycles on the Strength Characteristics of Biochar–Clay Mixture

Deyang Liu [1], Wenjing Sun [2,*], Yi Kong [3] and Shuyun Zhang [1]

1 Department of Civil Engineering, School of Mechanics and Engineering Science, Shanghai University, Shanghai 200444, China
2 Department of Civil Engineering, College of Environmental Science and Engineering, Donghua University, Shanghai 201620, China
3 Shanghai City Operations Group, Shanghai 200062, China
* Correspondence: wjsun@dhu.edu.cn

Abstract: Biochar is an economical and environmentally friendly "green material" with potential benefits in greenhouse gas emission reduction, soil performance improvement, and environmental restoration. Mixing biochar with clay and using it as a landfill cover can effectively reduce the escape of greenhouse gases into the air, which is important for environmental protection. It is suggested that biochar should be mixed with clay and used as a landfill covering layer. In this study, the shear strength was obtained by direct shear test, and the shear strength characteristics of biochar–clay mixture under the influence of different dry and wet cycles, biochar contents, and moisture conditions were studied. The results show that the shear strength of the biochar–clay mixture in the saturated state decreases with increasing wet and dry cycles, with shear strength decreases ranging from 6% to 19%. The cohesion and internal friction angles of the clays and mixtures show a decreasing trend under wet and dry cycles, with the cohesion and internal friction angles decreasing in the range of 2% to 16%. The shear stress–shear displacement curve for the biochar–clay mixture in the saturated state shows strain hardening after wet and dry cycles; the curve in the dry state shows strain softening with a distinct peak and a platform at the front end of the curve. The shear strength of clay in a dry state is larger than that of biochar–clay mixture and always larger than that of clay in a saturated state. The shear strength difference of the mixture between dry and saturated states is obviously smaller than that of pure clay. This paper, therefore, provides theoretical guidance for the application of biochar–clay mixtures to landfill covers.

Keywords: landfill covering layer; dry and wet cycles; biochar–clay mixture; shear strength

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1. Introduction

Landfills have become the most common method of municipal solid waste disposal in most countries [1]. In recent years, the thickness of landfills has reached tens or even hundreds of meters, and the overload of waste is prone to shear damage and cracks, which lead to methane escape, leachate leakage, and collapse in landfills, causing great safety hazards to the surrounding ecological environment [2–5]. Therefore, it is urgent to study the shear strength characteristics of the landfill covering layer.

In traditional landfills, compacted clay is used as a material for the landfill covering layer [6]. Unsaturated soils undergo drying and wetting cycles due to varying daily and yearly seasons change [7,8]. The void ratio, water content, water dispersion, porosity, particle flocculation, and cementation of soils are all dramatically altered by the drying–wetting cycles, which have been recognized as essential elements in the behavior of soil properties [8–12]. The incorporation of biochar increases the shear strength of the soil [13,14].

Xu et al. [13] studied the strength characteristics of biochar–clay mixture with different biochar contents and found that the shear strength of biochar–clay mixture increased with the increase in biochar contents. Hussain et al. [14] investigated the shear strength of biochar-modified clayey sandy soils and found that biochar incorporation increased the shear strength, cohesion, and internal friction angle of the mixture. Li et al. [15] studied the strength characteristics of biochar–clay mixture with different biochar contents and found that when the biochar contents are low, the soil's stress–strain curve shows a strain hardening state as the strain increases. When the biochar content is greater than 10%, the stress–strain curves of the biochar–clay mixtures showed a softened state.

In general, soils undergo alternate wetting–drying (W–D) cycles with seasonal moisture variations, which can significantly affect the enhancement of shear strength by biochar. In addition, the W–D cycle may damage the soil structure and reduce shear strength [16], thereby threatening the normal use of buildings such as slopes and landfills. Therefore, in order to promote the use of biochar in green infrastructure, it is important to investigate the long-term effects of the W–D cycles on the strength of clay amended with biochar. However, less research has been conducted on this topic. Wang et al. [17] found that the addition of biochar improved the internal friction angle and cohesion of expansive clay, and the W–D cycles affect shear strength mainly by the formation of microchemical bonds, the reduction of void ratio, and the crack intensity factor. Lu et al. [18] found that the surface crack ratio of soil without biochar addition first increased and then stabilized with an increase in the number of wetting–drying (W–D) cycles, while that of the biochar-amended soil decreased slightly. Influenced by precipitation and evaporation, the variation of shear strength of biochar–clay mixture is concerned with the safety of landfills. The dry and wet cycles, biochar contents, and water condition of the soil after the W–D cycles [17–19] affect the strength of biochar–clay mixture. As mentioned above, it is necessary to study the effects of W–D cycles on the strength properties of biochar–clay mixture.

In this study, direct shear tests were conducted on the biochar–clay mixture after experiencing different numbers of dry and wet cycles to obtain the variation of shear strength and investigate the effects of the number of dry and wet cycles (N = 0,1,3,6), biochar contents (α = 0%, 5%, 10%, 15%), and moisture condition (saturated, dry state) on the strength characteristics of the soil. A theoretical guide for the application of biochar–clay mixes to practical landfill overburden projects.

2. Materials and Methods

2.1. Materials

The test materials were clay, biochar, and deionized water. The biochar was produced by Liyang, Desheng Company and was obtained by pyrolysis of rice straw at a temperature of 500 °C under oxygen-limited conditions. Before the test, biochar was passed through a 74 µm sieve to prepare the biochar with a particle size of less than 74 µm. The clay used in the test belongs to the low-liquid limit clay. The basic physical and chemical indicators of the biochar and clay are shown in Table 1. Figure 1 shows the grain-size distributions of the clay and biochar. From Figure 2, we can observe that biochar has a porous structure. Table 1 and Figure 1 parameters are measured according to the standard for the soil test method (GB/T50123—2019) [20]. Its ash content was 18.8%, based on the ASTM D 1762–84 standard test method [21]. To obtain the mass loss rate, 20 g of biochar was placed in a muffle furnace at a temperature of 800 °C for 4 h, and the quality loss was obtained. The porosity of the internal structure of the biochar can be observed.

