

Article

Experimental Study on the Strength Characteristics of Organic-Matter-Contaminated Red Soil in Yulin

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Abstract: In order to study the strength characteristics of organic-matter-contaminated red soil and the improvement effects of different modifiers, the red soil in the Yulin area was taken as the research object, and triaxial compression tests were carried out to study the effects of different mass fractions (0%, 2%, 4%, 6%, 8%) of organic matter (sodium humate) on the strength characteristics of red soil. Unconfined compressive strength (UCS) tests and scanning electron microscopy (SEM) tests were carried out to study the improvement effects of different amounts of lignin, fly ash, and xanthan gum on organic-matter-contaminated red soil (organic matter content of 8%). The results of the tests showed that the cohesion and internal friction angle of red soil both tended to decrease with the increase in organic matter content. When the organic matter content increased from 0% to 8%, the cohesion of the red soil decreased from 60.98 kPa to 40.07 kPa, a decrease of 34.29%; and the internal friction angle decreased from 17.42° to 7.28°, a decrease of 58.21%. The stress–strain relationship curves of organic-matter-contaminated red soil all show a hardening type. Under different confining pressures, as the organic matter content increased, the shear strength of the red soil decreased continuously. The unconfined compressive strength of organic-matter-contaminated red soil increased with the increase in lignin content, and increased first and then decreased with the increase in fly ash content and xanthan gum content. Through comparative analysis, it was found that the fly ash with a content of 15% had the best improvement effect. The lignin-amended red soil enhanced the connection of soil particles through reinforcement, reduced pores, and improved soil strength. Fly ash improved the acidification reaction, and the hydrates filled the pores and enhanced the soil strength. Xanthan gum improved the red soil by absorbing water and promoting microbial growth, further enhancing the bonding force between soil particles. This study can provide a reference for engineering construction and red soil improvement in red soil areas.

Keywords: red soil; organic matter; strength characteristics; microstructure

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1. Introduction

Soil organic matter (SOM) is the general term for various carbon-containing organic compounds in the soil, which are derived from the decomposition residues of plants, animals, and microorganisms deposited in the soil over a long geological period [1]. The organic matter content of various types of soil commonly encountered in engineering projects varies greatly [2]. Generally, the organic matter content of non-organic soil is less than 5%, while the organic matter content of organic soil such as peat can be as high as 90% [3]. During engineering construction, due to the high organic matter content of

the main soil layer, engineering properties such as high compressibility and low strength appear, resulting in a low foundation bearing capacity, large deformations, and other problems, thus affecting the quality of the project [4]. When soils were compared at high moisture levels, soils with higher organic matter content were stronger than soils with lower organic matter content. Conversely, when soils were compared at low moisture levels, soils with higher organic matter content were weaker.

At present, there have been preliminary studies at home and abroad on the impact of organic matter on soil engineering properties. Ekwue et al. [5–7] found that organic matter in grass can improve the stability of aggregates and increase the shear strength of soil, and that peat causes aggregates to break down, thereby reducing the shear strength of the soil. Tremblay et al. [8] conducted experiments by adding 13 kinds of organic matter to two different soils, and found that organic matter such as humic acid caused the consolidation process to be ineffective due to the low pH value of the pore solution, which had a negative impact on the soil strength. Soane et al. [9] believed that highly humic substances would increase the stability of soil aggregates, thus reducing compaction. Based on knowledge of the storage form of soil organic matter, Zhu et al. [10] conducted shear strength tests under drained and undrained conditions and found that cohesion had no relationship with the storage form of organic matter. Under different drainage conditions, the internal friction angle decreased with the increase in organic matter content. However, Edil et al. [11] believed that there was no obvious relationship between the internal friction angle and the organic matter content. Olu et al. [12] conducted indoor experiments to study the effects of peanut straw, cow manure, and chicken manure on the hydraulic properties of compacted sandy loam, clay loam, and clay, and found that as the organic matter content increased, the shear strength of the soil decreased significantly. Through indoor experiments, Liu et al. [13,14] found that the presence of organic matter in red clay will reduce the shear strength and increase the compressibility of the soil. Develioglu et al. [15] studied the effect of organic matter content on the compressibility of solidified dredged soil and found that as the organic matter content increased, the compressibility coefficient increased continuously. Venda et al. [16] found that the one-dimensional compression creep coefficient of stabilized soil increased with the increase in organic matter. In summary, it can be seen from the field of geotechnical engineering that organic matter will contaminate the soil and reduce the strength of the soil, causing its stability and bearing capacity to decrease during engineering construction. Therefore, how to effectively improve the mechanical properties of organic-matter-contaminated soil and enhance its engineering strength and performance has become a key issue that urgently needs to be solved in the field of improved soil.

