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Study on the regulation effect of biochar on the engineering properties of domestic sources contaminated soil

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ABSTRACT
Domestic sources contaminated soil exhibits low strength and high carbon emissions, while biochar offers potential advantages for low-carbon green reinforcement. This study simulated the reinforcement treatment of domestic sources contaminated soil using biochar by remodeling biochar-added contaminated clay. It revealed that the adding biochar to domestic source contaminated clay significantly affecting its physicochemical and engineering properties. When the particle size of biochar is 1-3 mm and the dosage is 12%, a better comprehensive treatment effect can be achieved. The soil pH increased from 6.4 to 7.5, the cohesion increased from 23.57 kPa to 47.02 kPa, and internal friction angle increased from 0.45° to 5.04°. Meanwhile, the compression coefficient and permeability coefficient remained at low levels. In conclusion, the research results preliminarily confirmed the feasibility of using biochar for reinforcement of domestic sources contaminated soil.

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KEYWORDS
Biochar; domestic sources contaminated soil; engineering properties; reinforcement and treatment; mechanism

1. Introduction

With the improvement of living standards, the generation of municipal solid waste is increasing significantly. Concurrently, there is a lack of coordination between waste production and treatment, which includes both outdated management models and inadequate treatment facilities. Additionally, during the storage or post-landfill closure of municipal waste, issues such as leakage of wastewater and leachate into the soil can occur due to technical shortcomings, leading to the formation of domestic sources contaminated soil [1,2]. Domestic sources contaminated soil refers to soil that has undergone changes in its original properties due to the infiltration of leachate or wastewater rich in organic matter such as sugars, organic acids, alcohols, and esters. The degradation of organic pollutants causes significant alterations in the composition and structure of the soil. On one hand, organic acids produced during degradation dissolve alkaline binders within the soil; on the other hand, gases generated during this process accumulate and expand locally, weakening soil strength. Notably, the geotechnical properties of the soil exhibit a progressively worsening response as organic pollutants degrade [3]. This leads to geoenvironmental and geotechnical engineering issues such as surface and groundwater pollution, air contamination, uneven settlement of foundation soil, and cracking of structures [4–6]. Furthermore, the degradation of organic pollutants from domestic sources generates significant amounts of gases such as CH_4 and CO_2 [7], making it a potential source of greenhouse gas emissions.

Currently, domestic sources contaminated soil faces two major challenges: the degradation of organic pollutants weakens soil structure, reducing its strength, and the generation of large amounts of greenhouse gases increases carbon emissions (Figure 1). Low-carbon management of domestic sources contaminated soil has become a crucial practical need, highlighting the importance of identifying environmentally friendly remediation materials and developing green management methods. For a long time, the treatment of contaminated soil has been a research hotspot in the field of geotechnical engineering. However, previous studies have mainly focused on the methods and technologies of removing soil pollutants, covering three categories of remediation technologies: physical remediation (in-situ flushing, electrokinetic remediation, thermal treatment, etc.), chemical remediation (chemical oxidation, photochemical degradation, etc.), and biological remediation (phytoremediation, microbial remediation, etc.) [8–10]. Among contaminated soil treatment methods, Solidification/Stabilization (S/S) technology immobilizes pollutants through S/S materials to prevents their migration and diffusion, as well as reduce toxicity. Meanwhile, it constructs contaminated

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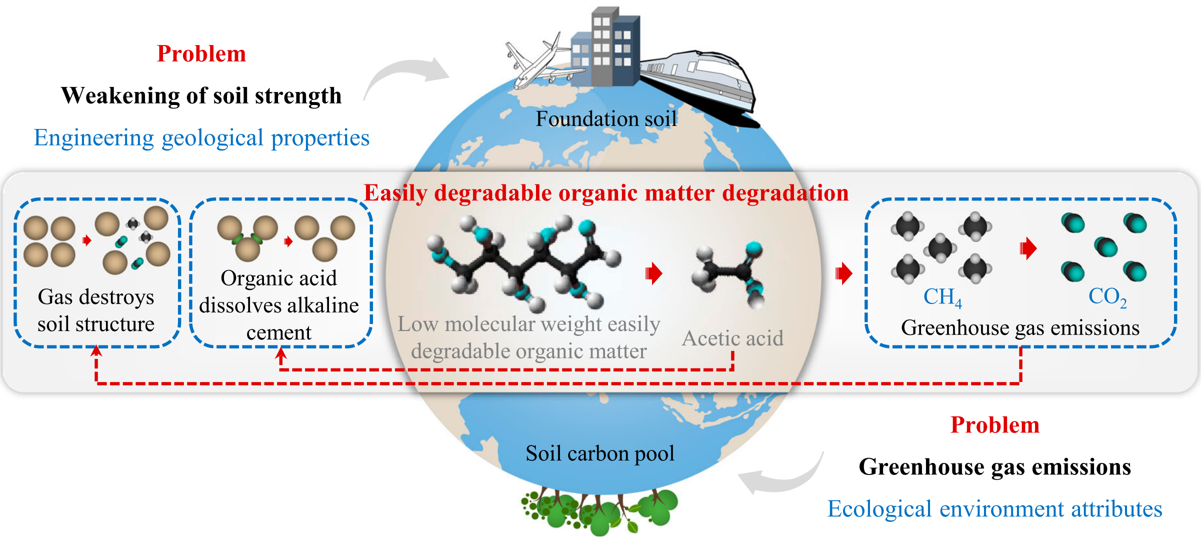