2.2. Apparatus

The 25SIXTY SHEAR direct shear apparatus developed by Humboldt, USA, was used for the direct shear test, as shown in Figure 3. The direct shear apparatus uses air pressure to apply vertical pressure. According to the experimental data, the shear stress–shear displacement curves of the mixture are drawn. If there is a peak in the curve, the shear stress corresponding to the peak is taken as the shear strength. If there is no obvious peak, the shear stress corresponding to the shear displacement of 4 mm is taken as the shear strength. The shear rate was 0.80 mm/min.

Table 1. Basic indicators of biochar–clay mixture.

Biochar							
Bulk Density ρ (g/cm^3)		**Specific Surface Area *AAS*/(m^2/g)**		**Specific Gravity d_s**	**pH**	**Ash Content (%)**	
0.55		385.60		1.99	9.8	18.80	
α (%)	Liquid limit w_L (%)	Plastic limit w_P(%)	Plasticity index I_p	Maximum dry density ρ_{dmax} (g/cm^3)	Optimum moisture content w_{opt} (%)	Specific gravity d_s	pH
0	35.98	22.20	13.78	1.65	22.40	2.72	7.70
5	41.13	22.96	18.17	1.56	23.80	2.64	7.90
10	42.15	25.92	16.23	1.42	28.70	2.60	8.00
15	45.44	28.39	17.05	1.27	29.30	2.57	8.30

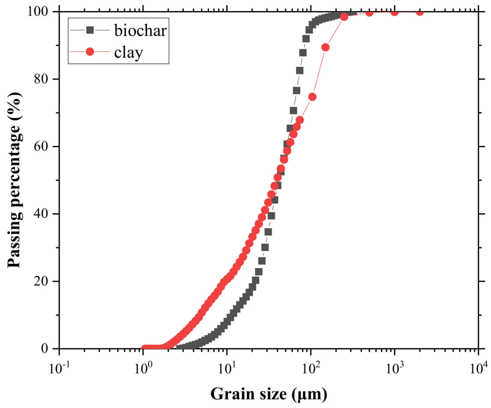

Figure 1. Grain-size distributions of the clay and biochar.

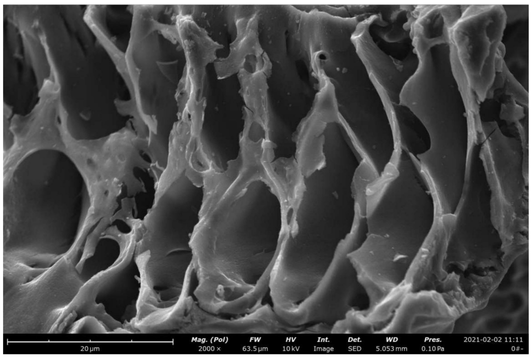

Figure 2. Microscopic morphological characteristics of biochar.

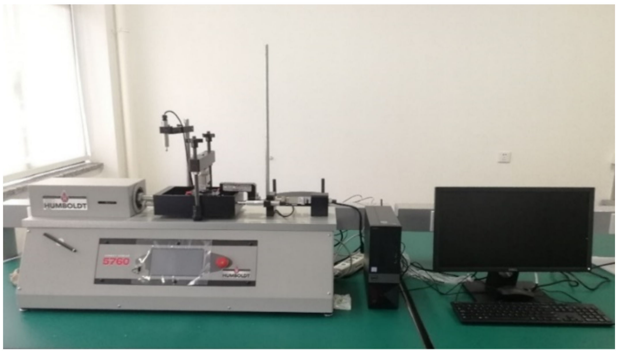

Figure 3. Pneumatic direct shear apparatus.

2.3. Test Method

The clay used in the test was placed in an oven at 105 °C and dried for 8 h. The mass percentages of the biochar mixed with soil were 0%, 5%, 10%, and 15%. The initial dry density was selected according to the technical code for municipal solid waste sanitary landfill closure [22]; the degree of compaction of the landfill cover soil should not be less than 90% of the standard proctor maximum dry density (SPMDD) of the clay. The initial water content of 14% is the natural water content measured according to the standard for the soil test method (GB/T50123—2019) [20]. The biochar–clay mixture was placed in a sealed plastic bag for 24 h to ensure they were mixed well. After standing for 24 h, the biochar–clay mixture was placed in a sample maker with a diameter of 4.95 cm and a height of 2 cm, and the specimens were compacted by a hydraulic jack.

The dry and wet cycle test is mainly based on the ASTM D559 test method, with minor adjustments to the engineering practice [23]. The compacted sample was put into a stacked saturator, vacuumed for 3 h with a vacuum pumping cylinder, and then saturated with deionized water for 24 h, which is a saturation process. At this time, the saturated state of the sample, named saturated state 1 (S1), represented a sample that was in a saturated state under a dry and wet cycle 1 time. The samples saturated after 24 h were placed in the oven for drying; the drying temperature was set to 40 °C, and the drying time was 24 h, which is a drying process. At this time, the dry state of the sample named dry state 1 (G1) represented a sample that was in a dry state under a dry and wet cycle 1 time. One saturation and one drying process is a dry and wet cycle process. The above test steps were repeated until the sixth dry and wet cycle was completed. The dry and wet cycle test program is shown in Figure 4.