At present, there are three main methods of soil improvement: physical improvement, chemical improvement, and microbiological improvement. Through dynamic triaxial tests, Wang et al. [17] found that lignin can significantly improve the ability of saturated loess to resist cyclic shear deformation. Kong et al. [18] conducted indoor tests and found that when the lignin content was 3%, the dry density and mechanical indicators (UCS, CBR, and rebound modulus) of high-liquid-limit soil all reached their maximum values. Wang et al. [19] used lignin fiber from the paper industry instead of lime as a modifier for expansive soil and found that 8% lignin content was the optimal content, which significantly improved the compressive strength and shear strength of the expansive soil. Hu et al. [20] studied the impact of fly ash on the strength index of granite residual soil through a triaxial strength test and found that when the fly ash content was 15%, the triaxial strength index of the improved soil increased the most significantly. Ozdemir et al. [21] used Class C fly ash to improve soft soil and conducted California bearing ratio tests and unconfined compressive strength tests. They found that the compression resistance of Class C fly ash

greatly improved the bearing capacity of soft soil. Cui et al. [22] used fly ash to improve clay-containing silt sand soil, and found that within a certain limit, increasing the amount of fly ash incorporated can effectively improve the soil shear strength, initial elastic modulus, and reduce the damping ratio and growth rate. Mendonça et al. [23] believed that using xanthan gum to improve soil could fill some of the pores in the soil and create additional connections between soil particles, thereby reducing the permeability coefficient and improving the mechanical properties of the soil. Gui et al. [24] used microbial technology to prepare a high-concentration bacterial solution of native bacteria to accelerate the decomposition rate of organic matter in the soil, achieve the goal of significantly reducing the organic matter content in a short period of time, and improve the engineering properties of the soil. Through indoor experiments, Singh et al. [25] found that increasing the xanthan gum content will slightly increase the compressibility, but will significantly reduce the expansion pressure, differential free expansion value, and hydraulic conductivity. At the same time, as the xanthan gum content increases, the compressive strength and resistance to mass loss will increase with respect to curing time.

Red soil is widely distributed in southern China. As a typical red soil distribution area, the Yulin area has an organic matter content of up to 8% [26], and the problem of soil organic matter pollution is particularly prominent. This kind of pollution reduces the stability and bearing capacity of red soil during engineering construction. Especially in terms of roads and infrastructure construction, the performance of red soil is far lower than that of other soil types. Therefore, it is of great theoretical significance and practical value to carry out research on the improvement of organic-matter-contaminated red soil in the Yulin area. This study conducted triaxial compression tests on red soil in the Yulin area with different contents of organic matter added to explore the changing rules of its strength characteristics. At the same time, lignin, fly ash, and xanthan gum were added to the organic-matter-contaminated red soil and then UCS tests and SEM tests were conducted. A preliminary discussion was conducted on the improvement of the red soil contaminated by organic matter from the following three aspects: physical improvement, chemical improvement, and microbial improvement. This study not only provides a scientific basis for red soil improvement in the Yulin area, but also provides a valuable reference for soil pollution control and engineering applications in similar areas. It has broad practical application significance.

2. Test Overview

2.1. Test Materials

The soil used for this test was taken from a construction site in Yulin City. The collected red clay was crushed and passed through a 2 mm sieve before being sealed and stored. According to the “Standard for Geotechnical Test Methods” (GB/T 50123-2019) [27], indoor basic physical property tests and chemical property tests were conducted on the red soil, and its basic physical parameters, chemical composition, and mineral composition were measured, as shown in Tables 1–3.

Table 1. Basic physical parameters of red soil.

Specific Gravity	Maximum Dry Density/g·cm ³	Optimum Moisture Content/%	Liquid Limit/%	Plastic Limit/%	Plasticity Index	Cohesion/kPa	Internal Friction Angle/°
2.65	18.94	1.78	49.86	25.22	24.64	60.98	17.42

Table 2. Chemical components of red soil.

Main Chemical Components	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	TiO ₂	P ₂ O ₅	NaO	MgO	SO ₃	CaO
Mass Percentage/%	60.09	24.55	6.90	4.80	1.00	0.07	0.11	2.03	0.09	0.10