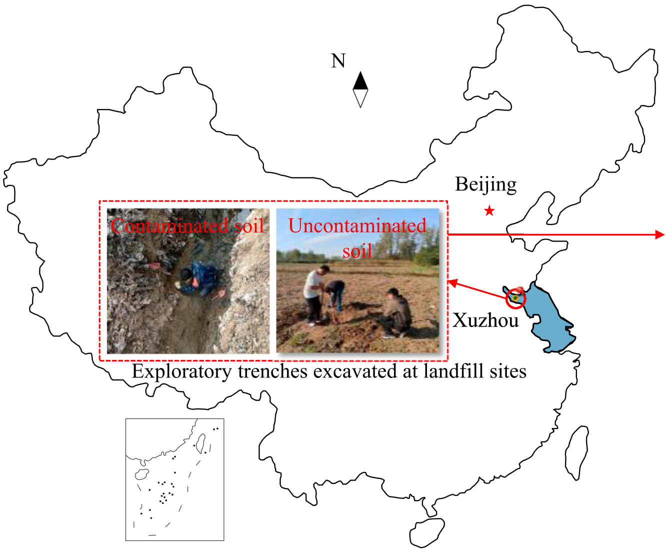
Figure 1. Remediation requirements of domestic sources contaminated soil.

soil into a structurally integral body [11,12]. This technology shows potential application efficiency in reinforcing domestic sources contaminated soil and carbon emission reduction treatment, as it not only enhances the mechanical properties of contaminated soil but also immobilizes soil organic carbon, thereby increasing the stability of carbon pool. Selecting suitable S/S materials is the primary prerequisite for the efficient treatment of contaminated soil by S/S technology [13]. Traditional S/S materials mainly include cement, lime, fly ash, etc. Studies have shown that the application of cement, lime, fly ash, etc., in the treatment of heavy metal-contaminated soil can significantly reduce the leaching characteristics and toxicity levels of Pb, As, Cr, etc., in the soil, while effectively improving the strength of contaminated soil [14–16]. However, traditional S/S materials present significant economic and environmental concerns, including high cost, substantial energy consumption, non-renewability, and potential secondary pollution risks [17]. Additionally, they exhibit limited applicability for organically contaminated soils, as organic pollutants weaken their cementing effect on the soil [18]. These limitations hinder their ability to meet the requirements for low-carbon and green treatment of domestic source contaminated soil.

Biochar is an insoluble, stable, and highly aromatic solid produced by high-temperature pyrolysis of biomass under oxygen-limited or anoxic conditions [19], and is widely used in the remediation of contaminated soil and the improvement of agricultural soil [20–22]. Studies have shown that biochar contains numerous pores and oxygen-containing functional groups, which can immobilize heavy metals and organic pollutants in contaminated soil through physical and chemical adsorption, preventing their migration and transformation [23,24]. Some studies have confirmed that the addition of biochar to soil can improve the stability of soil organic matter, reduce the emissions of greenhouse gases such as CO_2, CH_4, and N_2O, and exhibit obvious carbon emission reduction effects in soil [25–27]. This contributes to soil environmental management and the control of soil greenhouse gas emissions. Biochar can increase soil pH [28], adsorb water and organic matter, and play a role in water and nutrient retention in soil [29,30], leading to improvements in acidic, arid, and infertile soil. Additionally, biochar alters soil structure and influences the physical and mechanical properties of the soil [23,31]. Although biochar is commonly used in agriculture to reduce soil compaction and strength [32,33], some scholars have explored its effects from an engineering perspective, finding that biochar can enhance soil strength [34–36].

Thus, biochar is a highly promising new material for the reinforcement and carbon sequestration of domestic sources contaminated soil. It is expected to improve the stability of organic carbon in domestic sources contaminated soil, reduce carbon emissions, enhance the strength of the soil, and achieve the engineering governance goal of soil reinforcement. However, understanding the effect of biochar on the engineering properties of domestic sources contaminated soil is a prerequisite for its application in the remediation of this soil. Nevertheless, the regularity and mechanism of this effect remain unclear. Therefore, investigating and revealing the mechanism by which biochar modulates the engineering properties of domestic sources contaminated soil is one of the key basic scientific problems to be solved currently. The main purpose of this study is to explore the effect of biochar on the engineering properties of domestic sources contaminated soil and verify the feasibility of using biochar for the reinforcement treatment of its.

