Hindawi
International Journal of Polymer Science
Volume 2021, Article ID 1535772, 16 pages
https://doi.org/10.1155/2021/1535772

Research Article

Improving the Mechanical Properties of Red Clay Using Xanthan Gum Biopolymer

Lina Wang, [1,2,3] **Zhiyu Weng**, [2,4] **Qiang Liu**, [1] **Tianliang Wang**, [3,5] **Xuemin Pan**, [2] **Guoyu Li**, [6] **and Zhiliang Wang** [7]

[1] *Powerchina Kunming Engineering Corporation Limited, Kunming 650051, China*
[2] *School of Construction Engineering, Yunnan Agricultural University, Kunming 650201, China*
[3] *State Key Laboratory of Mechanical Behavior and System Safety of Traffic Engineering Structures, Shijiazhuang Tiedao University, Shijiazhuang 050043, China*
[4] *Fujian Research Center for Tunneling and Urban Underground Space Engineering, Huaqiao University, Xiamen 361021, China*
[5] *Key Laboratory of Roads and Railway Engineering Safety Control of Ministry of Education, Shijiazhuang Tiedao University, Shijiazhuang 050043, China*
[6] *State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Lanzhou 730000, China*
[7] *Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Kunming 650500, China*

Correspondence should be addressed to Tianliang Wang; wangtl@stdu.edu.cn

Received 27 August 2021; Revised 30 November 2021; Accepted 6 December 2021; Published 27 December 2021

Academic Editor: Domenico Acierno

The traditional treatment of red clay using inorganic materials leads to many serious environmental problems. The study investigates the mechanical properties of red clay using an environmental-friendly material—xanthan gum—through confined compression, direct shear, and scanning electron microscope tests. At the macroscale, xanthan gum content and curing age had obvious effects on the compressibility, presenting the treated red clay was in the category of low compressibility which gradually increased when xanthan gum content exceeded 1.5%. The xanthan gum content and curing age also had significant influences on the cohesion but not on the internal friction angle. The shear strength of red clay can be improved by increasing the cohesion without obviously changing the friction characteristics. After curing for 28 days, the cohesion and internal friction angle of 2.0% xanthan gum-treated soil were effectively improved to 170.44 kPa and 20.56°, which were increased by 69.79% and 9.36°, respectively, compared with untreated red clay. Microscopic analysis indicated that the strengthening mechanism by xanthan gum was derived from changing the arrangement characteristics of soil particles and forming hard biopolymer-red clay matrices. The proper xanthan gum can effectively wrap clay particles and fill pore spaces. However, the extensive stacking of gels would also reduce the effective connection of clay particles and produce local weak points in the soil, resulting in attenuation of mechanical properties. This study enriches the treatment measure of red clay and provides beneficial experiences for biopolymer application on special clay.

1. Introduction

Red clay is mainly a special brown-red soil formed from carbonate rocks by strong physical and chemical weathering and lateralisation in a warm and humid environment with abundant rainfall [1]. It is mainly distributed in tropical and subtropical regions between 30°N and 30°S latitude, especially in Asia, Europe, Africa, and South America [2] and also in Yunnan, Guangxi, Guizhou, Hunan, and other regions of China with a total exposed area of about 200,000 square kilometers [3]. Red clay has significant regional differences and undesirable characteristics such as poor compaction, high water content, high plasticity, low density, and reverse profile characteristics, leading a condition that it can not be used the correlation laws of general physical property indexes and mechanical parameters of ordinary clay to evaluate the engineering performances [4, 5]. However, red clay is closely related to actual engineering construction. The construction on the untreated red clay layer induces ground collapse, uneven deformation of the foundation, road cracking, slope instability, and other engineering defects. From the geotechnical engineering perspective and to meet construction needs, it is imperative to modify red clay to improve its strength and stability. Recently, many scholars conducted sufficient studies on the strength-growth law, strength characteristics, and action mechanism of inorganic solidified red clay. Traditional reinforcement of red clay is based on physical and chemical measures, utilising inorganic reinforcement materials (i.e., cement, fly ash, and lime) for soil treatment. Although these are effective solidification measures, the application of inorganic solidified soil leads to excessive stiffness, low permeability, and many residual, nondegradable inorganic materials, which cause significant influences on soil and ecological functions. However, the annual demand and production of cement have increased to 2.8 billion tonnes recently, making cement the world's largest source of carbon dioxide emissions. It is also reported that the amount of carbon dioxide emitted during cement production processes was close to 8% of the total global emissions [6]. Carbon dioxide emissions generated using cement materials in geotechnical engineering account for about 0.2% of the total global emissions [7]. Although industrial by-products (i.e., blast furnace slag and fly ash) can reduce cement use to a certain extent, there are still some problems such as insufficient emission reduction efficiency of carbon dioxide in the production process [8]. Simultaneously, many nondegradable pollutants produced from cement waste invades and pollutes the soil environment. Thus, the demand for the development and usage of relatively harmless, renewable, and environmental-friendly materials has significantly increased in the twenty-first century. Scholars are aware of the defects of traditional consolidation and environmental pollution and are actively exploring soil solidification ways for ecological protection.

Biological polymers (i.e., xanthan gum, gellan gum, and guar gum), as new soil consolidation agents, have attracted the attention of many international scholars. Biopolymers are mainly natural polysaccharides produced by algae, fungi, or bacteria and have functional properties such as adsorbability, rheology, and pseudoplasticity [9]. At present, biopolymers are widely used as thickeners, stabilizers, and rheological regulators in fields such as agriculture, food, medicine, and chemist shops [10]. Moreover, biopolymers have a carbon-capturing effect during production; therefore, they exhibit a low carbon dioxide footprint and are often classified as neutral, renewable, and environmental-friendly materials [11]. In the field of civil engineering, biopolymers are used as highly efficient water reducers or water-retaining agents in the dry mixed mortar or concrete admixtures. In the geotechnical engineering field, biopolymers are mainly applied to desertification prevention, slope protection, and water infiltration reduction [12]. However, some scholars use biopolymers to directly stabilize soil aggregates rather than activating microbial reactions in soil, and a homogeneous mixture of biopolymers can be formed in the soil to improve the mechanical properties [13]. At present, xanthan gum is the most widely used among biopolymers for producing polysaccharides [14], which are produced by *Xanthomonas campestris* with carbohydrate as the main raw material. Xanthan gum is odourless, safe, soluble in water, and cheap and has good stability and compatibility. Xanthan gum shows higher stability in temperature (28°C-80°C), salt, acid, and base (pH = 1-11), oxidation resistance, and resistance to enzymatic hydrolysis [15]. Latifi et al. [11] found that xanthan gum, as an environmental-friendly stabilizer, can improve the engineering properties of clay, and in the presence of clay particles, xanthan gum can produce a significant reinforcement effect. Chang et al. [16] pointed out that in the presence of clay particles, xanthan gum formed a firm biopolymer matrix through hydrogen bonding, which had a more significant treatment effect on soil with good particle grading. They believed that xanthan gum was an effective and sustainable soil stabilizer. Rashid et al. [17, 18] mixed xanthan gum with soil and found that xanthan gum can produce an effect within 28 days and significantly improve the soil strength and also pointed out that industrially produced water-insoluble bio gels (i.e., chitosan, polyglutamate, and sodium alginate) have great value in soil erosion control and antisoil liquefaction and play a positive role in reducing water conductivity of highly permeable soil. Ayeldeen et al. [19] showed that the permeability of sandy soil was significantly reduced after the biopolymer treatment, suggesting that xanthan gum mainly reduced water conductivity of soil by filling the pores. Smitha and Rangaswamy [20] believed that biopolymers can form direct hydrogen bonds with clay particles to achieve the purpose of soil reinforcement. Compared with sand particles, there were hydrogen and ionic bonds between xanthan gum and clay particles to maximise the strengthening effect of xanthan gum. Lee et al. [21] discovered that xanthan gum had more significant treatment effects on soil under the condition of low or shallow layers through triaxial shear tests. They believed that the strengthening effect of xanthan gum and other biopolymers mainly came from the improvement of soil cohesive force. Besides, xanthan gum and guar gum have been used to stabilize dispersive soil, which can cause dam erosion, embankment erosion, etc. [22]. Some studies [23] found that after xanthan gum is mixed with clay particles, it can directly combine with clay minerals such as kaolinite to produce accumulative face-to-face clay layers. Favorable modifications of dispersivity, erosion resistance, permeability, and swell shrink of soils, upon amendment of soil materials by biopolymers, have been enough reported [24–26].

Although many researchers mainly focused on the application of biopolymers on some soils (sand, soft soil, sand-clay, etc.) with insignificantly geotechnical specialties or good soil quality in recent studies. Besides, red clay treated by xanthan gum biopolymer has transferred to be a new composite soil material due to the changes of basic geotechnical properties, and its research on the treatment by utilizing xanthan gum biopolymer as a soil stabilizer is relatively rare at present. To achieve the actual engineering application, this study was based on the energy saving, emission reduction, and ecological protection of red clay reinforcement methods and further mainly focused on the typical

Table 1: Basic physical parameters of red clay.