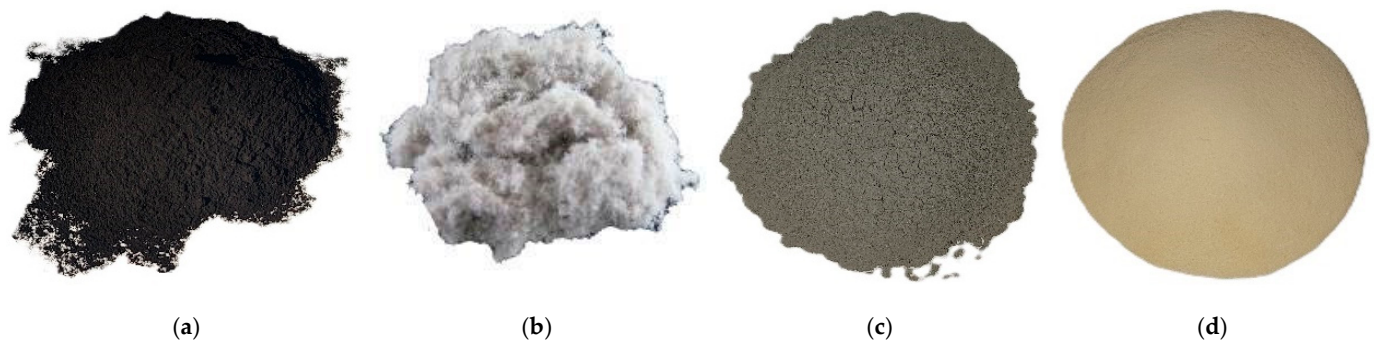
Table 3. Mineral components of red soil.

Main Mineral Components	Quartz	Hematite	Potassium Feldspar	Plagioclase	Kaolinite	Illite	Montmorillonite	Chlorite
Mass Percentage/%	34.40	3.30	0.90	2.00	1.19	29.70	26.14	1.78

Organic matter in soil generally exists in the form of humus [10]. Therefore, sodium humate is selected as the organic matter used in this experiment. The modifiers used in this test are lignin, fly ash, and xanthan gum, and their material parameters are shown in Table 4. The schematic diagram of the materials used in the test is shown in Figure 1.

Table 4. Material parameters.

Name	Material Parameters
Sodium Humate	Particle size of 200 mesh, black, powder, water-insoluble matter < 5%
Lignin	Particle size of <0.5 mm, white, thin strips, humidity < 3 %
Fly Ash	Class F secondary fly ash, SO ₃ ≤ 4.5%
Xanthan Gum	Ingredients: corn, light beige, powder

**Figure 1.** Test materials: (a) sodium humate; (b) lignin; (c) fly ash; and (d) xanthan gum.

2.2. Test Scheme

2.2.1. Triaxial Compression Test

This test assumed that the maximum dry density and optimum moisture content of the soil sample would not change with the organic matter content. The moisture content of the sample was controlled at 20%, and the compaction degree of the sample was controlled at 90% based on the maximum dry density of red soil. Sodium humate was added into the red soil at mass fractions of 0%, 2%, 4%, 6%, and 8%, respectively, and stirred thoroughly. Then, water was added and stirred thoroughly to prepare red soil samples with different organic matter contents. Then, the sample was wrapped in plastic wrap and placed in a curing box (temperature 20 °C, humidity 95%) for 7 days. The cured sample was placed in a vacuum saturation device for 48 h of vacuum saturation. After saturation was completed, the sample saturation was measured. When the saturation was greater than 95%, a consolidated undrained triaxial compression test was carried out. The test procedures were carried out in accordance with the Standard for Geotechnical Test Methods

(GB/T 50123-2019) [27]. The confining pressure was set to 100 kPa, 200 kPa, 300 kPa, and 400 kPa, and the shear rate was 0.08 mm/min. The peak value of the stress–strain curve was taken as the failure point. When there was no peak on the curve, the peak value when the axial strain was 15% was taken as the failure point. The test was stopped when the axial strain reached 20%. The triaxial compression test was performed using the TSZ-2 Fully Automatic triaxial instrument manufactured by Nanjing Soil Instrument Factory Co., Ltd., Nanjing, China.

2.2.2. Unconfined Compressive Strength Test

According to the Standard for Geotechnical Test Methods (GB/T 50123-2019) [27], the diameter of the UCS sample can be 35 mm to 40 mm, and the height should be 80 mm. Therefore, the sample size selection, moisture content, and compaction degree of this test were the same as those of the triaxial sample. When the organic matter content was 8%, the shear strength of the red soil was the worst (see the test results analysis below for details). Therefore, 8% sodium humate was added to the red soil to prepare red soil with 8% organic matter content. Lignin, fly ash, and xanthan gum were added to the red soil with an organic matter content of 8% at different mass fractions (ratio of the mass of the modifier to the mass of the organic-matter-contaminated red soil), and stirred thoroughly. Then, water was added and stirring continued to prepare organic-matter-contaminated red soil with different amendment contents. The preparation method of the UCS sample was the same as that of the triaxial sample. After the preparation was completed, it was placed in a curing box (temperature 20 °C, humidity 95%) for 7 days. The test was carried out using a universal testing machine. The test loading rate was 1 mm/min. The test was stopped when the peak stress appeared during the loading process. The gradient settings of the modifiers were determined with reference to the relevant literature research. The experimental scheme is shown in Table 5.

Table 5. Unconfined compressive strength test scheme.