This study focuses on domestic sources contaminated soil and bamboo biochar. Through laboratory



	Contaminated soil	Uncontaminated soil
Water content (%)	26.8	26.6
Liquid limit (%)	37.6	36.2
Plastic limit (%)	20.2	19.0
I_p	17.4	17.2
Organic matter content (%)	5.93	4.30
The angle of internal friction (°)	16.59	17.06
Cohesive forces (kPa)	16.65	20.48
pH	6.4	8.2

Figure 2. Domestic sources contaminated soil sampling locations.

simulations of biochar-reinforced domestic sources contaminated remoulded soil, combined with geotechnical tests, we characterized analyzed the effects of biochar on the dry density, pH, strength, deformation, permeability, and other physicochemical properties of the soil. The regulation of engineering properties by biochar was examined. Based on the key characteristics of biochar and the evolution of the soil's engineering properties, the mechanism by which biochar influences the engineering behaviour of domestic sources contaminated soil was revealed.

2. Materials and methods

2.1. Test materials and properties

(1) Domestic sources contaminated soil

The domestic sources contaminated soil used in this experiment was collected from an abandoned informal waste landfill in Xuzhou, Jiangsu, as shown in Figure 2. Both contaminated soil from within the landfill and uncontaminated soil from the surrounding area were obtained through trenching and excavation. The retrieved soil samples were stored in a refrigerator at 4°C.

The basic properties of domestic sources contaminated soil and uncontaminated soil were analyzed through indoor geotechnical tests. Domestic sources contaminated soil exhibits higher plasticity, liquid limit, and organic matter content, while its strength and pH are lower.

(2) Biochar

Bamboo biochar with large particle hardness was chosen as the experimental research object, as higher pyrolysis temperatures and longer charring times result in more developed pores, increased alkalinity, and greater stability [37]. Therefore, the experiments were set the pyrolysis temperature of the biochar at 700°C, and the charring time at 4 h. The biochar had a pH value of 8.22, measured following the method for determining acidity and alkalinity of biochar outlined in the Test Method for *Coal Granular Activated Carbon* (GB/T7702.16).

2.2. Experimental programme design for simulation testing of biochar treatment of domestic sources contaminated soil

To meet the basic requirements of the controlled variable method and simulate the actual conditions of biochar treatment for domestic sources contaminated soil, soil with natural water content was mixed with dry biochar. Samples of biochar-treated domestic sources contaminated soil were prepared by the static compaction method, as shown in Figure 3. A compaction pressure of 250 kPa was applied, and after preparation, the soil samples were sealed and placed in a constant temperature box at 20°C for 7 days for biochar-soil equilibrium. Four biochar particle sizes ($<$ 0.5, 0.5–1, 1–3, and 3–5 mm) and six biochar dosages (0%, 3%, 6%, 9%, 12%, and 15% of dry soil mass) were selected to simulate different biochar treatment conditions for domestic sources contaminated soil.

In accordance with the requirements of the *Specification of Soil Test* (GB/T 50124-2019), the density, pH, shear strength index, compression coefficient, permeability coefficient, and other engineering properties of biochar-treated domestic sources contaminated soil were tested through indoor geotechnical experiments.