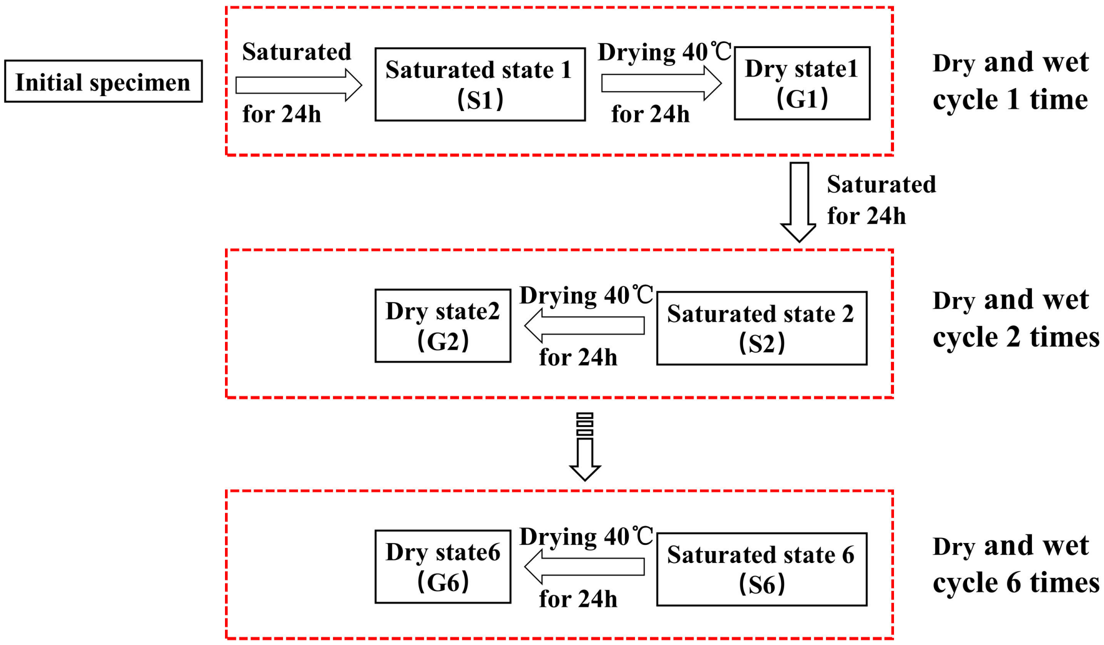

Figure 4. Dry and wet cycle test program.

Direct shear tests were conducted on the biochar–clay mixture in a saturated or dry state under 1, 3, and 6 dry and wet cycles. The shear test is mainly based on the Standard for Soil Test Method [20]. The shear rate was controlled to be 0.8 mm/min, and the loading vertical pressure was 100 kPa, 200 kPa, and 400 kPa. The specific direct shear test schemes for the samples are shown in Table 2. Two parallel samples were set up for each working condition, and repeated tests were carried out. The results were averaged.

Table 2. Direct shear test scheme for samples in saturated and dry states after dry and wet cycles.

Number	Biochar Contents α (%)	State	Dry Density ρ_d (g/cm^3)	Number of Cycles N	Vertical Pressure P (kPa)
0-S1				1	
0-S3	0			3	100/200/400
0-S6				6	
5-S1				1	
5-S3	5			3	100/200/400
5-S6		Saturated/Dry	1.5	6	
10-S1				1	
10-S3	10			3	100/200/400
10-S6				6	
15-S1				1	
15-S3	15			3	100/200/400
15-S6				6	

3. Results

3.1. Shear Stress–Shear Displacement Curves of Biochar–Clay Mixture after Dry and Wet Cycles

Figure 5 shows the shear stress–shear displacement curves of the biochar–clay mixture, which are in the saturated state with different dry and wet cycles and under normal stress of 200 kPa. It can be seen from the figure that the shear stress–shear displacement curve of the mixture in the saturated state is a weak hardening type without an obvious damage peak. The shear strength of the mixture in the saturated state increases with the increase in the biochar contents under the same conditions of the dry–wet cycles and normal stresses.