Type	w_P (%)	w_L (%)	I_P (%)	ρ_d (g/cm^3)	w_{opt} (%)	w (%)	G_s
Red clay	26.1	51.3	25.2	1.43	30.56	38	2.82

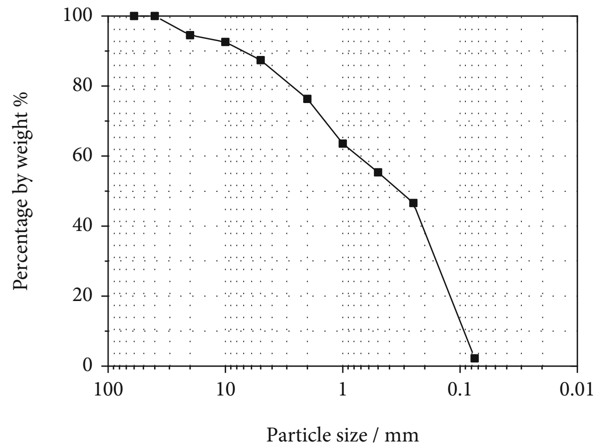
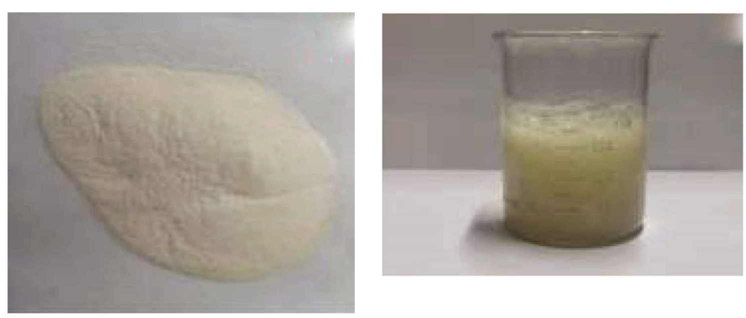


Figure 1: Gradation curve.



(a) (b)

Figure 2: Physical morphology of xanthan gum.

engineering problems of red clay to explore this new treatment measure and completely investigate the improvement effectiveness of the compressibility and shear strength properties, especially in considering the primary factors (xanthan gum content, curing ages, and vertical loads), providing some significant mechanical indexes for relative engineering calculation (i.e., slope stability design and foundation treatment). The influence roles of xanthan gum on compressibility, shear strength, and shear strength parameters of red clay under different xanthan gum ratios and curing ages were analysed. To elucidate the mechanism between xanthan gum and red clay, the microstructural characteristics of red clay and xanthan gum-treated soil were analysed using a scanning electron microscopy (SEM) test.

2. Materials and Methods

2.1. Materials

2.1.1. Red Clay. Red clay was sampled from a foundation pit at 3-5 m depth in Kunming, Yunnan province, China. The latitude and longitude coordinates of the sampling site are $102^{\circ}42'31''$E and $25^{\circ}02'11''$N, respectively. The natural moisture content is 38%, air-dried moisture content is 2%, surface of the soil is brownish red, soil quality is relatively hard, overall particles are fine and uniform, and clay content is high. The basic physical properties of red clay were determined according to GB/T50123-2019 [27]. The physical properties of red clay are shown in Table 1. The particle size distribution curve is shown in Figure 1. According to GB50007-2011 [28], the test soil is a kind of representative red clay.

2.1.2. Xanthan Gum Biopolymer. The biopolymer in the present study was industrial-grade xanthan gum (XG), which is yellow powder at room temperature and can form gels with high consistency and viscosity in aqueous solutions. Xanthan gum ($C_{35}H_{49}O_{29}$) is an anionic polysaccharide with a molecular weight of about 2×10^6 [29]. The main chain is composed of glucose connected at 1 and 4 positions, and the branch chain is composed of two mannose units connected by a β-D-glucuronic acid unit [30].

(a) (b)

Figure 3: (a) Specimens of mechanical tests. (b) Red clay.

Table 2: The compressibility indexes of confined compression test.

Test groups	Curing ages (days)	a_v (MPa^{-1})	E_s (MPa^{-1})	m_v (MPa^{-1})	C_c
Red clay	0	0.176	12.129	0.082	0.053
Red clay + 0.5%XG		0.109	20.687	0.048	0.034
Red clay + 1.0%XG		0.098	20.530	0.049	0.040
Red clay + 1.5%XG		0.102	19.697	0.051	0.043
Red clay + 2.0%XG		0.130	15.247	0.066	0.063
Red clay + 2.5%XG		0.129	15.510	0.064	0.053
Red clay	7	0.143	15.276	0.065	0.042
Red clay + 0.5%XG		0.108	19.247	0.052	0.037
Red clay + 1.0%XG		0.097	20.674	0.048	0.040
Red clay + 1.5%XG		0.080	24.985	0.040	0.033
Red clay + 2.0%XG		0.103	20.917	0.049	0.032
Red clay + 2.5%XG		0.122	16.405	0.061	0.030
Red clay	14	0.121	17.423	0.057	0.047
Red clay + 0.5%XG		0.104	19.079	0.052	0.042
Red clay + 1.0%XG		0.069	29.025	0.034	0.033
Red clay + 1.5%XG		0.065	30.674	0.033	0.029
Red clay + 2.0%XG		0.087	22.879	0.044	0.039
Red clay + 2.5%XG		0.104	19.079	0.052	0.043
Red clay	28	0.096	20.734	0.048	0.036
Red clay + 0.5%XG		0.081	24.420	0.041	0.036
Red clay + 1.0%XG		0.071	28.100	0.036	0.031
Red clay + 1.5%XG		0.058	33.140	0.030	0.029
Red clay + 2.0%XG		0.092	21.448	0.047	0.037
Red clay + 2.5%XG		0.102	19.536	0.051	0.026

There is a strong mutual attraction between the main chain and branch chain. Thus, the molecular chains are closely aggregated to form a network structure, benefiting to agglomerate and adsorb more clay particles. Figure 2 shows xanthan gum physical morphology. In the present study, it is aimed at investigating the geotechnical properties of biomodified sample to evaluate the effects of xanthan gum biopolymer content on the modifying mechanical properties of red clay. Thus, the certain xanthan gum contents (from 0% to 2.5% of soil mass weight ratio, respectively) have been set based on the previous studies [9, 23, 31–34] and the purpose of the paper. Also, the appropriate and effective small percentage of the additive to reduce the economic cost is a significant concern when we use biopolymer material to stabilize or treat the soil.

2.2. Sample Preparation and Test Methods

2.2.1. Sample Preparation. Specimen preparation was carried out according to GB/T50123-2019 procedures [27]. Before

TABLE 3: Groups and conditions of direct shear test.

Test groups	Curing ages (days)	Vertical pressure (kPa) 100 kPa	200 kPa	300 kPa	400 kPa
A: red clay	3	A-3-1	A-3-2	A-3-3	A-3-4
	7	A-7-1	A-7-2	A-7-3	A-7-4
	14	A-14-1	A-14-2	A-14-3	A-14-4
	28	A-28-1	A-28-2	A-28-3	A-28-4
B: red clay + 0.5%XG	3	B-3-1	B-3-2	B-3-3	B-3-4
	7	B-7-1	B-7-2	B-7-3	B-7-4
	14	B-14-1	B-14-2	B-14-3	B-14-4
	28	B-28-1	B-28-2	B-28-3	B-28-4
C: red clay + 1.0%XG	3	C-3-1	C-3-2	C-3-3	C-3-4
	7	C-7-1	C-7-2	C-7-3	C-7-4
	14	C-14-1	C-14-2	C-14-3	C-14-4
	28	C-28-1	C-28-2	C-28-3	C-28-4
D: red clay + 1.5%XG	3	D-3-1	D-3-2	D-3-3	D-3-4
	7	D-7-1	C-7-2	D-7-3	D-7-4
	14	D-14-1	C-14-2	D-14-3	D-14-4
	28	D-28-1	C-28-2	D-28-3	D-28-4
E: red clay + 2.0%XG	3	E-3-1	E-3-2	E-3-3	E-3-4
	7	E-7-1	E-7-2	E-7-3	E-7-4
	14	E-14-1	E-14-2	E-14-3	E-14-4
	28	E-28-1	E-28-2	E-28-3	E-28-4

the specimen preparation, soil samples were placed in a 105°C drying oven for 24 h, and then, the dried samples were ground and passed through a geo-sieve of diameter 2 mm. Next, the moisture content of the soil sample was measured first, replenishing water to reach the set moisture content ($W_{opt} = 30.56\%$), and then, the configured soil sample was put into the standard curing apparatus for 24 h. The mixture was configured with $\rho_d = 1.43\,g/cm^3$ and $W_{opt} = 30.56\%$, and the xanthan gum content was controlled by the mass ratio ($M = m_{XG}/m_s \times 100\%$). Detailed preparation steps are as follows: first, the xanthan gum powder and soil were uniformly mixed; then, the required amount of water was divided into two equal parts and evenly sprayed onto the mixture. The dry mixing method was adopted to configure the mixture to ensure that xanthan gum can be completely dissolved at room temperature to obtain a homogeneity soil mixture. After mixing, the specimen was resized to 61.8 mm diameter and 20 mm height using a ring knife. The static sample pressing method was used for moulding, and the dry density error was controlled to be within $0.02\,g/cm^3$. After preparation, the specimens were cured under standard conditions (the temperature of 20 ± 2°C, 80% relative humidity) for avoiding water loss until the set time (i.e., 0, 3, 7, 14, 21, and 28 days) [27, 35, 36]. It is aimed at investigating the various curing periods which are aimed at exploring the early mechanical properties and the mechanical laws with time span to red clay treated by various xanthan gum contents. Specifically, selecting 0-3 days of curing is that we want to understand the effectiveness of xanthan gum to the early mechanics of red clay, which is significant for actual engineering construction such as slope protection and foundation treatment; the 7-28 days of curing is aiming at understanding the strengthening mechanism with long time span to red clay treated by various xanthan gum content. Figure 3 shows the specimens and soil samples.

2.2.2. Test Methods. The GZQ-1 automatic air pressure consolidation was used in the confined compression test. The basic variables were the content of xanthan gum (m_{XG}/m_s =0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) and curing ages (0, 7, 14, and 28 days). The pressure grades were 12.5, 25, 50, 100, 200, 400, 800, and 1600 kPa. The time sequence of data acquisition under each loading was 6 s, 15 s, 30 s, 60 s, 1 min 15 s, 4 min, 6 min 15 s, 9 min, 12 min 15 s, 16 min, 20 min 15 s, 25 min, 30 min 15 s, 36 min, 49 min, 1 h 40 min, 3 h 20 min, 6 h 40 min, 23 h, and 24 h. The stability standard of all levels of loading was that specimen deformation under each level of loading was no more than 0.01 mm/h. For the convenience of data comparison, the compression index corresponding to the pressure interval between $P_1 = 100$ kPa and $P_2 = 200$ kPa was used to evaluate the compressibility [18]. For each group of test conditions, 10 parallel specimens and a total of 240 specimens were prepared. Table 2 shows the compressibility indexes measured in the tests.