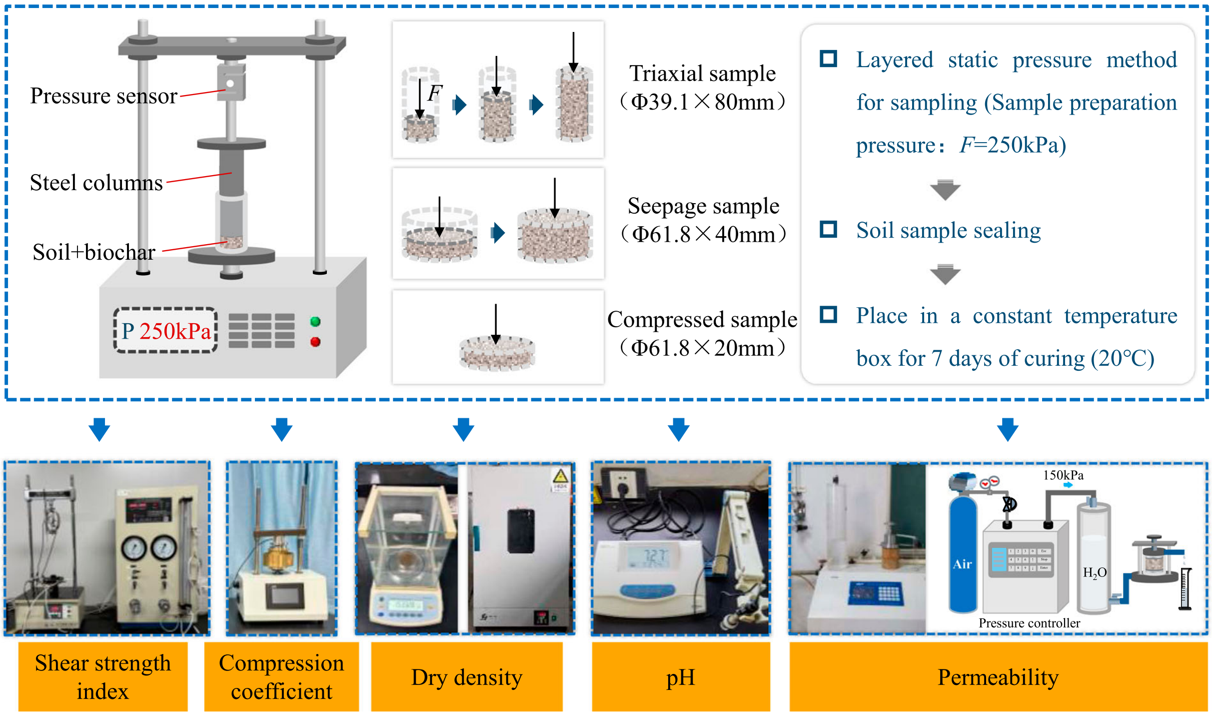


Figure 3. Sample preparation and testing process.

a. Shear strength index: The Unconsolidated-undrained (UU) triaxial compression tests were conducted using a TSZ-1 triaxial apparatus. The shear loading rate was set at 1 mm/min, and the confining pressures were 100, 200, 300, and 400 kPa, respectively. The tests were terminated at 20% axial strain, with the shear strength defined as the peak or ultimate deviator stress.

b. Compression coefficient: Standard consolidation tests were conducted with sequential loading increments of 12.5, 25, 50, 100, 200, and 400 kPa. The stability criterion required consolidation under each pressure level for 24 h, or until the deformation rate was ≤ 0.01 mm/h. After meeting stability, the displacement gauge reading was recorded, and the loading was incrementally increased to the final pressure level.

c. Dry density: The ring-cutter method was used to test the wet density of soil samples, and the oven-drying method was used to determine the water content. The dry density of soil samples was calculated using Formula (1):

$$\rho_{\mathrm{d}} = \frac{\rho}{1+w}.$$

Where ρ_d is the dry density of the soil sample, g/cm^3; ρ is the wet density of the soil sample, g/cm^3; w is the water content of the soil sample.

d. pH: The pH was assessed by mixing the soil with distilled water in a 1:5 ratio, stirring the mixture, after setting for 30 min, pH was measured in the supernatant using a pH metre.

e. Permeability: The permeability coefficient was analyzed using a custom constant-head permeameter with pneumatic pressure control, as shown in Figure 3. The infiltration end pressure was controlled at 150 kPa, and the permeability coefficient was measured by recording the final stable water discharge.

All the above-mentioned testing and characterization experiments were conducted in triplicate, and the average value was taken as the final result.

3. Results

3.1. Effect of biochar on physicochemical properties of domestic sources contaminated soil

Figure 4 presents the relationship between dry density, pH, and the biochar dosage in domestic sources contaminated soil. As the biochar dosage increased, the dry density of the contaminated soil decreased, with larger biochar particle sizes corresponding to lower dry densities. This can be attributed to two factors: first, biochar is lighter, and its addition reduces the specific gravity of the soil; second, biochar contains numerous internal pores, which increase soil porosity upon incorporation. Larger biochar particles have more internal pores, further reducing the dry density of the soil. Additionally, the pH of the contaminated soil increased with higher biochar dosages, primarily due to the alkaline substances in biochar [28], which neutralized the organic acids present in the contaminated soil.

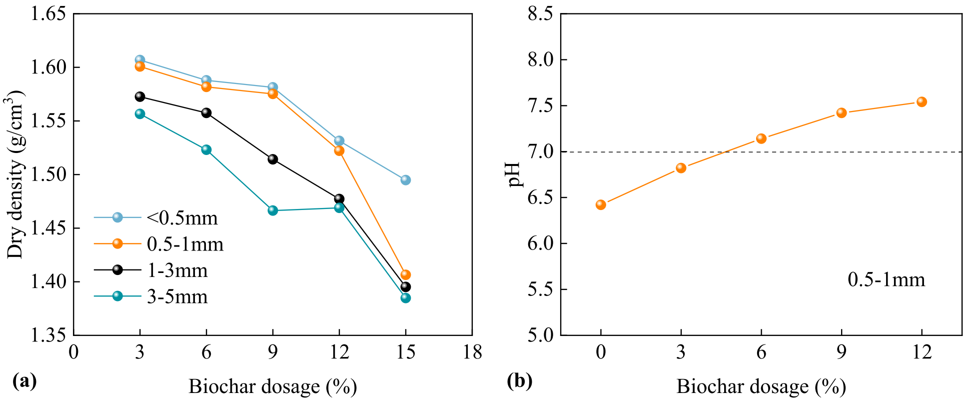


Figure 4. Curves of basic physicochemical properties of domestic sources contaminated soil as a function of biochar incorporation: (a) Dry density; (b) pH.