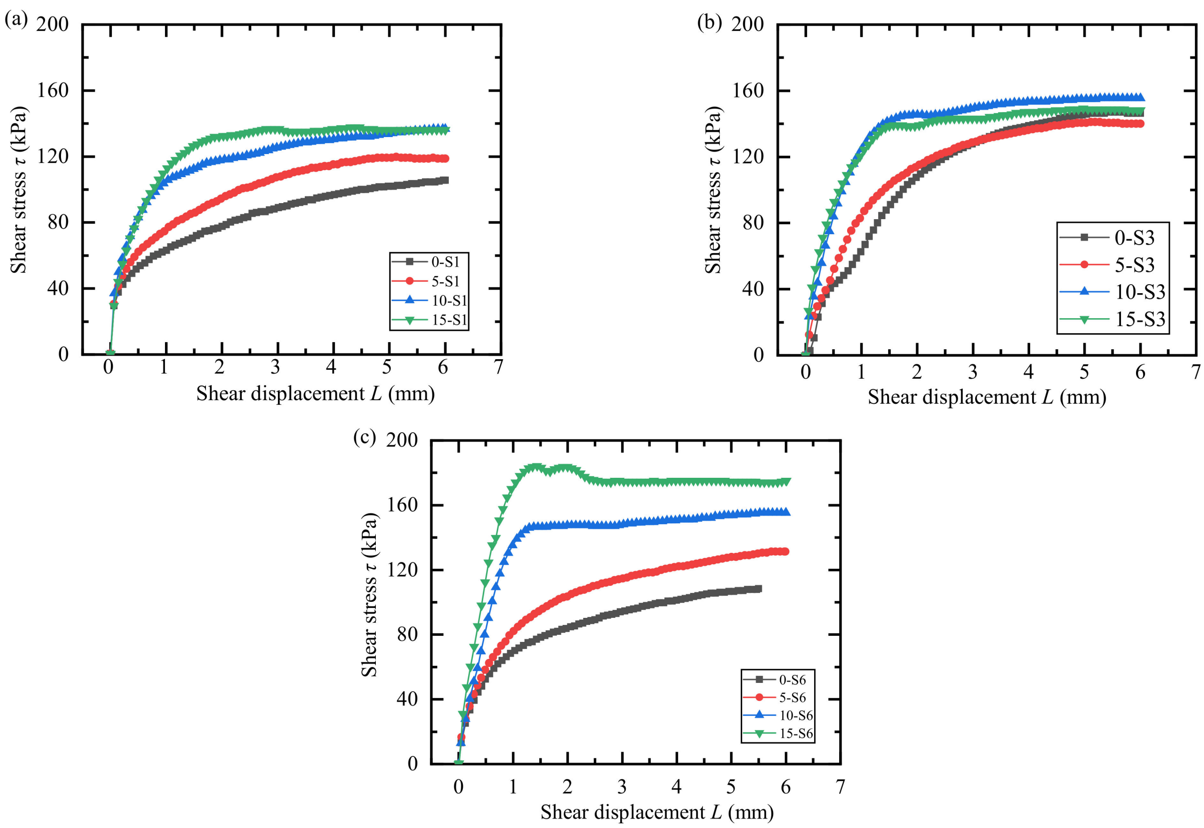

Figure 5. Shear stress–shear displacement curves of biochar–clay mixture in saturated state under dry and wet cycles (Normal stress 200 kPa): (**a**) N = 1; (**b**) N = 3; (**c**) N = 6.

Figure 6 shows the shear stress–shear displacement curves of the biochar–clay mixture in a dry state with different biochar contents under different dry–wet cycles and normal stress of 200 kPa, and the same for other normal stresses. It can be seen that the shear stress–shear displacement curve of the mixture in a dry state under the dry and wet cycles is strongly strain-softening with an obvious damage peak. After the damage peak, the stress decreases with the increase in the shear displacement. The shear strength of the mixture increases with the increase in the normal stress. Under the same dry–wet cycles and normal stress, the shear strength of the clay in the dry state is greater than that of the mixture. Under the same biochar contents, the shear strength does not change uniformly with the increase in the dry and wet cycles. When the biochar contents are 0% and 5%, the front of the curve appears plateaued; that is, the shear stress is basically unchanged with the increase in the shear displacement; when the biochar contents are 10% and 15%, the front of the curve does not appear plateaued.

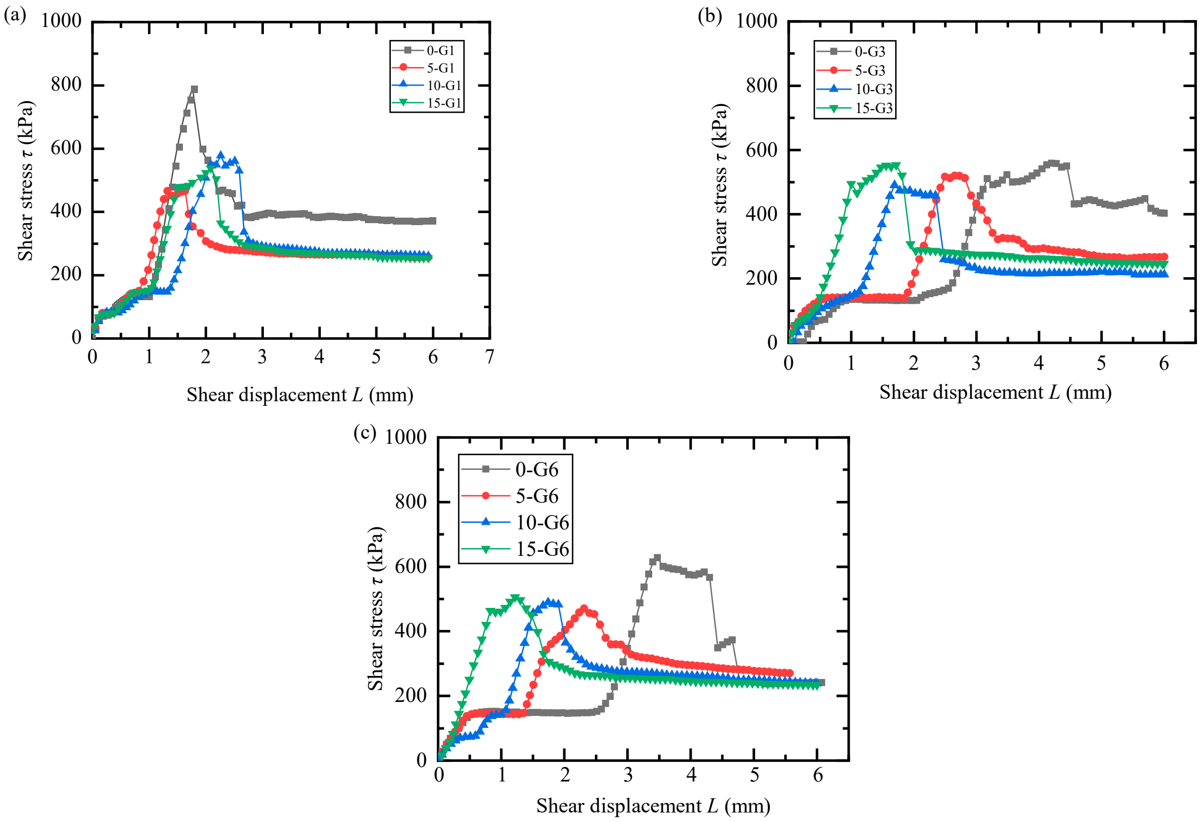

Figure 6. Shear stress–shear displacement curves of biochar–clay mixture in dry state under dry and wet cycles (Normal stress 200 kPa): (**a**) $N = 1$; (**b**) $N = 3$; (**c**) $N = 6$.