Name of Modified Material	Content/%	Number of Parallel Tests
Lignin	0, 2, 4, 6, 8	3
Fly Ash	0, 5, 10, 15, 20	3
Xanthan Gum	0, 0.5, 1, 1.5, 2	3

2.2.3. Scanning Electron Microscopy Test

The test instrument adopted was the KYKY-EM6200 tungsten filament scanning electron microscope instrument. First, SEM samples of plain soil, organic-matter-contaminated red soil (organic matter content 8%), and three types of red soil with the best content of modifiers were prepared. Then, they were sprayed with gold. The processed samples were scanned in a high vacuum environment. For each sample, a representative scanning point was selected for photography. The magnification selected in this test was set to 1000 times.

3. Analysis of Test Results

3.1. Effect of Organic Matter Content on Stress–Strain Relationship Curve of Red Soil

Figure 2 shows the stress–strain relationship curve of red soil under different organic matter contents (“Y” in the figure represents the organic matter content). In this test, the peak deviatoric stress was used as the shear strength of the sample. As shown in Figure 2, under different confining pressures, as the organic matter content increases, the shear strength of the sample decreases continuously. When the confining pressure is 100 kPa, the shear strength of the sample decreases from 244.22 kPa to 118.67 kPa. When the confining pressure is 200 kPa, the shear strength of the sample decreases from 339.21 kPa to 151.53 kPa.

When the confining pressure is 300 kPa, the shear strength of the sample decreases from 442.75 kPa to 177.34 kPa. When the confining pressure is 400 kPa, the shear strength of the sample decreases from 493.02 kPa to 206.76 kPa. Regardless of the organic matter content and confining pressure, as the axial strain increases, the increase in the deviatoric stress of the specimen begins to decrease at the axial strain of 2–3%, and the growth trend gradually slows down. The stress–strain relationship curves all show a hardening type. The increase in the organic matter content in red soil changes the particle distribution and soil structure of the red soil. Organic matter forms a film or coating on the surface of soil particles, which will reduce the bonding force and friction between soil particles. As a result, the pores in the soil increase and the soil structure becomes loose. The loose structure makes the soil prone to large deformation when subjected to shear force, resulting in a decrease in the shear strength of the soil.