A Z-J strain control type direct shear instrument was used to carry out a fast shear test. The test variables of were xanthan gum content (m_{XG}/m_s = 0%, 0.5%, 1.0%, 1.5%, and

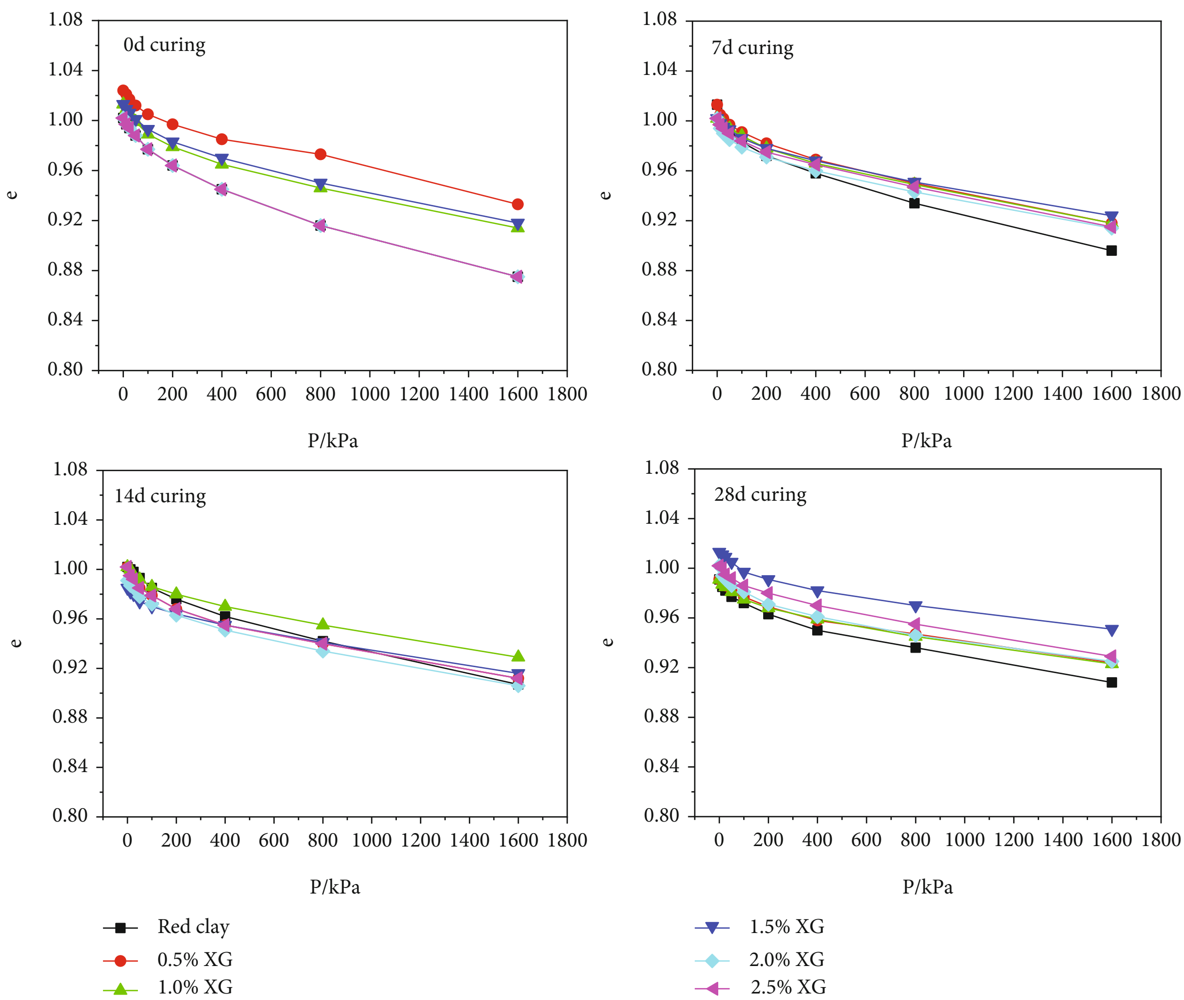


Figure 4: Relationship of e-p.

2.0%) and curing ages (3, 7, 14, and 28 days). The vertical loads were 100, 200, 300, and 400 kPa, respectively, and the shear rate was 0.8 mm/min. The shear of the specimen was completed within 5-8 min [27]. If the values of the dynamometer continued to increase, the test was stopped when the shear deformation reached 6 mm. For each test condition, 6 parallel specimens and a total of 120 specimens were prepared. Table 3 shows the test conditions and grouping.

The SEM tests were used by the Flexsem1000 device to qualitatively observe and compare the microstructure characteristics of the red clay and xanthan gum-treated red clay ($m_{XG}/m_s = 1.0\%$, 1.5%, and 2.0%) after curing for 28 days. A cubic soil strip with a size of about 0.5 cm^3 (height 5 mm, length 10 mm, and width 10 mm) was obtained by a fine steel wire in the direction of soil deposition and avoiding the smooth surface as much as possible, and the sampling point was the center of the interior of the specimen to ensure that the part of the soil sample taken can represent the structural features as much as possible. Before scanning, the surface of the specimen was blown away with a rubber ball to remove the disturbing particles and sprayed with gold to eliminate the charging phenomenon, and the specimen was quickly moved into the sample table for testing. This study provides a microscopic basis for further explaining the effects of xanthan gum on the mechanical properties of red clay.

3. Results and Discussion

3.1. Confined Compression Test

3.1.1. Effect of Xanthan Gum Content on the Compressibility of Red Clay. Figure 4 shows the e-p relationship of specimens with various xanthan gum contents ($m_{XG}/m_s = 0.0\%$, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) at curing for 0, 7, 14, and 28 days, respectively. It can be noted that red clay was the medium compressible soil, whereas the xanthan gum-treated soils were basically as low compressible. The e-p relationship showed that the initial stage was slightly steep, and the compression of red clay and xanthan gum-treated soil was large because of the rearrangement of clay particles. Then, the curves gradually flattened and the compression decreased, which was because of the decrease in porosity ratio, which led to the limited movement of particles. At

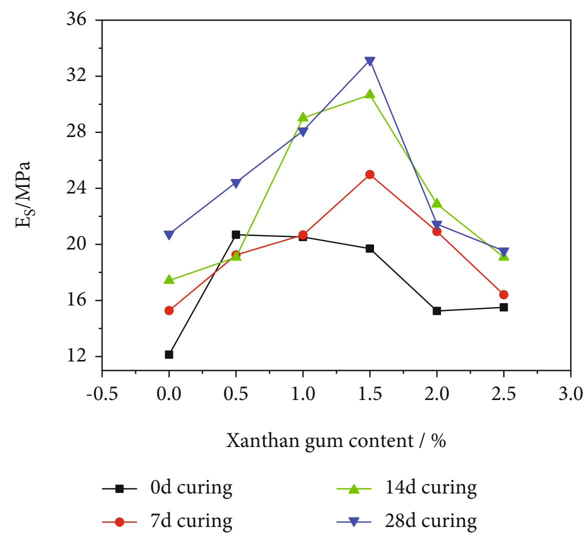


FIGURE 5: Relationship of xanthan gum content and compression modulus.

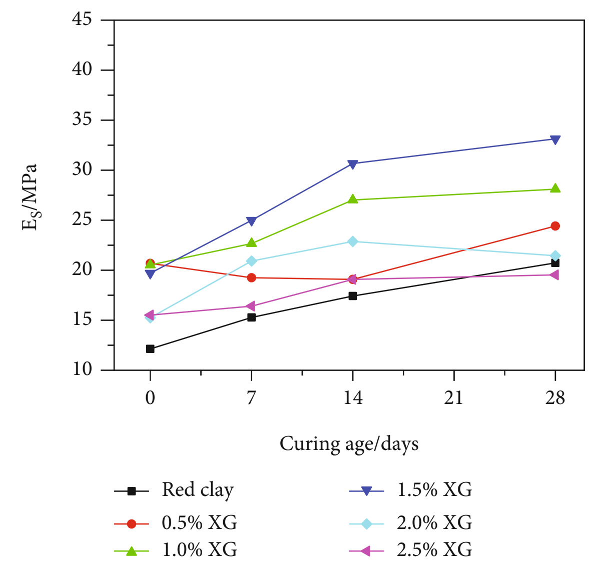


FIGURE 7: Relationship of curing ages and compression modulus.

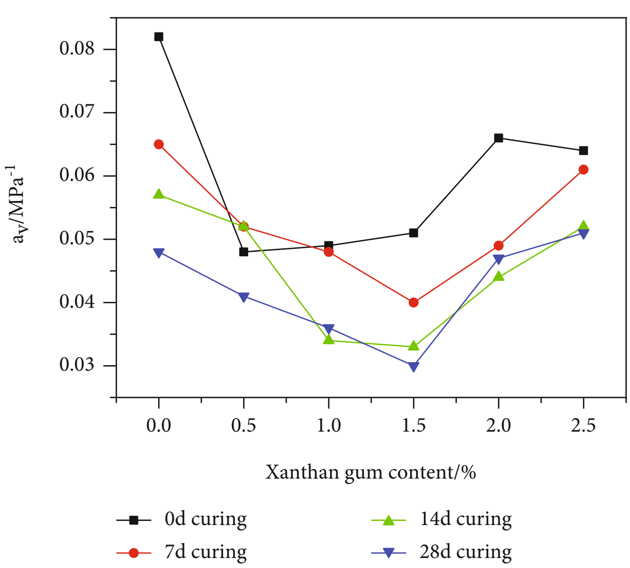


FIGURE 6: Relationship of xanthan gum content and compression coefficient.