3.2. Shear Strength of Biochar–Clay Mixture after Dry and Wet Cycles

Figure 7 shows the variation relationship between the shear strength and normal stress of the biochar–clay mixture with different biochar contents under different dry and wet cycles. It can be seen from the figure that the shear strength in both the saturated and dry states increases with the increase in the normal stress. The change in the increase in positive stress with one, three, and six wet and dry cycles in the saturated condition was 72%, 84%, and 70%, respectively; the change in the increase in positive stress with one, three, and six wet and dry cycles in the dry condition was 267%, 147%, and 200%, respectively. The increase with positive stress in the saturated state is smaller than the increase with positive stress in the dry state. When the number of dry and wet cycles is the same, the relationship between the shear strength and normal stress of the dry mixture is located above the saturated mixture, indicating that the shear strength of the dry mixture is greater than that of the saturated mixture.

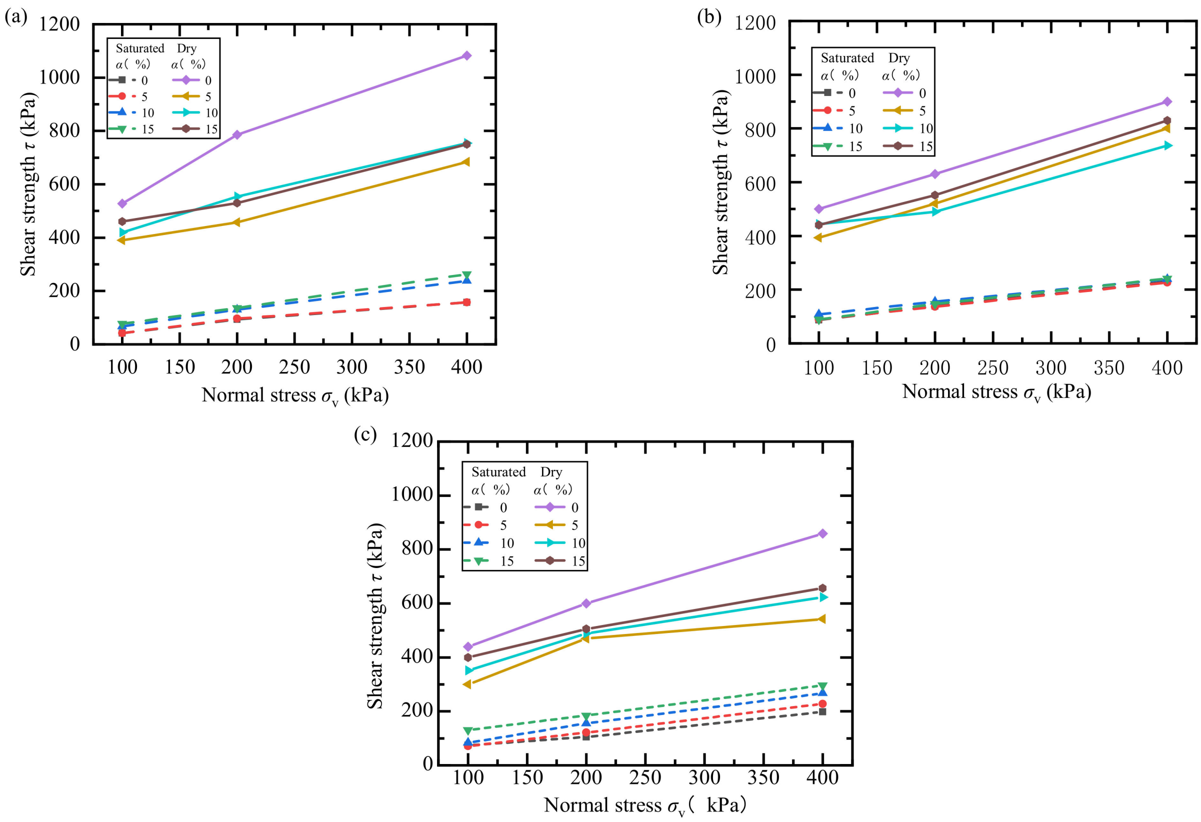

Figure 7. Variation relationship between shear strength and normal stress of biochar–clay mixture with different biochar contents under different dry and wet cycles: (**a**) $N = 1$; (**b**) $N = 3$; (**c**) $N = 6$.

The reason why the shear strength in the saturated state is less than the shear strength in the dry state is that the water film on the surface of the soil particles in the saturated state becomes thicker, the free water in the pores increases, the water plays a lubricating role, and the friction between the soil particles decreases, resulting in a weaker frictional resistance between the particles; the soil particles in the dry state see no water, which has no effect on the frictional resistance between the soil particles and, therefore, the shear strength is greater than the shear strength in the saturated state. This is because, in the dry state, the soil particles will lose water and shrink, the volume becomes smaller, and the friction force between the particles is larger, so the shear strength of the mixture in the dry state is larger. While in the saturated state, the water film on the surface of the soil particles thickens, the free water in the pores increases, the water plays a lubricating role, and the cohesion and friction between the soil particles decrease, resulting in a weaker frictional resistance between the particles. The cohesive force between the soil particles is reduced, which [14] makes it easier to produce sliding, so the shear strength is small. Therefore, the shear strength of the biochar–clay mixture in the saturated state is less than the shear strength of the biochar–clay mix in the dry state.

Figure 8 shows the variation relationship between the shear strength and the number of dry and wet cycles of the biochar–clay mixture with different biochar contents under different normal stresses. It can be seen that the shear strength of the mixture in the dry state decreases with the increase in the dry and wet cycles. The reductions at 100 kPa, 200 kPa, and 400 kPa are 21%, 14.5%, and 14%, respectively. The shear strength of the mixture in the saturated state with 15% biochar contents increases with the increase in the dry and wet cycles. The increases at 100 kPa, 200 kPa, and 400 kPa are 24%, 35%, and 13%, respectively. The shear strength of the other mixture increases first and then decreases with the increase in the dry and wet cycles.