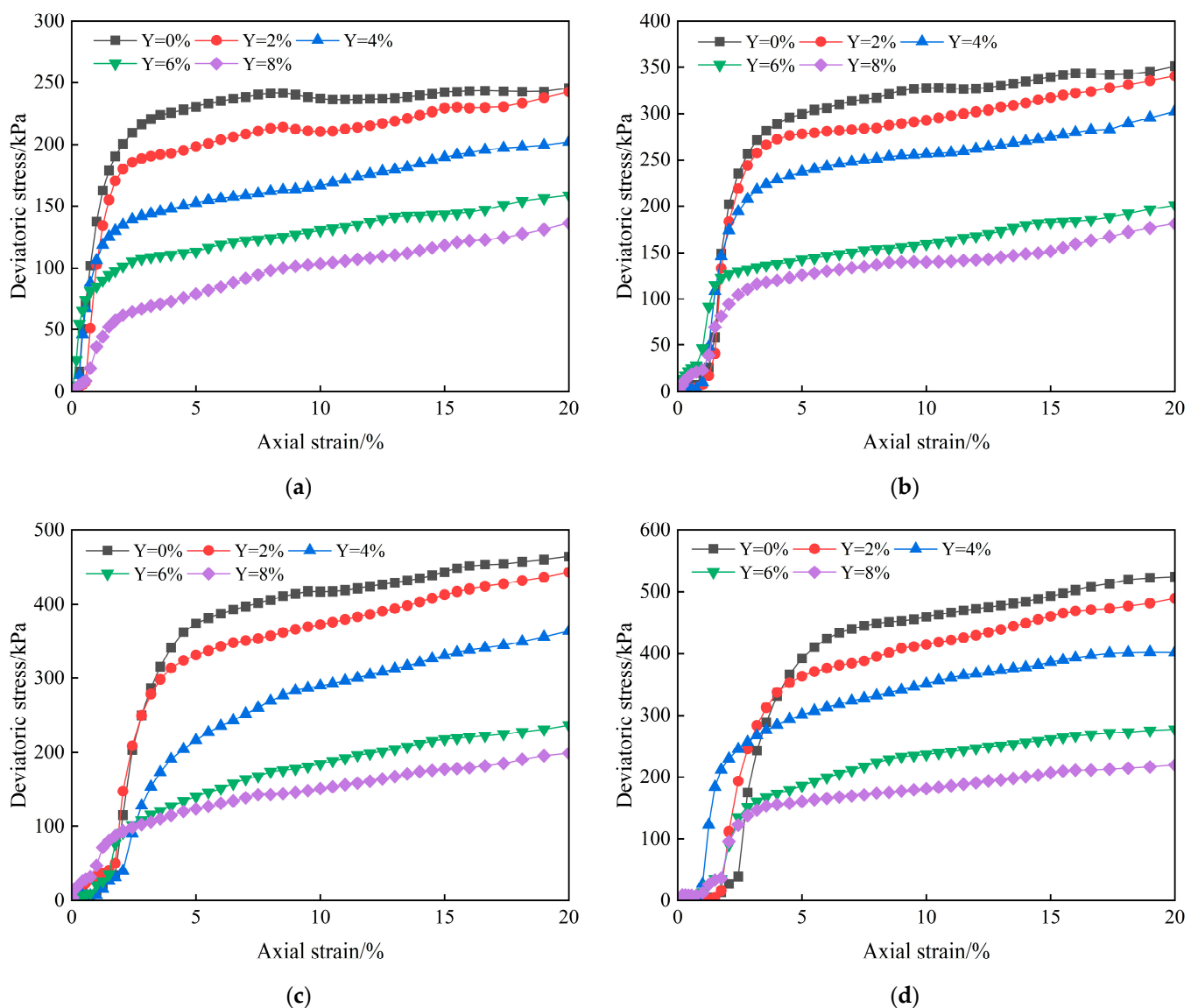


Figure 2. The stress–strain relationship curves of red soil under different organic matter contents: (a) 100 kPa; (b) 200 kPa; (c) 300 kPa; and (d) 400 kPa.

3.2. Effect of Organic Matter on Shear Strength Index of Red Soil

Figure 3 is the relationship curve between the red soil shear strength index and the organic matter content. With the increase in organic matter content, the cohesion and internal friction angle of red soil show a downward trend. When the organic matter content

increases from 0% to 8%, the cohesion of red soil decreases from 60.98 kPa to 40.07 kPa, a decrease of 34.29%, and the internal friction angle decreases from 17.42° to 7.28° , a decrease of 58.21%. It can be seen that the organic matter content has a significant effect on the shear strength index of red soil. Organic matter contains organic acids, which can react with metal ions in the soil (such as calcium, magnesium, sodium, etc.). Divalent cations such as calcium ions play a bridging role in soil particles, helping soil particles to combine into aggregates and maintaining soil stability. When the organic matter content increases, the concentration of organic acids also increases. At this time, organic acids will combine with these metal ions to form soluble organometallic complexes. This causes the metal ions in the soil that can stabilize the soil particles to be “chelated” or removed, thereby weakening the bonding force between the particles. However, at a certain moisture content, organic matter will absorb water and form hydrated colloids. This improves the soil’s water retention capacity and increases the cohesion between soil particles. The test results in this article show that as the organic matter content increases, the cohesion decreases. This is because the acidification effect of organic matter in the soil is greater than the hydration effect of organic matter at a certain moisture content. At the same time, there are a certain amount of clay minerals in red soil, which make the surface of soil particles negatively charged. The surfaces of organic matter molecules also have negative charges. Organic matter has a strong water absorption capacity. Under hydration, the organic matter molecules combine with the surface of soil particles to form an “electric double layer” effect. This phenomenon will dissipate the original electrostatic attraction on the surface of soil particles and reduce the direct contact between soil particles, thus leading to a decrease in the friction between particles.

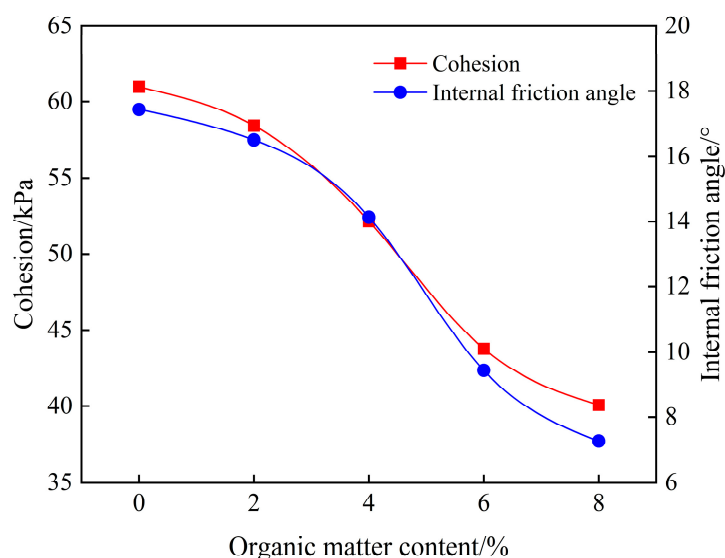


Figure 3. Relationship curve between red soil shear strength index and organic matter content.