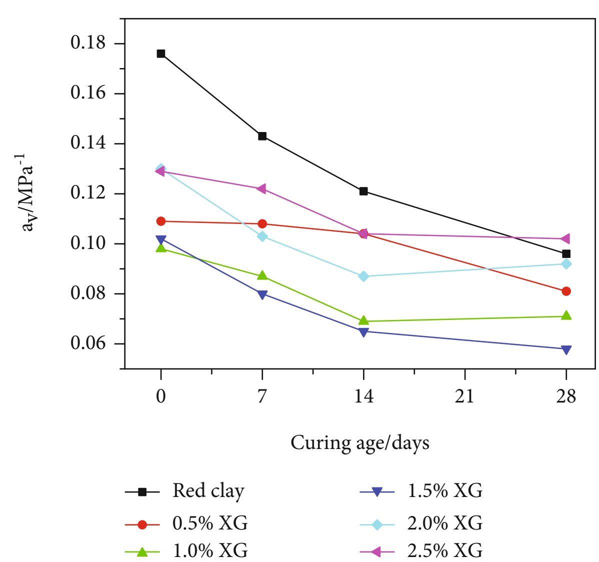


FIGURE 8: Relationship of curing ages and compression coefficient.

the same curing age, the porosity ratio of the modified soil changed greatly with the increase in xanthan gum content. However, with the increase in curing ages, the variation range of porosity ratios of the treated soil was limited. When the xanthan gum content remained unchanged, the porosity ratio of the treated soil decreased with the increase in curing ages under the similar compressive stress.

Figure 5 shows the relationship between xanthan gum content and compression modulus. It can be discovered that when curing is for less than 0 days, the compression modulus of treated soil showed a decreasing trend with the increase in xanthan gum content, and the compression modulus of the 0.5% xanthan gum-treated soil was the largest (20.69 MPa). The compression modulus of 2.0% and 2.5% treated soil was 15.25 MPa and 15.51 MPa, respectively, which was close to that of red clay (12.13 MPa). The reason is that a large amount of xanthan gum in the uncured red clay did not effectively react with water and clay particles to form the biopolymer red clay matrix. Instead, more xanthan gum gels remained in the red clay, which reduced the contact between clay particles and expanded the pore spaces, leading to a decrease in compression modulus. After curing for 7 days, the compressive modulus of the treated soil first increased and then decreased with the increase in the xanthan gum content. The compressive modulus of the 1.5% treated soil cured for 28 days was the largest, which increased by 59.83% compared with that of the red clay. The 2.5% xanthan gum-treated red clay cured for 28 days had the lowest compressive modulus, which was close to that of the red clay (20.73 MPa).

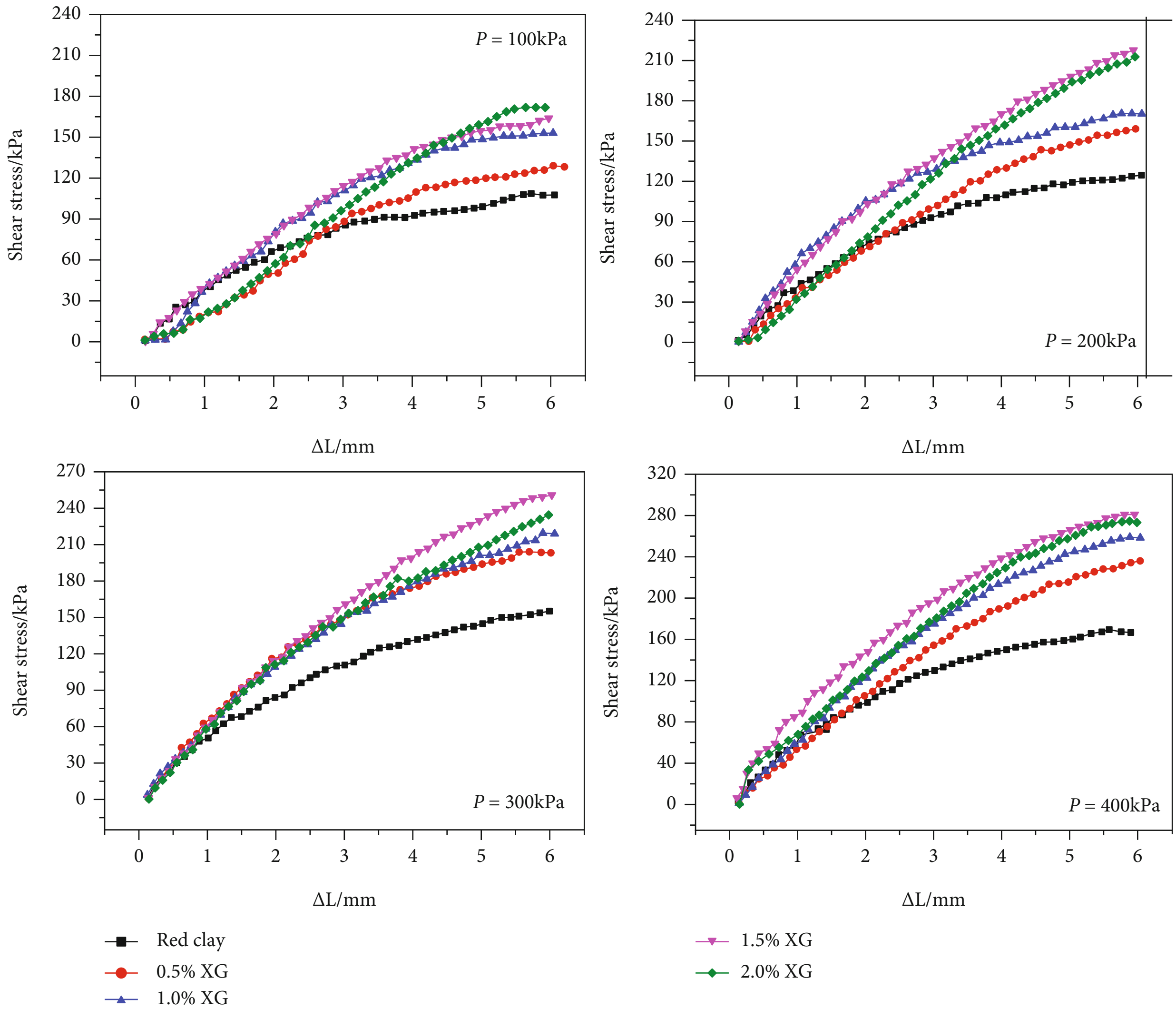


Figure 9: Shear stress and shear displacement of soil after curing for 7 days.

Figure 6 shows the relationship between xanthan gum content and compressibility coefficient. At curing for 0 day, the compressibility coefficient of the treated soil gradually increased with the increase in xanthan gum content, and the compressibility coefficient of the 0.5% treated soil was the smallest (0.053 MPa^{-1}). The compressibility coefficient of 2.0% and 2.5% treated soil were 0.063 MPa^{-1} and 0.053 MPa^{-1}, respectively, which were close to that of red clay (0.053 MPa^{-1}). After curing for 7 days, with the increase in xanthan gum content, the treated soil compressibility decreased first and then increased, among which the 1.5% treated soil compressibility was the smallest and 2.5% treated soil compressibility was the largest.

3.1.2. Effect of Curing Ages on the Compression of Xanthan Gum-Treated Red Clay. Figure 7 shows the relationship between curing ages and compression modulus. The compression modulus of red clay gradually improved with the increase in curing ages, because red clay had many aggregate structures in the formation process. Colloid formation through the interaction between free iron oxide and aqueous solutions filled the pore spaces of the aggregate structures, and strong chemical bonds were formed between water molecules and iron molecules [37]. For xanthan gum-treated soil, the compression modulus of 0.5% and 1.0% soil did not significantly change after curing for 0-7 days; however, the compression modulus gradually increased with the xanthan gum content of more than 1.0%. With the increase in ages (7-28 days), the compression modulus of the modified soil increased first and then became flat, and the soil consolidation effect of 1.5% content was the best. Compared with the compression modulus of red clay during each curing age, the compression modulus of xanthan gum-treated soil increased by 7.57, 9.71, 13.25, and 12.41 MPa, respectively. However, the presence of a large number of xanthan gum gels ($M > 1.5\%$) in the soil can reduce the effective contact points between soil particles. Meanwhile, the prolonged curing ages led to water loss and the hardening of the gels to form crystalloid structures expanded the pore space of soil particles, increasing the compressibility.

Figure 8 shows the relationship between curing ages and compression coefficient. It can be observed that the