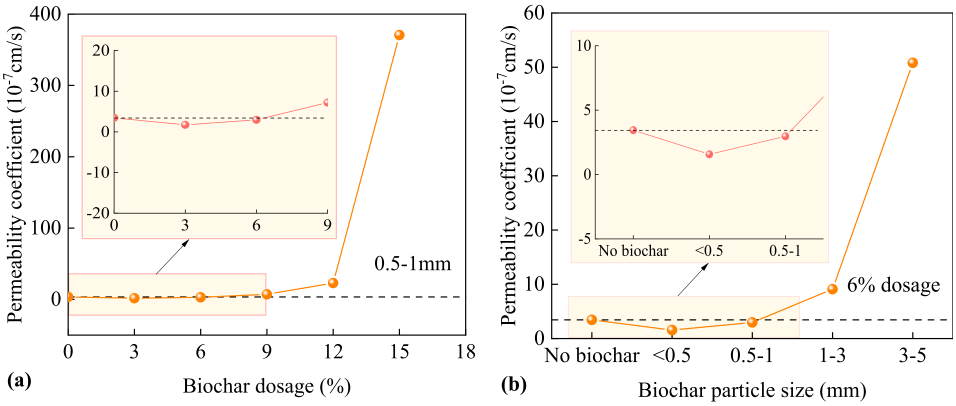


Figure 5. Curves of permeability coefficients of domestic sources contaminated soil versus biochar treatment parameters: (a) Biochar dosage; (b) Biochar particle size.

3.2. Effect of biochar on the permeability of domestic sources contaminated soil

Figure 5 illustrates the variation in the permeability coefficient of domestic sources contaminated soil in relation to biochar dosage and particle size. It indicated that, in general, the permeability coefficient of the contaminated soil increases gradually with higher biochar dosages and larger biochar particle sizes. However, when either the biochar particle size or dosage was low, the permeability coefficient of the biochar-treated contaminated soil was lower than that of untreated soil. This phenomenon can be attributed to two main factors. On the one hand, biochar exhibits strong adsorption properties [38], which increase the resistance to pore water seepage in the soil; on the other hand, biochar's porosity enhances the overall porosity of the soil, while larger biochar particles create a skeletal structure among soil particles, increasing the connectivity of pore spaces. When the biochar particle size was small and the dosage was low, the primary effect was an improvement in the resistance to pore water seepage. Conversely, when the biochar particle size was large and the dosage was high, the effect shifted toward enhancing soil porosity and pore connectivity.

3.3. Effect of biochar on the mechanical properties of domestic sources contaminated soil

(1) Response characteristics of shear strength indicators of domestic sources contaminated soil under the effect of biochar

Figure 6 illustrates the relationship between cohesion and internal friction angle of domestic sources contaminated soil treated with biochar of varying particle sizes as a function of biochar dosage. It indicated that the effect of biochar dosage on the strength of the contaminated soil was more pronounced than the effect of biochar particle size. The addition of biochar increased both the cohesion and internal friction angle of the contaminated soil, thereby enhancing its strength, and this improvement was positively correlated with the biochar dosage. Since the natural water content of the domestic sources contaminated soil used in the experiment was 26.8%, biochar, owing to its strong adsorption properties [38], redistributed the pore water within the soil. The pore water, which was initially concentrated in the soil matrix, was transferred to the biochar particles, reducing the saturation of the soil

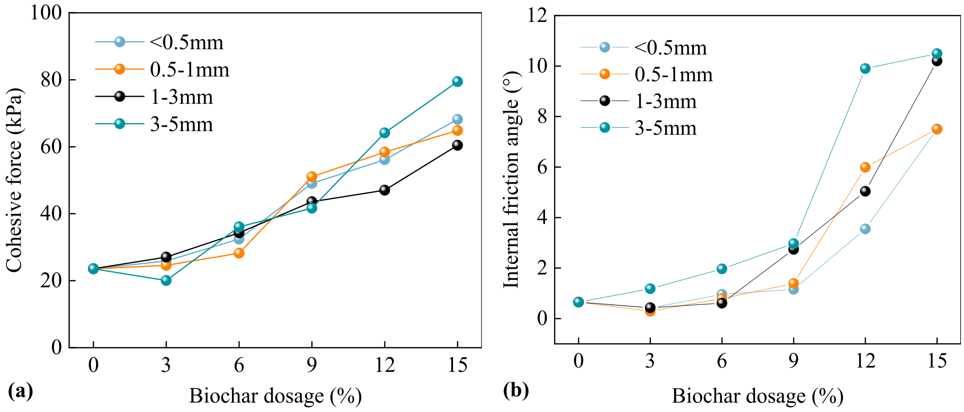


Figure 6. Shear strength index of domestic sources contaminated soil versus biochar treatment parameters: (a) Cohesive force; (b) Internal friction angle.