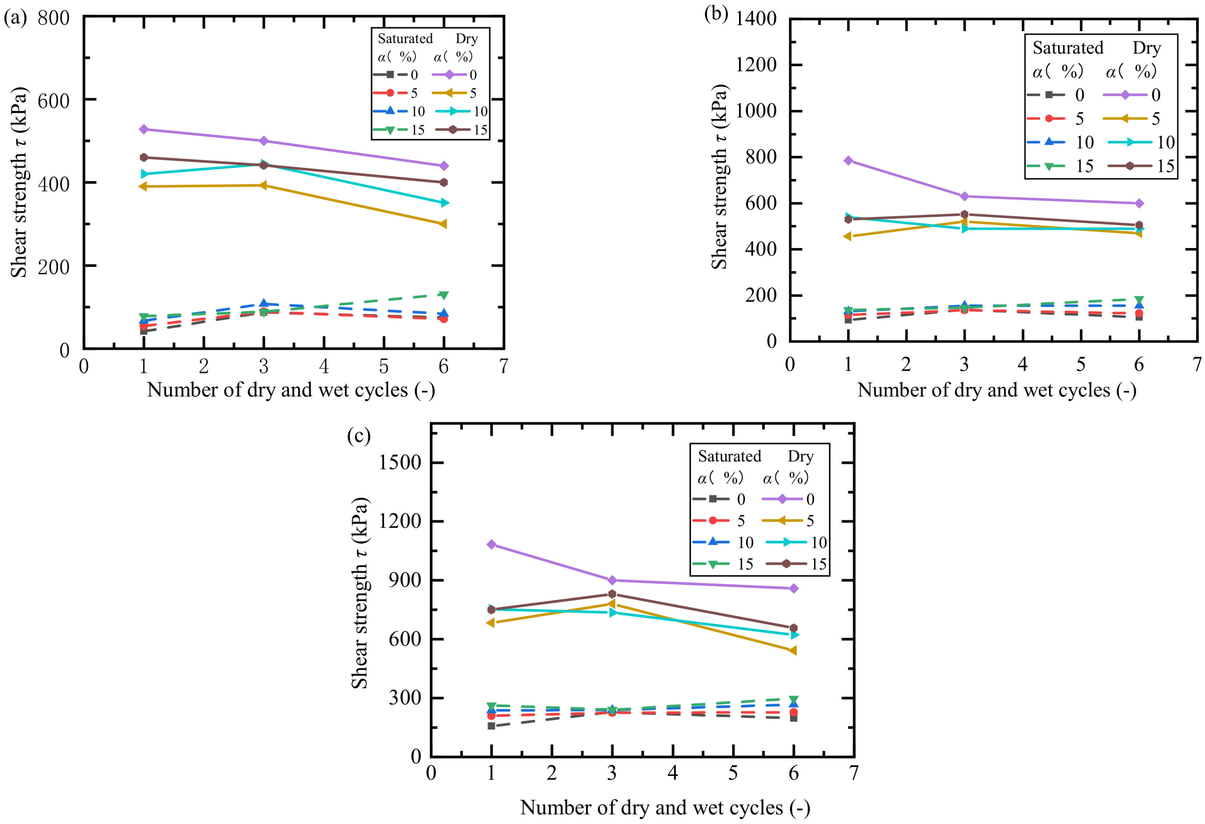

Figure 8. Variation relationship between shear strength and the dry–wet cycles under different normal stresses: (**a**) σ_v = 100 kPa; (**b**) σ_v = 200 kPa; (**c**) σ_v = 400 kPa.

It can be seen from Figures 6 and 7 that the moisture state of the sample after the dry and wet cycles has a great influence on the shear strength of the biochar–clay mixture, and $d_{\tau f}$ is defined as the peak strength difference in the shear stress–shear displacement curve between the biochar–clay mixture in the dry state and the saturated state.

Figure 9 shows the difference in shear strength between the biochar–clay mixture in the dry and saturated states at different normal stresses. It can be seen from the figure that the difference in shear strength between the clay at the two water content states is the largest and decreases with increasing wet and dry cycles. The reduction is 25%, 28%, and 28% at 100 kPa, 200 kPa, and 400 ka, respectively. The difference in shear strength for mixtures with 5%, 10%, and 15% biochar contents is less than the difference in shear strength for clay; the difference in shear strength decreases overall with increasing and decreasing wet and dry cycles, with reductions of 22%, 25%, and 21% respectively.