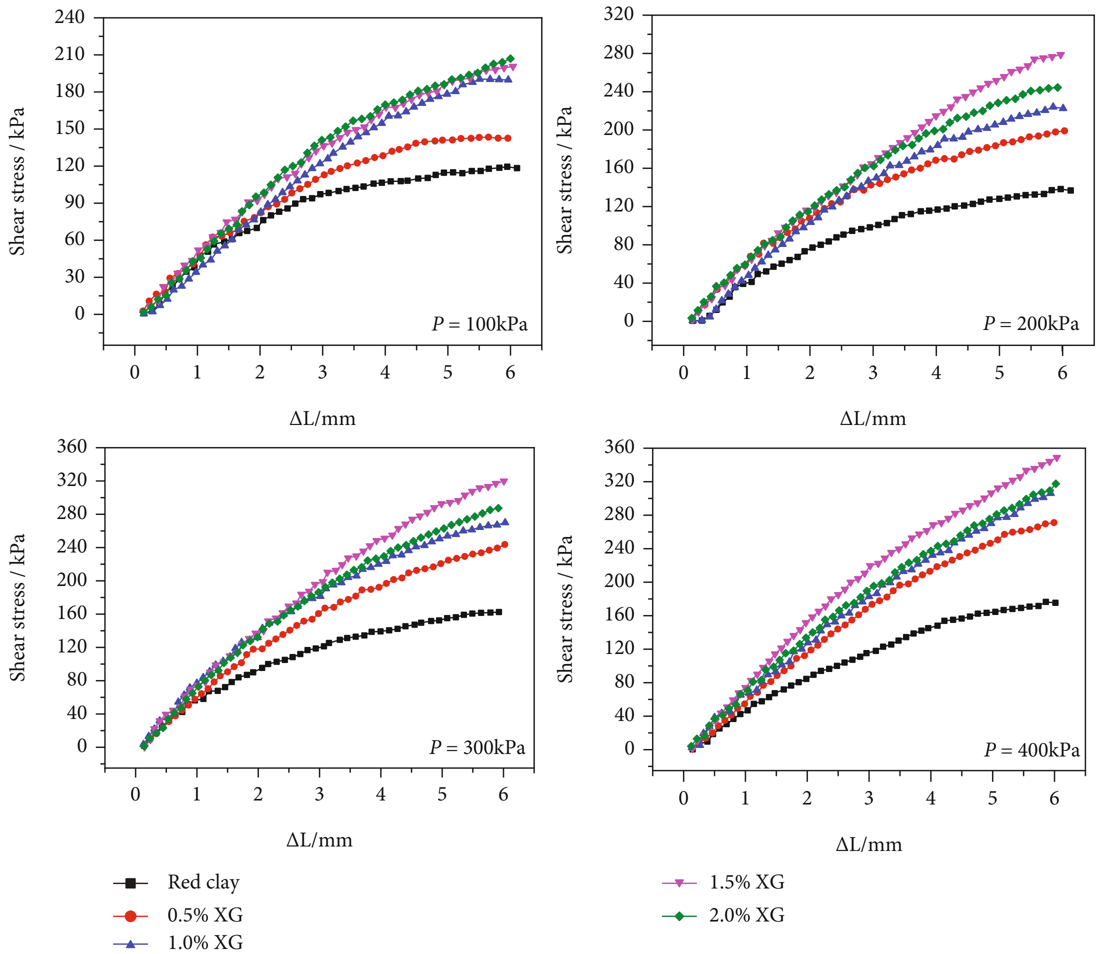


Figure 10: Shear stress and shear displacement of soil after curing for 28 days.

compression coefficient of red clay gradually decreased with the increase in curing ages, whereas that of xanthan gum-treated soil gradually decreased and tended to be flat. The compression coefficients of 0.5%, 1.0%, 1.5%, and 2.0% xanthan gum-modified soil in each curing age were significantly lower than those of red clay. The compressibility coefficient of 2.5% treatment soil cured for 28 days was slightly higher than that of red clay. To decrease the compressibility of red clay, 1.5% xanthan gum content was the threshold, decreasing by 62.40%, 6.3.56%, 76.50%, and 59.83%, respectively, compared with the compression coefficient of red clay during each curing age.

3.2. Direct Shear Test

3.2.1. Relationship between Shear Stress and Shear Displacement. Figure 9 shows the shear stress and shear displacement curves of red clay and xanthan gum-treated soil after curing for 7 days. The shear stress of both red clay and the treated soil had not shown obvious peak points. Under various loads, the stress-displacement curves of red clay increased first and then became flat. The stress-displacement curves of the modified soil were similar to that of red clay under 100 kPa. However, with the continuous increase in loads ($P = 200$-400 kPa), the shear displacement of the treated red clay changed a little at the initial shear stage, and the stress-displacement showed linear growth and changed to nonlinear rapid growth with the continuous shear process. After curing for 7 days, the shear stress of the 0.5% treated soil was significantly greater than that of the red clay, and the shear stress of the 2.0% treated soil was slightly greater than that of the 1.5% under lower load ($P = 100$ kPa). However, the differences between the shear stress of the 2% and 1.5% treated soil under higher load were small. Figure 10 shows the relationship curves between shear stress and shear displacement of the red clay and xanthan gum-treated soil curing for 28 days. The variation form of stress-displacement curves of red clay in the shear process was similar to other curing ages. With increasing loads ($P = 200$-400 kPa), the stress-displacement of the treated red clay showed a significant linear increase without obvious peak points.

The shear properties of red clay treated by xanthan gum were greatly improved, and the stress displacement of the treated soil was the typical hardening type. There was a positive correlation between the xanthan gum ratio and improvement effects. The differences in positive correlation gradually expanded with the increase of curing ages and

Table 4: Results of shear strength in direct shear tests.

Test groups	Fitting equation	R^2	τ (kPa) 100 kPa	200 kPa	300 kPa	400 kPa
A-3	$y = 0.213x + 83.585$	0.954	108.00	119.37	151.36	168.2
B-3	$y = 0.275x + 84.850$	0.963	116.65	136.53	161.07	200.13
C-3	$y = 0.298x + 101.330$	0.937	136.28	158.23	180.62	228.13
D-3	$y = 0.350x + 116.630$	0.989	150.19	186.08	227.19	253.2
E-3	$y = 0.300x + 132.680$	0.999	161.25	194.82	222.86	251.96
A-7	$y = 0.213x + 86.200$	0.968	108.69	124.51	155.15	169.49
B-7	$y = 0.339x + 97.060$	0.996	132.06	162.03	200.98	231.97
C-7	$y = 0.367x + 108.795$	0.956	153.01	170.51	219.53	258.94
D-7	$y = 0.385x + 132.180$	0.969	163.84	217.77	250.86	281.09
E-7	$y = 0.330x + 140.935$	0.981	171.82	212.78	234.47	274.55
A-14	$y = 0.201x + 95.480$	0.953	118.02	128.30	157.69	173.38
B-14	$y = 0.357x + 101.910$	0.989	139.48	168.24	213.05	243.38
C-14	$y = 0.364x + 131.430$	0.939	176.08	190.22	243.99	279.52
D-14	$y = 0.412x + 151.655$	0.878	178.38	250.39	285.93	303.84
E-14	$y = 0.383x + 149.200$	0.988	185.28	226.04	270.15	298.20
A-28	$y = 0.198x + 100.375$	0.986	119.42	138.28	162.50	176.37
B-28	$y = 0.411x + 109.355$	0.980	145.37	196.1	238.63	268.13
C-28	$y = 0.415x + 143.520$	0.996	186.38	223.05	271.00	308.77
D-28	$y = 0.446x + 165.590$	0.924	200.66	278.68	319.84	348.82
E-28	$y = 0.375x + 170.435$	0.994	206.95	244.46	287.34	317.49

vertical loads. Under $P = 100$ kPa, the stress-displacement curves of 1.0%-2.0% xanthan gum-treated soil were close to each other, indicating that the xanthan gum effect and the ability to resist shear deformation were similar under low load. Under $P = 200$-400 kPa, the improvement of 1.5% xanthan gum ratio on the shear strength of the red clay was the strongest. When the ratio exceeded 1.5%, the effect gradually became stable between 1.0% and 1.5%. Table 4 shows the shear strength values.

Figure 11 shows the strength envelope obtained by linear fitting of the strength of the red clay and xanthan gum-treated soil under four vertical loads at various curing ages. The shear strength of the treated soil at four different curing ages was significantly greater than that of red clay, and the differences between 2.0% and 1.5% xanthan gum-treated soil were small at curing for 3 and 7 days. After curing for 14 and 28 days, the shear strength of the 1.5% xanthan gum-treated soil was greater than 2.0%. The effect of xanthan gum content on the shear strength of the red clay was 1.5% > 2.0% > 1.0% > 0.5%. Meanwhile, the increase in curing ages had significant effects on the shear strength of red clay treated by xanthan gum. The cohesion and internal friction angle of the red clay and xanthan gum-treated soil were obtained by linear fitting of the shear strength of each testing. Table 5 shows the shear strength parameters.

3.2.2. Effect of Xanthan Gum Content on Shear Strength Indexes of Red Clay. The strength of soil is essentially the shear strength of soil [38, 39]. In the direct shear test, the shear strength of soil can consist of the cohesion on sliding surface and the internal friction resistance according to Mohr-Coulomb strength criterion [40]. Based on Mohr-Coulomb formula, the internal friction angle and cohesion are two mechanical indexes of soil shear strength (the ultimate resistance to shear failure) [41]. The internal friction angle depends on the friction resistance, reflecting the friction properties of soil. Cohesion is the characteristic index of cohesive soil, including the solidified cohesion formed by the cementation of soil compounds. Figure 12 shows the relationship between xanthan gum content and cohesion. The red clay cohesion at four curing ages showed a gradually improving trend with the increase in the xanthan gum content. Using the red clay as the control group, 0.5% xanthan gum-treated soil cohesion increased the least under each curing age and was similar to that of the red clay at the early stage of curing. With the increase in curing ages, the increment in cohesion was 1.26, 10.86, 6.43, and 8.98 kPa, respectively. The cohesion of the 1.0% xanthan gum-treated soil increased by 21.22%, 26.22%, 37.65%, and 42.98%, respectively, which had little effect on the cohesion from curing for 3-7 days. The cohesion of the 1.5% xanthan gum-treated soil, respectively, increased by 39.53%, 53.34%, 58.83%, and 64.96%. The 2.0% xanthan gum had the most significant effects on cohesion. This content also had obvious influences on the improvement of the cohesion at the early curing stage, which increased by 58.73%, 63.50%, 59.40%,