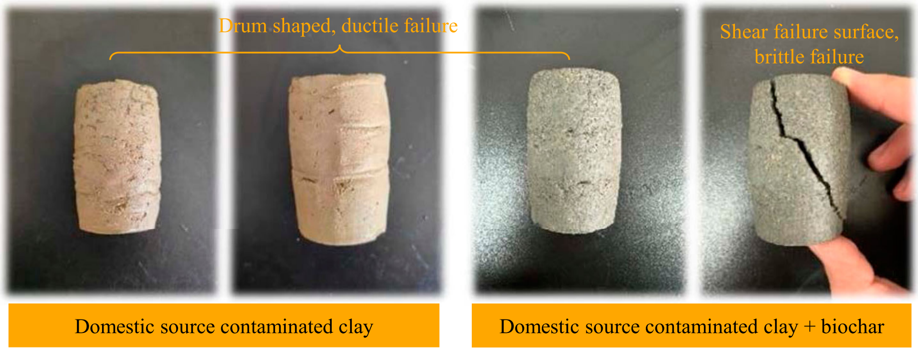


Figure 7. Triaxial shear damage pattern of soil samples.

matrix and consequently increasing the strength of the soil.

(2) Response characteristics of shear damage patterns of domestic sources contaminated soil under biochar action

Figure 7 shows the damage morphology of triaxial shear tests conducted on domestic sources contaminated clay, both with and without the addition of biochar. The clay without biochar exhibited a smooth texture, characteristic of pure clay, without visible granularity. In contrast, the clay with added biochar had a rough texture, resembling sandy soil, with noticeable granularity. This indicated that the biochar transforms the clay from a typical clay-like texture to one resembling sandy soil. When comparing the shear damage morphology under different conditions, it can also be observed that the domestic sources contaminated soil without biochar exhibited ductile deformation, with a drum-like shape after triaxial shear, and no clear shear failure surface. However, in samples with biochar, a shear failure surface appeared, indicating brittle deformation similar to that observed in sandy soil.

3.4. Effect of biochar on deformation characteristics of domestic sources contaminated soil

Figure 8 presents the variation curves of the compression coefficient of domestic sources contaminated soil (pressure of 100–200 kPa) with biochar dosing and biochar particle size. Based on the *Design Code for Foundations of Railway Bridges and Culverts* (TB10094-2017), the compression coefficients for the 100–200 kPa pressure interval are used to classify soil mass compressibility into low, medium, and high categories, with boundaries at 0.1 and 0.5 MPa^{-1}. Therefore, all domestic sources contaminated soil in this study belong to medium compressibility soil and have relatively high compressibility between 0.3 and 0.5 MPa^{-1}. The figure illustrated that the addition of biochar reduces soil compressibility, and as the biochar dosage increased, the compression coefficient decreased, making the soil less compressible. This trend was consistent with the observed increase in soil strength, likely due to biochar's ability to dry and desaturate the soil, enhancing its resistance to external deformation. With the increase of biochar particle size, on the other hand, the compression coefficient of soil mass gradually increased, mainly

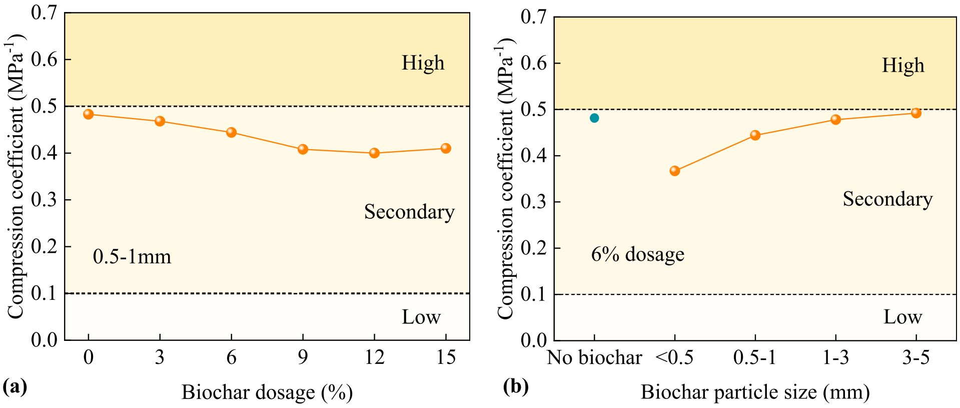


Figure 8. Compression coefficients of domestic sources contaminated soil versus biochar treatment parameters: (a) Biochar dosage; (b) Biochar particle size.

because the pore structure of biochar with large particles was more developed, which led to the improvement of the pore space and the compressibility of the domestic sources contaminated soil.

4. Discussion

4.1. Microstructural characterization of domestic sources contaminated soil under the effect of biochar

To investigate the regulatory mechanism of biochar on domestic sources contaminated soil from a microscopic perspective, SEM imaging was performed on: (1) bamboo biochar, (2) untreated domestic sources contaminated soil, and (3) biochar-amended soil, as shown in Figure 9. It can be found that the bamboo biochar contains a large number of primary fibre pores and pyrolysis carbonization pores. The untreated soil showed a flocculent structure with uniformly distributed aggregates and limited porosity. In contrast, the biochar-amended soil showed a more developed and uneven pore structure due to the formation of a biochar framework within the soil. This resulted in larger pores and increased heterogeneity across different regions of the soil matrix.