3.3. Effects of Modifiers on the Unconfined Compressive Strength of Organic-Matter-Contaminated Red Soil

Figure 4 shows the UCS change curve of organic-matter-contaminated red soil with different gradient modifiers added. As shown in Figure 4a, the UCS of organic-matter-contaminated red soil increases nearly linearly with the increase in lignin content. When the lignin content is 8%, the UCS of the sample is the largest, which is 737.13 kPa. Lignin plays a reinforcing role in the soil. When lignin is added to organic-matter-contaminated red soil, it will form a network structure in the soil, linking the soil particles together. This will eliminate some of the negative effects of organic matter on the red soil.

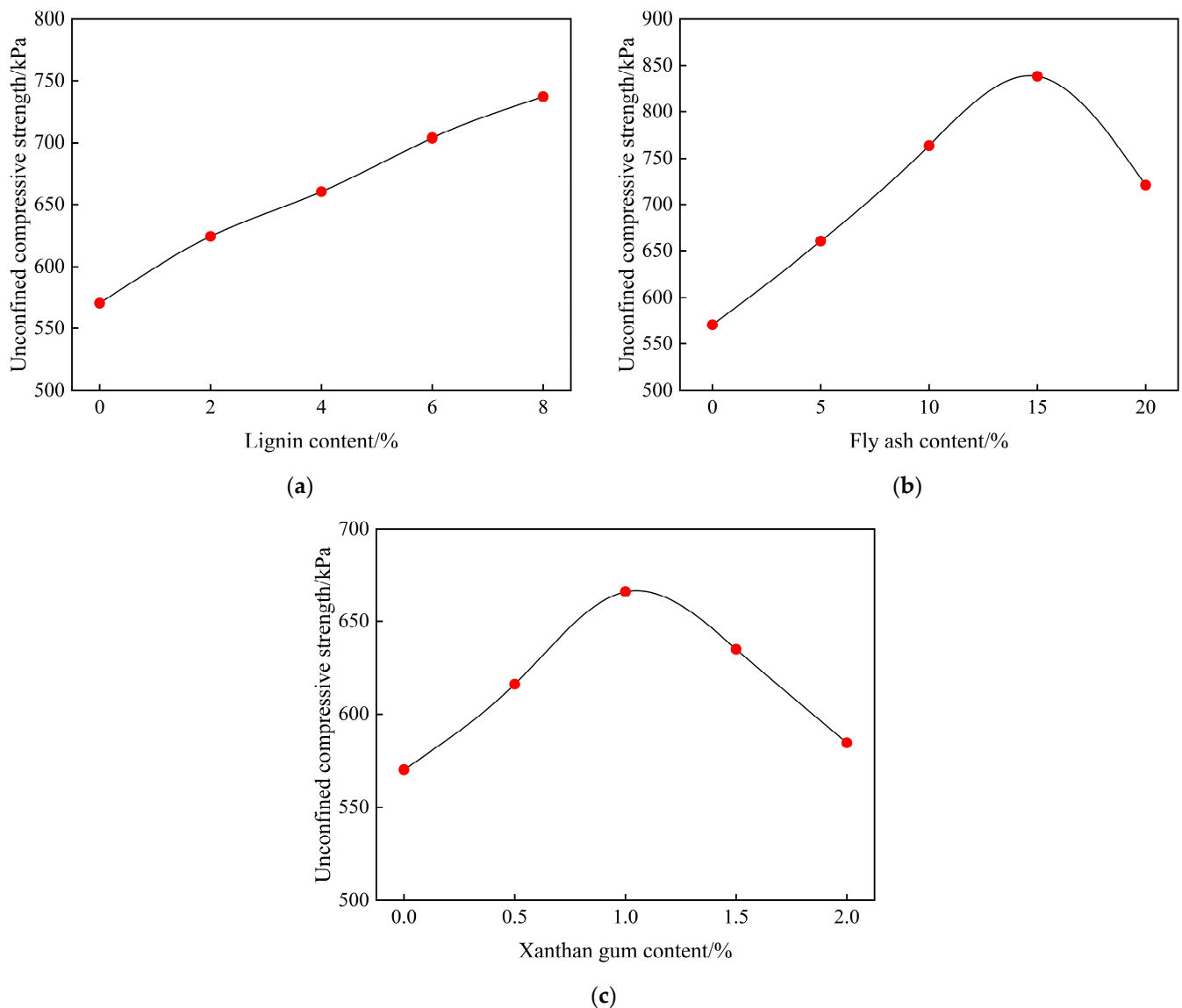


Figure 4. The UCS change curve of organic-matter-contaminated red soil with different gradient modifiers added: (a) lignin; (b) fly ash; and (c) xanthan gum.