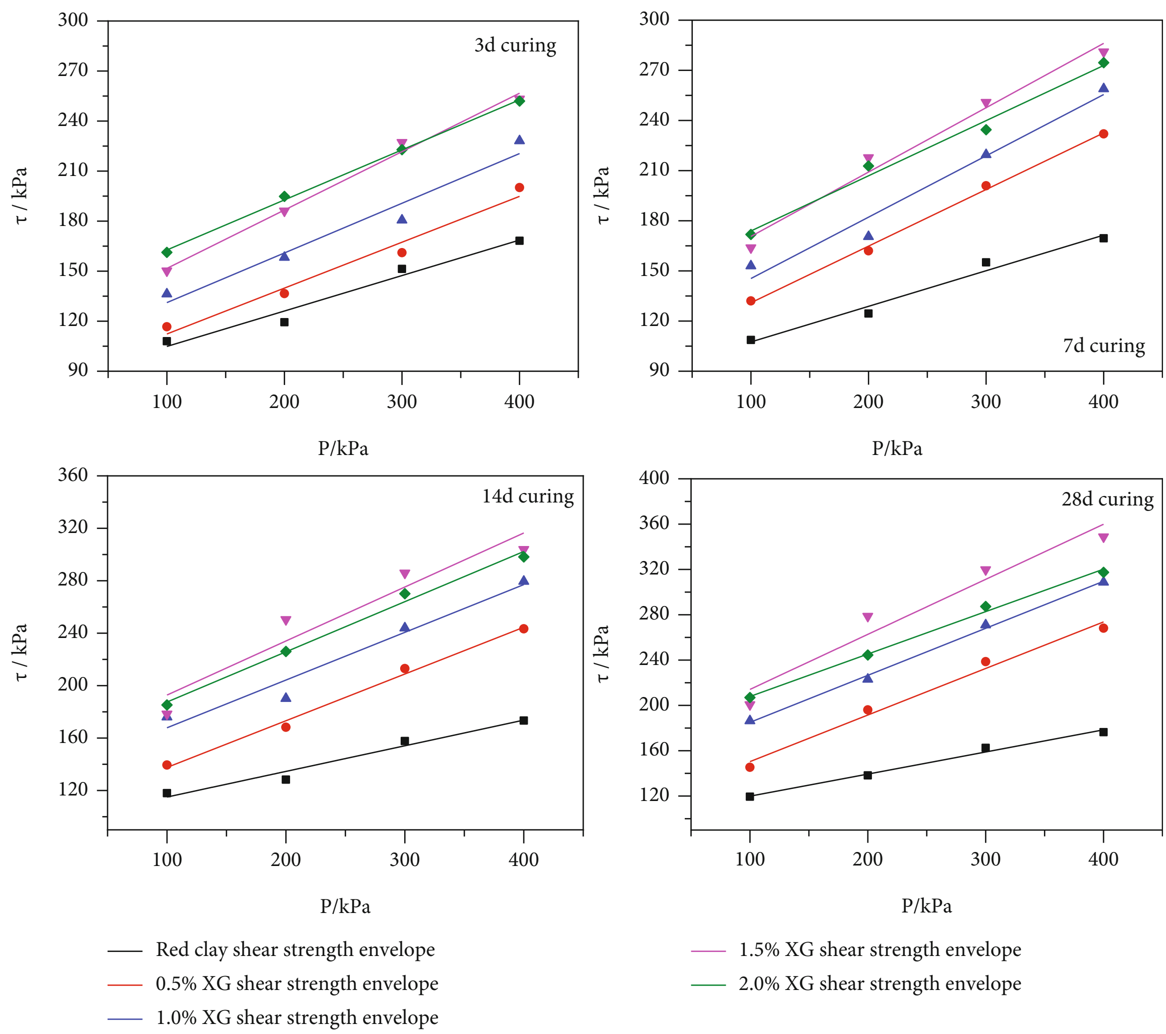


FIGURE 11: Strength envelope for curing for 3, 7, 14, and 28 days.

and 69.79%, respectively. When the xanthan gum content was low, the biopolymer-red clay matrix was not formed in the soil and the pores were not be filled effectively. However, with the increase in the xanthan gum content, the xanthan gum monomers adsorbed water to form gels, leading to a more compact soil particle arrangement and limiting the particle displacement, thereby increasing the cohesive strength of the red clay.

Figure 13 shows the relationship between the xanthan gum content and the internal friction angle. The internal friction angle of red clay was between 11.2° and 12.02° under the curing time. However, with the increase in the xanthan gum content, the internal friction angle of red clay first increased and then decreased. Using the internal friction angle of red clay as the control group, under each curing time, the effect of 0.5% ratio on the internal friction angle was the least, which increased by 3.36°, 6.73°, 8.28°, and 11.14°, respectively. The internal friction angle of 1.0% treated soil increased by 4.57°, 8.15°, 8.63°, and 11.34°, respectively. The internal friction angle of 1.5% treatment soil increased by 7.27°, 9.06°, 11.02°, and 12.83°, respectively. When the ratio exceeded 1.5%, the increase in the internal friction angle gradually decreased and was close to the 1.0% effect. The xanthan gum influence on the internal friction angle of red clay was due to the change in the contact characteristics on the clay particle surfaces and the change in work by particle rearrangement. These changes were caused by the occlusal damage of the soil particles [42]. When the xanthan gum content was too high, the gaps between particles were filled with gels, and the conjunctiva surrounding the particles became thicker, reducing the contact points between clay particles and making the particles more prone to sliding. As a result, the interlinked particles were more likely to be destroyed and their antifriction ability was reduced.

3.2.3. Effect of Curing Ages on Shear Strength Parameters of Modified Soil. Figure 14 shows the relationship between curing ages and cohesion. The cohesion of red clay changed slightly with the increase in curing ages, and the cohesion increment was 16.79 kPa, while the cohesion of xanthan gum-treated soil rapidly increased at first and then tended to flatten. Using the red clay cohesion as the control group, with the increase in curing ages, the cohesion of 0.5%

Table 5: Fitting results of shear strength index.

Test groups	c (kPa)	φ (°)	R^2
A-3	83.59	12.02	0.954
B-3	84.85	15.38	0.963
C-3	101.33	16.59	0.937
D-3	116.63	19.29	0.989
E-3	132.68	16.70	0.999
A-7	86.20	12.00	0.968
B-7	97.06	18.73	0.996
C-7	108.80	20.15	0.956
D-7	132.18	21.06	0.969
E-7	140.94	18.26	0.981
A-14	95.48	11.37	0.953
B-14	101.91	19.65	0.989
C-14	131.43	20.00	0.939
D-14	151.66	22.39	0.878
E-14	152.2	20.93	0.988
A-28	100.38	11.20	0.986
B-28	109.36	22.34	0.980
C-28	143.52	22.54	0.996
D-28	165.59	24.03	0.924
E-28	170.44	20.56	0.994

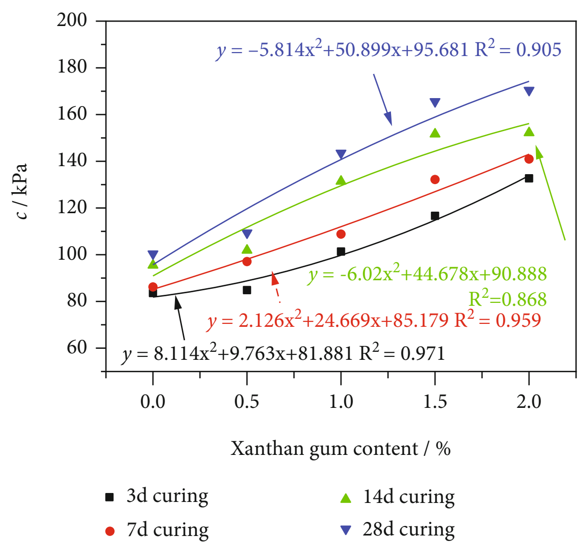


Figure 12: Relationship between xanthan gum content and cohesion.

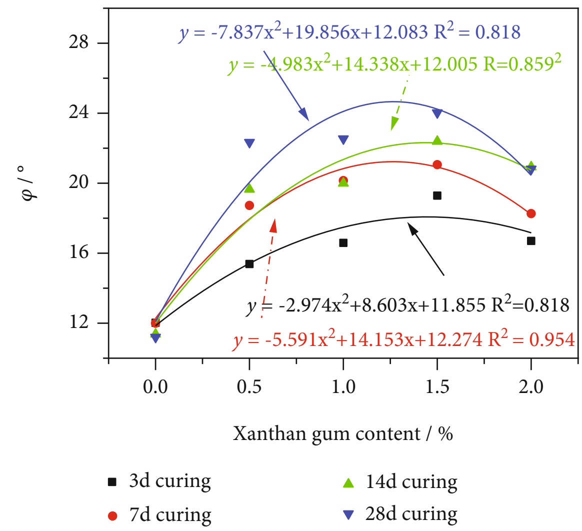


Figure 13: Relationship between xanthan gum content and internal friction angle.

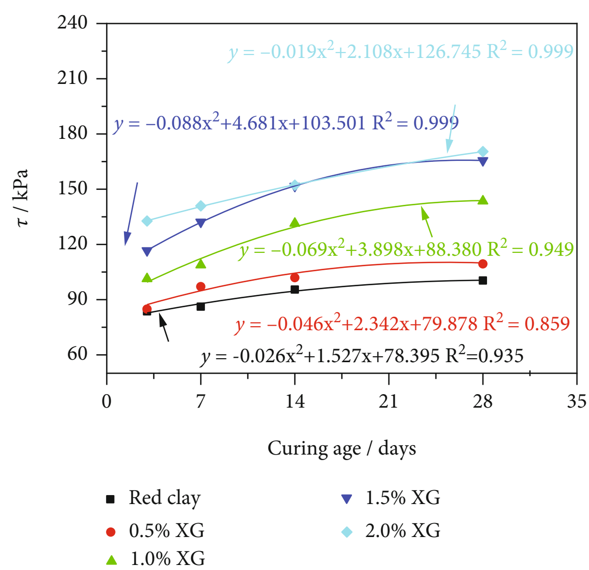


Figure 14: Relationship between curing ages and cohesion.

modified soil increased by 1.51%, 12.60%, 6.73%, and 8.95%, respectively. The strengthening effect was limited and had no obvious effect at the early curing stage. The cohesion of 1.0% xanthan gum-treated soil increased by 21.22%, 26.22%, 37.65%, and 42.98%, respectively, and the improvement effect was obviously enhanced after curing for 14 days. The cohesion of 1.5% treatment soil increased by 39.53%, 53.34%, 58.84%, and 64.96%, respectively. The cohesion of 2.0% xanthan gum-modified soil increased by 58.73%, 63.50%, 59.41%, and 69.79%, respectively. With the increase in curing ages, the proper content of xanthan gum can significantly improve cohesion. At the early curing stage, the interaction between xanthan gum and clayey particles had not been fully exerted. With the increase in curing ages, xanthan gum can interact better with water solution and clay particles, and the network structure of xanthan gum molecules can form highly viscous gels on combining with water [43]. The cementation gradually eliminated the particle gaps, enhanced the connectivity of clay particles, reduced the fluidity of particles, and improved the soil compactness. Additionally, the larger the xanthan gum content, the longer the curing ages can make the cementation function play more fully.