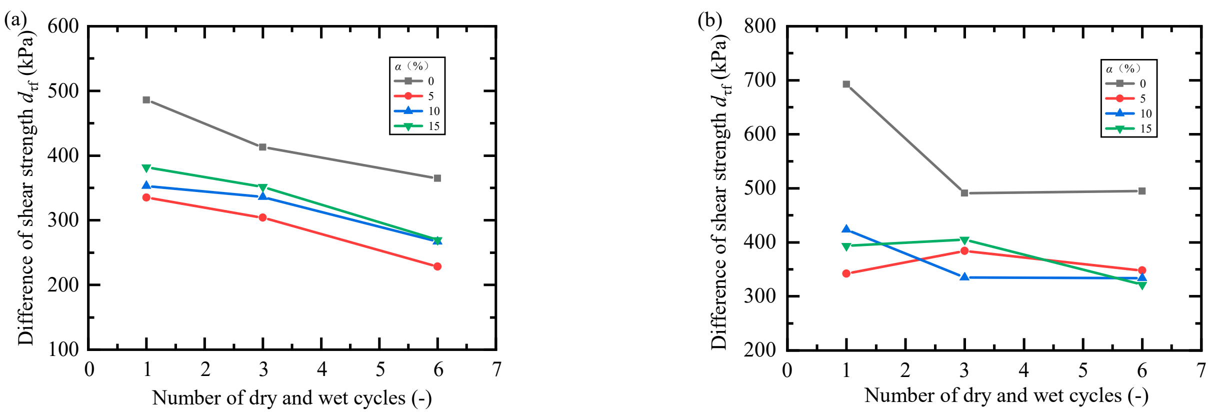

Figure 9. *Cont.*

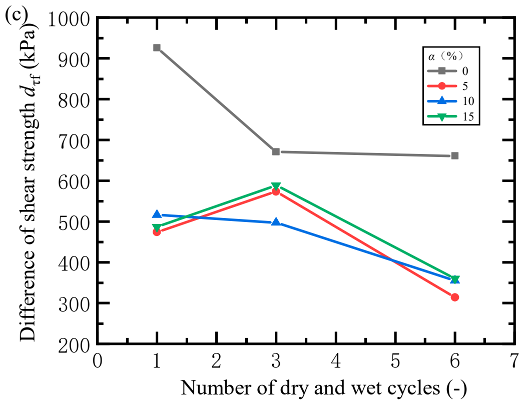

Figure 9. Shear strength difference in biochar–clay mixture between dry and saturated states under dry–wet cycles and different normal stresses: (**a**) σ_v = 100 kPa; (**b**) σ_v = 200 kPa; (**c**) σ_v = 400 kPa.

3.3. Cohesion and Internal Friction Angle of Biochar–Clay Mixture after Dry and Wet Cycles

Figure 10 shows the relationship between the cohesion of samples and different dry–wet cycles. It is found that the cohesion of the clay is the largest in the dry state, and the cohesion of the biochar–clay mixture increases with the increase in the biochar content. The increase in biochar fills the pores between the particles and, thus, increases the friction between the particles, making the cohesion increase with the increase in biochar. The cohesion of the mixture decreases with the increase in the dry and wet cycles. In the saturated state, the cohesion of the mixture with 15% biochar contents increases with the increase in the dry and wet cycles. The cohesion of the clay and the mixture with 5% and 10% biochar contents increases first and then decreases with the increase in the dry and wet cycles.

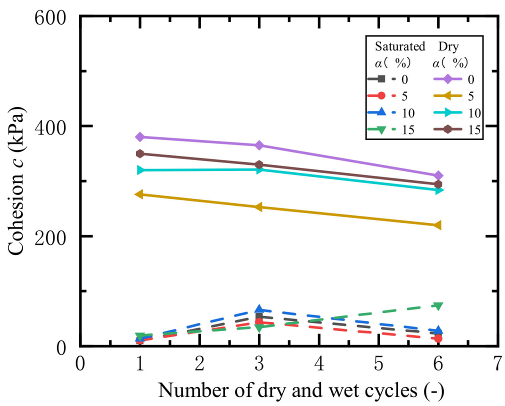

Figure 10. Relationship between cohesion and the number of dry–wet cycles.

Figure 11 shows the relationship between the internal friction angle of the samples and the different wet and dry cycles. It can be found that the internal friction angle of the clay in the dry state decreases with increasing wet and dry cycles, decreasing to 11%. The internal friction angle of the biochar–clay mixture decreases with the overall trend of dry and wet cycles, with a decrease of 16%, 14%, and 2% for biochar doping of 5%, 10%, and 15%, respectively. The internal friction angle of the clay in saturated conditions decreases with increasing wet and dry cycles, and shear strength reduces by 5%. The internal friction angle of the biochar–clay mixture increased with the overall trend of dry and wet cycles, with increases of 12.7%, 7%, and 7% for 5%, 10%, and 15% of biochar doping, respectively. The internal friction angle of the clay and mixture in the saturated state was smaller than in the dry state.

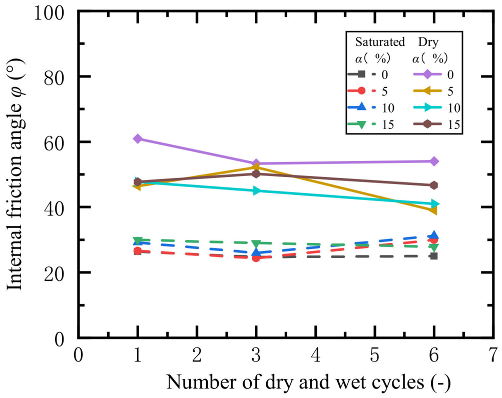

Figure 11. Relationship between internal friction angle and the number of dry–wet cycles.

4. Discussion

4.1. Mechanisms of Biochar Contents on the Strength Characteristics of Biochar–Clay Soil Mix

Figure 12 shows the microstructure of the mixture with different biochar contents. When the biochar content is 0%, that is, pure clay, it can be seen from the figure that the clay particles bond and aggregate to form clay agglomerates, the soil particles forming the agglomerates are arranged closely, and the adjacent agglomerates are interconnected to form a clay skeleton. When the biochar contents are 5% and 15%, the soil particles of the biochar–clay mixture are evenly distributed without forming obvious agglomerates. The soil particle arrangements become more uniform and compact, and the number of pores in the soil samples decreases with the increase in the biochar contents. Li [14] conducted SEM micro-morphological tests on specimens of biochar–clay hybrid soil in the initial state with different biochar admixtures. The test results were consistent with Li.