4.2. Response mechanisms of engineering properties of clay contaminated by domestic sources under the effect of biochar

The pH value of bamboo biochar used in the experiment was 8.22. Meanwhile, it can be observed from Figure 9 that bamboo biochar contains abundant pore structures. In addition, based on the infrared spectroscopy analysis of bamboo biochar in literature [39], it is found that bamboo biochar contains a large number of oxygen-containing functional groups such as hydroxyl and carbonyl groups. These characteristics endow biochar with excellent carbon stability, porosity, adsorption capacity, and acid–base buffering properties [40]. Based on these key properties and the results of experimental result analyses in this study, biochar's effects on the strength, deformation, permeability, and other engineering properties of clays contaminated by domestic sources were evaluated. The mechanism of biochar's influence can be attributed to two main factors: soil modification and desaturation effects, as illustrated in Figure 10.

(1) Soil modification: The addition of biochar can significantly alter the texture of domestic sources contaminated clay, changing it from a sticky to a more sandy. The effects of biochar on the soil mass of domestic sources contaminated soil are primarily reflected in four aspects: (a) Biochar particles have a rougher surface than domestic sources contaminated soil particles, and the addition of biochar increases the overall roughness of the soil particles, which is macroscopically reflected in an increased internal friction angle. (b) Biochar has strong adsorption properties [38], which enhances the water retention capacity of the soil and increases its resistance to pore water seepage. This effect is particularly noticeable when the biochar dosage and particle size are small, as the permeability coefficient of the treated soil is lower than that of untreated soil. (c) Biochar contains numerous pores, and larger biochar particles can form a supporting skeleton within the soil, increasing soil porosity and the number of connected pores. This is macroscopically reflected in the increased permeability and compressibility of domestic sources contaminated clay. When the dosage and particle size of biochar are large, the addition of biochar significantly increases the soil's permeability coefficient. The larger the biochar particle size, the higher the compression coefficient of the domestic sources contaminated soil. (d) Biochar contains a substantial amount of alkaline substances [28], which can neutralize the organic acids in domestic sources contaminated soil, raising the soil's pH and preventing the corrosion and dissolution of alkaline cementing agents in the soil. This enhances

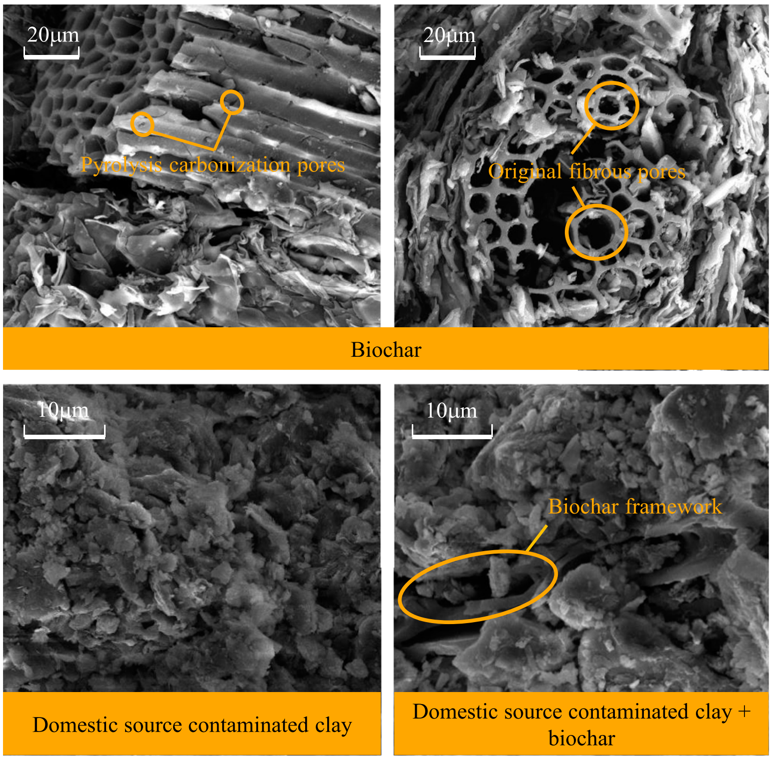


Figure 9. SEM image of biochar and domestic sources contaminated soil.

soil strength and improves its ability to resist deformation.

(2) Desaturation effect: The oxygen-containing functional groups within and on the surface of biochar impart strong adsorption properties for water molecules [24], which alters the spatial distribution of pore water in the soil. Biochar competes for pore water, leading to its adsorption onto the biochar, resulting in the desaturation of the soil matrix. This desaturation significantly affects the strength and deformation properties of the soil, improving its strength and resistance to deformation. The influence of biochar on domestic sources contaminated soil during desaturation can be explained by the following three aspects: (a) When the soil has a high-water content, pore water acts as a lubricant between soil particles. Upon desaturation, the rough surfaces of the soil particles become exposed, increasing inter-particle friction. This is reflected in the macroscopic increase in the internal friction angle of domestic sources contaminated soil, enhancing its resistance to deformation. (b) During partial desaturation, salt crystals precipitate from the pore water, cementing the soil particles together, which macroscopically manifests as an increase in cohesion, strengthening the soil's resistance to external forces, and reducing its compressibility. (c) After partial desaturation, the surface tension of the pore water between soil particles increases, which is macroscopically manifested as an increase in soil strength and enhanced resistance to deformation due to biochar.