Figure 15 shows the relationship between curing ages and internal friction angle. The internal friction angle of red clay decreased with the increase in curing ages, with a

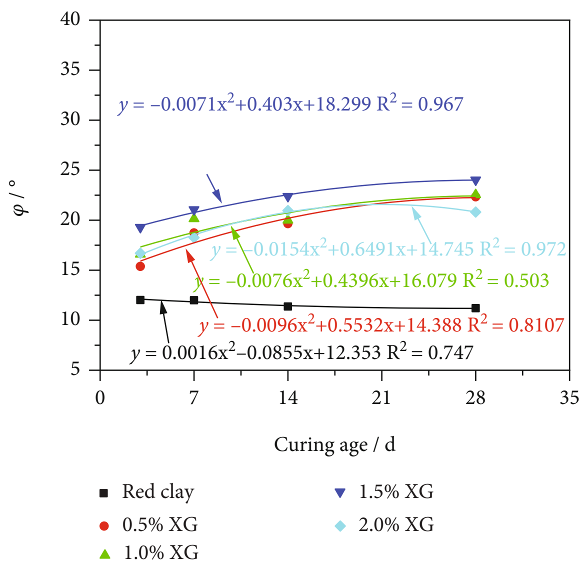


Figure 15: Relationship between curing ages and internal friction angle.

decrease of 7.32%. However, with the increase in curing ages, the internal friction angle of the treated soil with various contents first increased and then tended to be flat. At each curing age, the internal friction angle of the treated soil was obviously larger than that of red clay, and the 1.5% treated soil had the largest internal friction angle. With the increase in curing ages and the contents, the increment in the internal friction angle gradually decreased. The internal friction angle of 0.5%, 1.0%, 1.5%, and 2.0% of the treated soil cured for 28 days only increased by 6.96°, 5.95°, 4.74°, and 4.11°, respectively, compared with that of soil cured for 3 days. The reason is that xanthan gum formed cementations with water and clay particles. With the increase in curing ages, the cement continued to harden and form a crystallisation matrix in the soil and continued to extend and fill the gaps between soil particles, increasing the internal friction angle [44]. With excess xanthan gum in the soil, the gels lost water and hardened to form stackable crystal structures, reduced the connection, and formed local weak points during stress and deformation, leading to a decrease in the internal friction angle.

3.2.4. Significant Analysis of Shear Strength Parameters. Table 6 shows the fitting results of the correlation between test variables and shear strength parameters. The cohesion of the treated soil had a significant positive correlation with the curing age ($P < 0.01$). The cohesion of red clay was affected by xanthan gum in varying degrees. The regression-fitting effect was better with the increase in the xanthan gum content. The correlation between the cohesion and the low content (0.5%) of xanthan gum was not significant ($P > 0.05$). When the xanthan gum content continuously increased ($M > 0.5\%$), the correlation between xanthan gum and cohesion reached a significant level ($P < 0.05$). Besides, there was no significant correlation between the xanthan gum content and the internal friction angle ($P > 0.05$) and no correlation between the curing age and the internal friction angle. The xanthan gum content and the curing age had significant influences on the cohesion; however, these variables belonging to secondary influencing factors had no obvious effects on the internal friction angle. The phenomenon is similar to the previous results [19] that the improvement of shear strength of red clay mainly comes from the changes of cohesion without obviously changing the friction characteristics. It can be concluded that the red clay particles covered with xanthan gum did not have obvious particle breakage during the deformation process, which has not improved the roughness of the contact surface.

3.3. Microscopic Analysis. Figure 16(a) is the 12000x SEM image of red clay. It was observed that the microscopic structure of red clay was relatively loose and weak, showing clear boundaries between each clay aggregate. Besides, no other obvious substances were found on the soil surfaces. Figure 16(b) shows the 1500x SEM image of the 1.0% xanthan gum-treated red clay. Compared with Figure 16(a), xanthan gum gels not only covered the surrounding clayey particles but also filled the pore spaces, showing that the boundaries between the unearthed particles were no longer obvious. The shear strength of the treated soil increased by 75.07% at the ratio of 1.0% xanthan gum. Figure 16(c) shows the 3500x SEM image of the 1.5% xanthan gum-treated red clay. Red clay particles were firmly cemented and adsorbed by xanthan gum and were stacked to form the continuous smooth clayey layers [34], improving the overall structures, presenting the shear strength of 1.5% xanthan gum-treated red clay increased by 97.78%. Figure 16(d) is the 1500x SEM image of the 2.0% xanthan gum-treated red clay. We observed that the boundaries between clayey aggregates were no longer visible, and a large amount of xanthan gum biopolymer matrix was stacked on the soil surfaces. Compared with the 1.5% treated soil, the shear strength of the 2.0% treated soil decreased slightly, indicating that the high content of xanthan gum can produce more viscosity gels, producing thicker glue conjunctiva between soil particles, thereby reducing the effective contacts between the clay particles. Moreover, the strength of gel products was lower than that of the soil particles so that it was easy to form local vulnerabilities in the stress deformation, reducing the treated soil strength. The phenomenon explained how the interaction between soil and long-chained biopolymer strings changed the soil morphology to the engineering properties of biotreated soil [45].

4. Conclusions

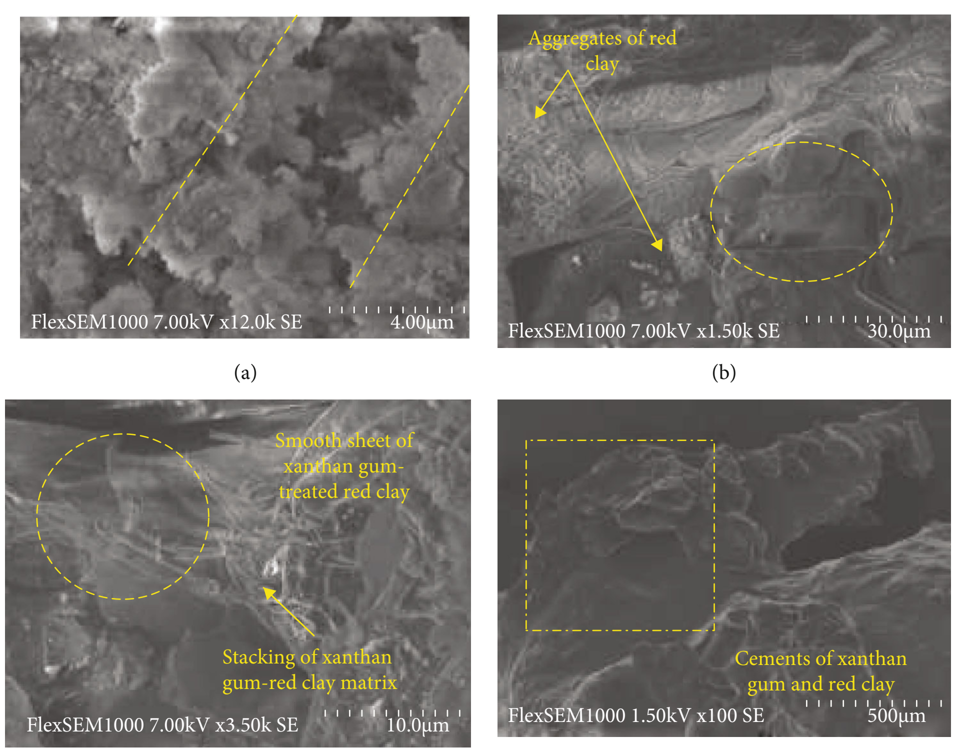
The influence of mechanical properties of red clay treated by xanthan gum was studied through the confined compression and direct shear tests. The mechanism between red clay and xanthan gum was revealed using the scanning electron microscope test. The main conclusions are as follows:

(1) The porosity ratio changed greatly with the increase in xanthan gum content; however, it changed less

Table 6: Correlation analyses of the influencing factors with shear strength parameters.

Variate	Parameter	F	P	Significance	Fitting equation	R^2
3 d curing	c	60.791	0.004	***	$y = 25.992x + 77.82$	0.937
	φ	9.992	0.091	*	$y = -2.9746x2 + 8.603x + 11.86$	0.818
7 d curing	c	31.899	0.001	***	$y = 28.92x + 84.12$	0.970
	φ	42.219	0.023	**	$y = -5.591x2 + 14.153x + 12.27$	0.954
14 d curing	c	36.049	0.009	***	$y = 32.638x + 93.90$	0.898
	φ	13.220	0.070	*	$y = -4.983x2 + 14.338x + 12.01$	0.859
28 d curing	c	51.608	0.006	***	$y = 39.27x + 98.59$	0.927
	φ	11.295	0.081	*	$y = -7.837x2 + 19.856x + 12.08$	0.837
0.0% XG	c	22.206	0.042	**	$y = 0.6853x + 82.50$	0.876
	φ	5.437	0.290	*	$y = 0.0016x2 - 0.0855x + 12.35$	0.747
0.5% XG	c	10.753	0.082	*	$y = 0.8604x + 87.11$	0.765
	φ	7.404	0.252	*	$y = -0.0096x2 + 0.5532x + 14.34$	0.810
1.0% XG	c	22.010	0.043	**	$y = 1.7075x + 99.072$	0.875
	φ	2.521	0.407	*	$y = -0.0076x2 + 0.4396x + 16.08$	0.504
1.5% XG	c	20.032	0.046	**	$y = 1.8678x + 117.23$	0.864
	φ	45.376	0.104	*	$y = -0.0071x2 + 0.403x + 18.30$	0.967
2.0% XG	c	244.49	0.004	***	$y = 1.4817x + 129.80$	0.988
	φ	53.399	0.096	*	$y = -0.0154x2 + 0.6491x + 14.75$	0.972

Note: ∗∗∗ means very significant; ∗∗ means significant; ∗ means not significant.