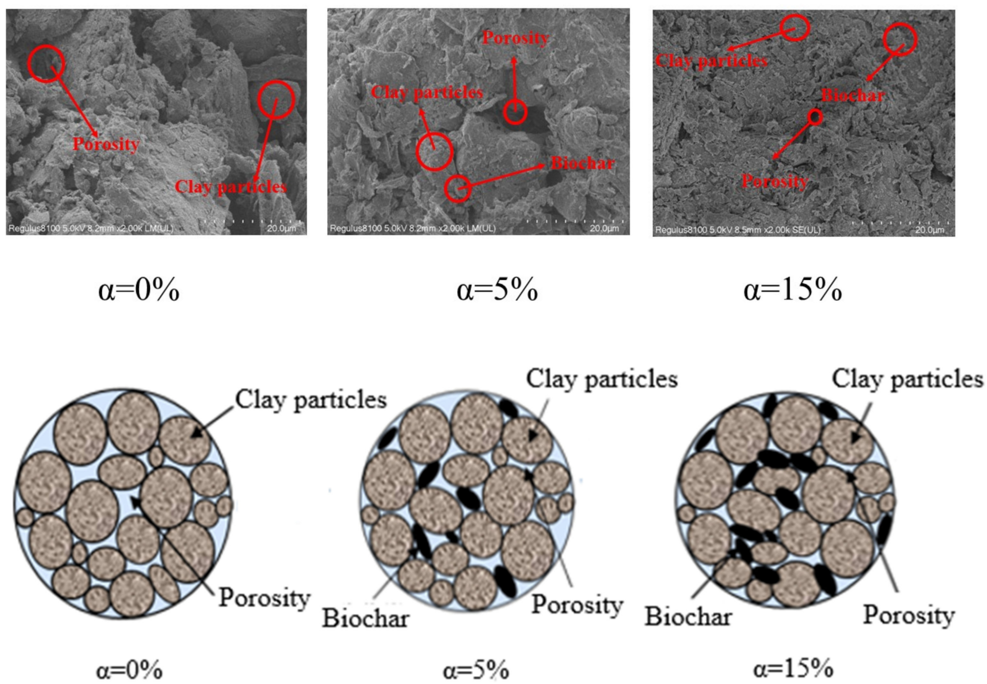

Figure 12. The microstructure of the mixture with different biochar contents.

In the dry state, the water loss inside the clay makes the agglomerates close and contact closely, while the volume of the soil shrinks and the dry density increases, causing the shear strength to increase. For the mixture, because of the incorporation of biochar, the cohesive force of the mixture is smaller than that of the clay, the number of clay agglomerates is reduced, and the texture of the mixture is looser than that of the clay, and the volume of the mixture does not reduce after a water loss, so the shear strength of the mixture is smaller than that of the clay. In the saturated state, the clay has a large number of internal pores and a large water content. Water will play a lubricating role between the soil particles, reducing the frictional resistance between the particles and becoming prone to the relative movement between the particles, so the shear strength is small. While the biochar–clay mixture is more uniform and has fewer pore numbers, less water content, and less lubrication, the shear strength of the mixture in the saturated state is greater than that of the clay. The amount of water in the pores of the sample decreases with the increase in the biochar contents, so the shear strength of the mixture in the saturated state increases with the increase in the biochar contents.

4.2. Mechanism of the Effect of Dry and Wet Cycles on the Strength Characteristics of Biochar–Clay Mixture

In the drying path, soil deterioration and crack propagation occur owing to the effect of desiccation kinetics, causing the loss of water [24,25]. In the subsequent wetting process, the internal available pore spacing and cracks of the soil are gradually filled with water. After the dry and wet cycles, the cohesion of the clay and biochar–clay mixture shows a decreasing trend. When the dry–wet cycles happen more often, cracks appear, the connection between the soil particles is not close, and the cohesion is weak [26]. During the drying process, the soil is dehydrated and contracted, and the clay and biochar–clay mixture particles are bonded to each other. The friction between the particles and the internal friction angle is larger. In the saturation process, the pores are filled with water which plays a lubricating role between the soil particles, reduces the friction resistance between particles, and is prone to relative motion between the particles, weakens the cementation between the particles [27], and reduces the internal friction angle. However, as the number of dry and wet cycles increases, the internal friction angle of the clay and biochar–clay mixture decreases as a whole. The above analysis further shows that the volume of macropores in the biochar–clay mixture increases after a wet–dry cycle, and the microcracks that form can be connected, resulting in a decrease in the biochar–clay mixture strength [28].

The reason why the angle of internal friction did not increase significantly with increasing biochar content in saturated conditions is mainly due to the fact that the available pores and cracks within the biochar–clay mix are gradually filled with water in saturated conditions and that the water acts as a lubricant between the soil particles and weakens the effect of the biochar on the angle of internal friction due to the strong water holding capacity of the biochar [29]. So biochar addition at saturation did not change the angle of internal friction, obviously.

5. Conclusions

In this paper, direct shear tests were conducted on the biochar–clay mixture after different numbers of dry and wet cycles to obtain the variation of shear strength. The influence of biochar contents, dry–wet cycles, and moisture conditions on the shear strength of biochar–clay mixture was studied. It provides a reference for the landfill covering layer. The main conclusions are as follows:

(1) In the saturated state, the shear stress–shear displacement curve of the mixture after dry and wet cycles is weakly hardened; under the same dry and wet cycles, the shear strength increases with increasing biochar contents, with increases of 18%, 18%, and 10% at 100 kPa, 200 kPa, and 400 kPa of vertical pressures, respectively; under the same normal stress, the shear strength generally decreases with dry and wet cycles, with a decrease of approximately 11%. Shear strength reduction range from 6% to 19%;

(2) In the dry state, the shear stress–shear displacement curve of the mixture is strain-softened; at the same biochar contents, the shear strength of the clay and the mixture

decreases with the number of dry–wet cycles. Shear strength reduction range from 14% to 21%;

(3) After the clay and biochar–clay mixture undergoes dry–wet cycles, the particles are denser, and the cohesion and internal friction angle of the clay and biochar–clay mixture in the dry state are greater than those in the saturated state. The cohesion and internal friction angle of clay and biochar–clay mixture show a decreasing trend after dry and wet cycles. The angles of internal friction and cohesion reduction range from 2% to 16%.

The shear strength behaviors of biochar–clay mixtures were investigated regarding wetting–drying cycles only under two extreme conditions, i.e., saturation and dryness. However, in real situations, the saturation degree of biochar–clay landfills complicatedly varies with rainfall, evaporation, and seasonal climate; that is to say, the unsaturation conditions prevail in engineering practice. Thus, there is still a need for further efforts to study the shear strength behaviors regarding wetting–drying cycles for unsaturated soils.

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Conflicts of Interest: The authors declare no conflict of interest.

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