4.3. Basic principles for high-efficiency remediation of unsaturated domestic sources contaminated soil by biochar

Through the previous experiments and mechanism analysis, the selection principles for the treatment conditions of biochar in efficiently remediating the unsaturated domestic sources contaminated soils are analyzed from three perspectives: strength, deformation, and permeability:

a. Strength perspective: With the increase in biochar content and particle size, the strength of the unsaturated domestic sources contaminated soils gradually increases under the dual mechanisms of soil modification and desaturation effect. Therefore, selecting biochar with larger particle sizes and higher dosages is more conducive to the reinforcement of such soils.
b. Deformation perspective: As the biochar content increases, the compression resistance of unsaturated domestic source contaminated soils enhances. Conversely, increasing biochar particle size weakens this resistance. Therefore, it is more advantageous to choose biochar with larger particle sizes and greater doses for reinforcing such soils.
c. Permeability perspective: As biochar content and particle size increase, the permeability of domestic source contaminated soils remains relatively stable within certain ranges (content $< 12\%$, particle size < 1–3 mm). However, when the content exceeds 12% and particle size exceeds 1–3 mm,

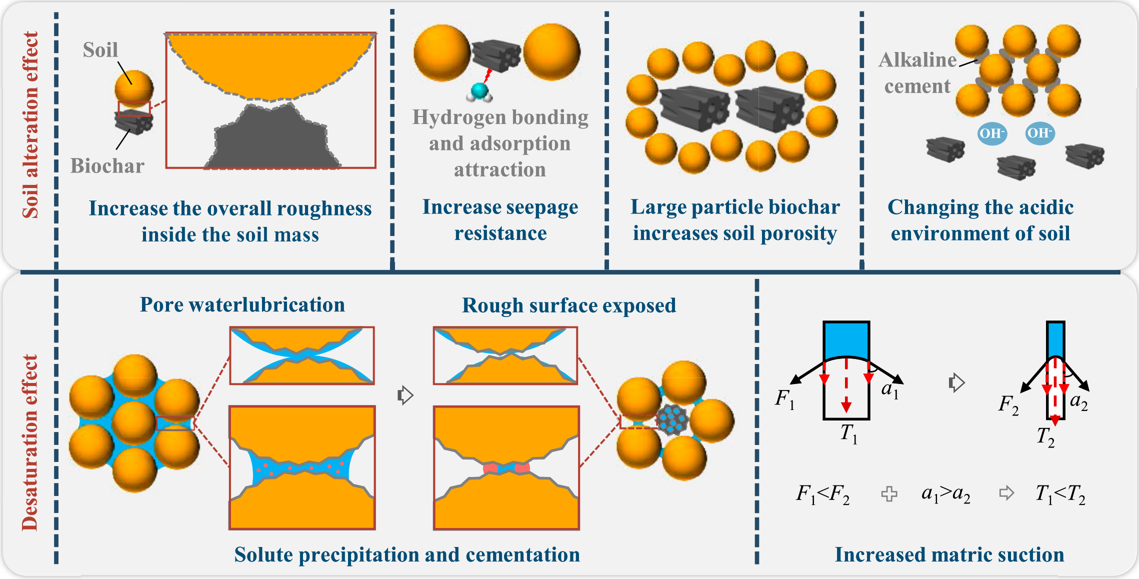


Figure 10. Schematic diagram of the mechanism of biochar influence on the engineering properties of domestic sources contaminated soil.

permeability exhibits a sudden increase. Therefore, there exists a threshold for maintaining impermeability when selecting biochar particle size and dosage.

In summary, to enhance the strength, deformation resistance, and impermeability of unsaturated domestic sources contaminated soil, while maximizing the use of large-particle biochar and high dosages to improve soil strength, it is necessary to consider both the threshold for maintaining soil impermeability and the reduction in deformation resistance caused by large biochar particles.

5. Conclusion

In conclusion, biochar exhibited alkalinity, porosity, and strong adsorption properties, and its addition to domestic sources contaminated soil transformed the soil's engineering properties from clayey to sandy. This modification increased the alkalinity, strength, and deformation resistance of the soil under natural water content (unsaturated conditions). However, it also raised the permeability of the soil. The application of biochar in the consolidation of domestic sources contaminated soil was feasible. The influence of biochar on the engineering properties of such clay is primarily driven by two mechanisms: soil modification and desaturation.

Although this study initially confirmed the feasibility of using biochar for the reinforcement of domestic sources contaminated soil, further attention is needed regarding its impact on the degradation processes of organic matter within the soil. Considering the susceptibility of organic matter in domestic sources contaminated soil to degradation, it is crucial to investigate the dynamic response of the soil's geotechnical properties. Future research should focus on uncovering the synergistic coupling mechanisms between soil reinforcement and the prevention of organic matter degradation and emissions (carbon sequestration) in domestic sources contaminated soil.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

All relevant data are within the paper.

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