As shown in Figure 4b, the UCS of organic-matter-contaminated red soil increases nearly linearly with the increase in fly ash content. When the lignin content is 15%, the UCS of the sample is the largest, which is 838.21 kPa. Fly ash contains alkaline components such as calcium oxide and magnesium oxide. Adding fly ash to organic-matter-contaminated red soil can neutralize acidic substances such as humic acid and organic acid in the organic matter. This can reduce the corrosion of these acidic substances on soil particles, prevent the loosening of the soil structure, and thus improve the strength of the soil. At the same time, the active silicon and aluminum components in the fly ash react with the moisture in the soil to form cementing products such as hydrated silicate and hydrated aluminate. These products fill the pores between soil particles, thereby enhancing the soil's ability to resist compression. However, when the fly ash content is too high, the hydration reaction becomes saturated. Too much fly ash will increase the pores between soil particles, making it impossible for the hydration products to effectively bond the soil particles, which in turn leads to a decrease in the compressive strength of the soil.

As shown in Figure 4c, the UCS of organic-matter-contaminated red soil increases nearly linearly with the increase in xanthan gum content. When the xanthan gum content

is 15%, the UCS of the sample is the largest, which is 665.99 kPa. Xanthan gum can absorb water and swell in the soil, improving the moist environment of the soil and helping to neutralize the acidification of organic acids. This provides a more suitable growth environment for microorganisms. In addition, xanthan gum can enhance the binding force between soil particles to reduce the problems of loose soil and excessive porosity caused by organic matter pollution. However, too much xanthan gum will reduce the porosity of the soil and change the water properties of the soil. This makes it too sticky, hindering the respiratory metabolism of microorganisms and inhibiting the activity of microorganisms. This in turn affects the decomposition rate of organic matter and reduces the compressive strength of the soil.

Through comparative analysis, it was found that fly ash has the best effect on improving organic-matter-contaminated red soil, followed by lignin, and xanthan gum has the worst effect on improving organic-matter-contaminated red soil. Therefore, when a single improver is used to improve organic-matter-contaminated red soil, 15% fly ash can be used for improvement.

3.4. Effects of Modifiers on the Microstructure of Organic-Matter-Contaminated Red Soil

In this SEM test, images with a magnification of 1000 were selected for analysis, as shown in Figure 5. Figure 5a is the SEM image of the red soil. It can be seen from the figure that the soil particles are closely connected. The particles are connected in the form of point-to-point, point-to-surface, and surface-to-surface, and their distribution is relatively scattered. At the same time, there are many pores and cracks. Figure 5b is the SEM image of organic-matter-contaminated red soil. As can be seen from the figure, due to the acidification of organic matter, the bonding force between particles decreases. This leads to the appearance of many cracks and pores, and the soil strength decreases. Figure 5c is the SEM image of red soil improved with 8% lignin. It can be seen from the figure that the lignin is in a strip shape and is wrapped in soil particles. Lignin acts as a reinforcement, making the soil particles more closely connected to each other and reducing the number of pores and cracks [28]. This increases the strength of the soil. Figure 5d is the SEM image of red soil improved with 15% fly ash. It can be seen from the figure that fly ash neutralizes the effect of the organic matter acidification reaction. At the same time, the active silicon and active aluminum in the fly ash react with water in the soil to produce colloidal hydrates. These hydrates will fill the pores and cracks between soil particles, tightly connecting the soil particles together, thereby enhancing the strength of the soil. Figure 5e is the SEM image of red soil improved with 1% xanthan gum. It can be seen from the figure that xanthan gum can absorb water and swell in the soil. Xanthan gum in the soil will promote the exchange of metal ions and the production of hydrated gel inside the soil [29]. The filamentous gel enhances the bonding between soil particles through stretching, and part of the gel fills the pores to make the soil structure dense, thereby improving the strength of the soil [29].

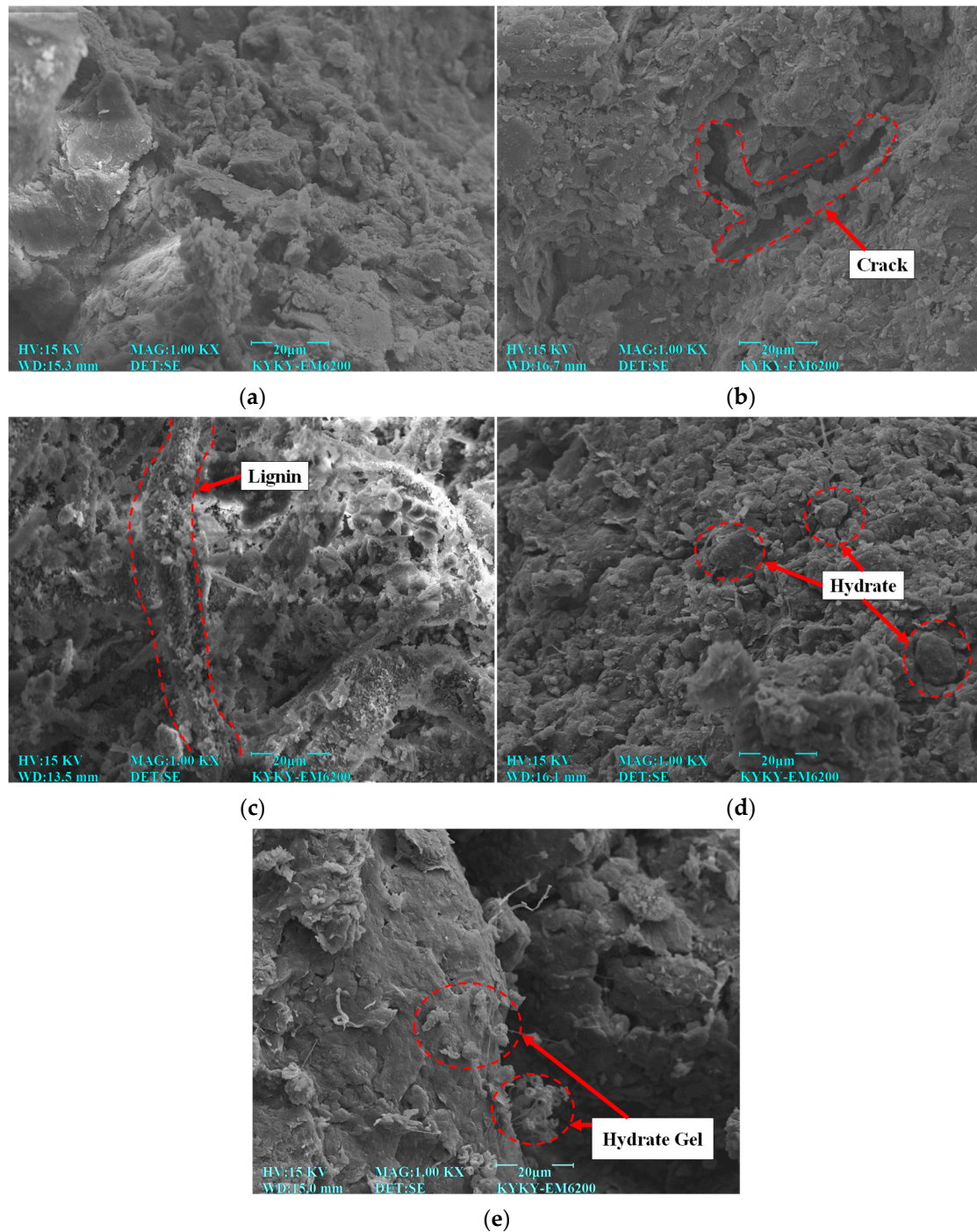


Figure 5. The SEM images of different modified soils at 1000 times magnification: (a) red soil; (b) 8% organic matter; (c) 8% lignin; (d) 15% fly ash; and (e) 1% xanthan gum.

4. Conclusions

(1) With the increase in organic matter content, the cohesion and internal friction angle of red soil both tend to decrease. When the organic matter content increases from 0% to 8%, the cohesion of red soil decreases from 60.98 kPa to 40.07 kPa, a decrease of 34.29%; and the internal friction angle decreases from 17.42° to 7.28° , a decrease of 58.21%. It can be seen that the effect of organic matter content on the internal friction angle of red soil is more significant than its effect on cohesion.

(2) Under different confining pressures, the stress–strain relationship curves of organic-matter-contaminated red soil all show a hardening type. With the increase in organic matter

content, the shear strength of red soil continues to decrease. Due to the acidification of organic matter and the “electrical double layer” effect, the direct contact between soil particles is reduced. This reduces the bonding force between soil particles, which in turn leads to an increase in soil pores, a loose internal structure, and a decrease in the shear strength of the soil.

(3) The UCS of organic-matter-contaminated red soil increases with the increase in lignin content, and increases first and then decreases with the increase in fly ash content and xanthan gum content. Through comparative analysis, it is found that fly ash has the best improvement effect. Therefore, when a single amendment is used to improve organic-matter-contaminated red soil, 15% fly ash can be used for improvement.

(4) Different modifiers have significant effects on the microstructure of red soil. The unimproved soil particles are loosely connected and contain many pores and cracks, resulting in a lower soil strength. The acidification of organic-matter-contaminated red soil reduces the bonding force between particles, increases cracks and pores, and further reduces soil strength. Lignin-improved red soil strengthens the connection between soil particles, reduces pores, and improves soil strength through reinforcement. Fly ash improves the acidification reaction, and the hydration products fill the pores, thereby enhancing the strength of the soil. Xanthan-gum-improved red soil further enhances the bonding force between soil particles by absorbing water and swelling and promoting microbial growth.

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