(a) (b) (c) (d)

Figure 16: SEM images of (a) red clay, (b) 1.0% treated soil, (c) 1.5% treated soil, and (d) 2.0% treated soil.

with the increase in curing ages. The anticompression of red clay increased first and then decreased with the increase in xanthan gum content. 1.5% ratio was the threshold (increased by 59.83%-76.05%), and 1.0%-1.5% ratio can effectively limit compression deformation. The maximum compression modulus and minimum compression coefficient of 1.5% treated soil curing 28 days were 33.14 MPa and 0.03 MPa^{-1}, respectively

(2) Xanthan gum content and curing ages had significant effects on cohesion but not on internal friction angle. The cohesion of 2.0% treated soil increased by 69.79% compared with red clay. The improvement in red clay shear properties by xanthan gum was significant with prolonging the curing ages. Compared with 3 days of curing, the cohesion and internal friction angle of 0.5%, 1.0%, 1.5%, and 2.0% treated soil curing for 28 days increased by 28.89%, 41.64%, 41.98%, and 28.46% and 6.96°, 5.95°, 4.74° and 4.11°, respectively

(3) The microstructure changes in red clay were due to the formation of xanthan gum and water molecules as gels with adsorption and aggregation effects, increased the contacting areas, and changed the arrangement characteristics of soil particles. Moreover, the regionally formed biopolymer-soil matrices via ionic bondings to improve the mechanics of red clay

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant nos. 52108346 and 42067043), the State Key Laboratory Project of China (Grant nos. KF2020-12 and SKLFSE202019), and the Yunnan Science and Technology Department Basic Research Project of China (Grant nos. 202101AT070253 and 2019FD097). The authors thank Prof. Biyu Rao and Jing Li (College of Civil and Architectural Engineering, Yunnan Agricultural University, Kunming, Yunnan, China) for their helpful and professional suggestions on the experiments.

References

[1] R. M. Madu, "An investigation into the geotechnical and engineering properties of some laterites of Eastern Nigeria," *Engineering Geology*, vol. 11, no. 2, pp. 101–125, 1977.

[2] S. A. Ola, "Mineralogical properties of some nigerian residual soils in relation with building problems," *Engineering Geology*, vol. 15, no. 1-2, pp. 1–13, 1980.

[3] L. Kong and Z. Chen, "Advancement in the techniques for special soils and slopes," *China Civil Engineering Journal*, vol. 45, no. 5, pp. 141–161, 2012.

[4] Z. Huang, "Study on mechanical properties of red clay with will-developed fissures," *Geotechnical Investigation & Surveying*, vol. 38, no. 4, pp. 9–12, 2004.

[5] Y. Z. Tan, L. W. Kong, A. G. Guo, X. Feng, and Z. Wan, "Discussion on the compaction degree index of subgrade filled with laterite," *Rock and Soil Mechanics*, vol. 31, no. 3, pp. 851–855, 2010.

[6] A. Rao, K. N. Jha, and S. Misra, "Use of aggregates from recycled construction and demolition waste in concrete," *Resources, Conservation and Recycling*, vol. 50, no. 1, pp. 71–81, 2007.

[7] C. le Quéré, R. M. Andrew, P. Friedlingstein et al., "Global carbon budget 2018," *Earth System Science Data*, vol. 10, no. 4, pp. 2141–2194, 2018.

[8] H. G. Oss and A. C. Padovani, "Cement manufacture and the environment part ii: environmental challenges and opportunities," *Journal of Industrial Ecology*, vol. 7, no. 1, pp. 93–126, 2003.

[9] S. P. Singh and R. Das, "Geo-engineering properties of expansive soil treated with xanthan gum biopolymer," *Geomechanics and Geoengineering*, vol. 15, no. 2, pp. 107–122, 2020.

[10] I. Chang, M. Lee, A. T. Tran et al., "Review on biopolymer-based soil treatment (Bpst) technology in geotechnical engineering practices," *Transportation Geotechnics*, vol. 24, article 100385, 2020.

[11] N. Latifi, S. Horpibulsuk, C. L. Meehan, M. Z. Abd Majid, M. M. Tahir, and E. T. Mohamad, "Improvement of problematic soils with biopolymer–an environmentally friendly soil stabilizer," *Journal of Materials in Civil Engineering*, vol. 29, no. 2, 2017.

[12] H. R. Khatami and B. C. O'Kelly, "Improving mechanical properties of sand using biopolymers," *Journal of Geotechnical & Geoenvironmental Engineering*, vol. 139, no. 8, pp. 1402–1406, 2013.

[13] I. Chang and G. C. Cho, "Strengthening of Korean residual soil with β-1,3/1,6-glucan biopolymer," *Construction and Building Materials*, vol. 30, pp. 30–35, 2012.

[14] D. F. S. Petri, "Xanthan gum: a versatile biopolymer for biomedical and technological applications," *Journal of Applied Polymer Science*, vol. 132, no. 23, 2015.

[15] S. Rosalam and R. England, "Review of xanthan gum production from unmodified starches by *Xanthomonas comprestris* sp.," *Enzyme & Microbial Technology*, vol. 39, no. 2, pp. 197–207, 2006.

[16] I. Chang, J. Im, A. K. Prasidhi, and G. C. Cho, "Effects of xanthan gum biopolymer on soil strengthening," *Construction and Building Materials*, vol. 74, pp. 65–72, 2015.

[17] A. S. A. Rashid, N. Latifi, C. L. Meehan, and K. N. Manahiloh, "Sustainable improvement of tropical residual soil using an environmentally friendly additive," *Geotechnical & Geological Engineering*, vol. 35, no. 6, pp. 2613–2623, 2017.

[18] A. Rashid, S. A. Tabatabaei, S. Horpibulsuk, N. Z. Mohd Yunus, and W. H. W. Hassan, "Shear strength improvement of lateritic soil stabilized by biopolymer based stabilizer,"

Geotechnical and Geological Engineering, vol. 37, no. 6, pp. 5533–5541, 2019.

[19] M. Ayeldeen, A. Negm, M. El-Sawwaf, and M. Kitazume, "Enhancing mechanical behaviors of collapsible soil using two biopolymers," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 9, no. 2, pp. 329–339, 2017.

[20] S. Smitha and K. Rangaswamy, "Experimental study on unconfined compressive and cyclic triaxial test behavior of agar biopolymer–treated silty sand," *Arabian Journal of Geosciences*, vol. 14, no. 7, pp. 1–12, 2021.

[21] S. Lee, J. Im, G. C. Cho, and I. Chang, "Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands," *Geomechanics and Engineering*, vol. 17, no. 5, pp. 445–452, 2019.

[22] K. Swain, M. Mahamaya, S. Alam, and S. K. Das, "Stabilization of dispersive soil using biopolymer," in *International Congress and Exhibition" Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology"*, pp. 132–147, Sharm El Sheikh, Egypt, 2017.

[23] I. Chang, A. K. Prasidhi, J. Im, and G. C. Cho, "Soil strengthening using thermo-gelation biopolymers," *Construction and Building Materials*, vol. 77, pp. 430–438, 2015.

[24] M. S. Biju and D. N. Arnepalli, "Effect of biopolymers on permeability of sand-bentonite mixtures," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 12, no. 5, pp. 1093–1102, 2020.

[25] H. Dehghan, A. Tabarsa, N. Latifi, and Y. Bagheri, "Use of xanthan and guar gums in soil strengthening," *Clean Technologies and Environmental Policy*, vol. 21, no. 1, pp. 155–165, 2019.

[26] C. C. Ikeagwuani and D. C. Nwonu, "Emerging trends in expansive soil stabilisation: a review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 2, pp. 423–440, 2019.

[27] "Standard for geotechnical test methods," GB/T 50123-2019.

[28] "Code for design of building foundation," GB 50007-2011.

[29] R. Nugent, G. Zhang, and R. Gambrell, "Effect of exopolymers on the liquid limit of clays and its engineering implications," *Transportation Research Record Journal of the Transportation Research Board*, vol. 2101, no. 1, pp. 34–43, 2009.

[30] M. C. Cadmus, L. K. Jackson, K. A. Burton, R. D. Plattner, and M. E. Slodki, "Biodegradation of xanthan gum by *Bacillus* sp," *Applied and Environmental Microbiology*, vol. 44, no. 1, pp. 5–11, 1982.

[31] I. Chang, J. Im, and G.-C. Cho, "Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering," *Sustainability*, vol. 8, no. 3, p. 251, 2016.

[32] I. Chang, M. Jeon, and G. C. Cho, "Application of microbial biopolymers as an alternative construction binder for earth buildings in underdeveloped countries," *International Journal of Polymer Science*, vol. 2015, Article ID 326745, 9 pages, 2015.

[33] I. Chang and G. C. Cho, "Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay," *Acta Geotechnica*, vol. 14, no. 2, pp. 361–375, 2019.

[34] Z. Weng, L. Wang, Q. Liu, X. Pan, Y. Xu, and J. Li, "Improving the unconfined compressive strength of red clay by combining biopolymers with fibers," *Journal of Renewable Materials*, vol. 9, no. 8, pp. 1503–1517, 2021.

[35] "Specification for design of highway roadbed," JTG D30-2004.

[36] "Technical specification for building foundation treatment," JGJ 79-2002.

[37] C. Chen, L. Wu, M. Perdjon, X. Huang, and Y. Peng, "The drying effect on xanthan gum biopolymer treated sandy soil shear strength," *Construction and Building Materials*, vol. 197, pp. 271–279, 2019.

[38] S. V. Baars, *Advanced Soil Mechanic*, Taylor & Francis, 2008.

[39] H. Matsuoka and T. Nakai, "Relationship among Tresca, Mises, Mohr-Coulomb and Matsuoka-Nakai failure criteria," *Soils and Foundations*, vol. 25, no. 4, pp. 123–128, 1985.

[40] G.-X. Li, *Advanced Soil Mechani*, Tsinghua University Press, Beijing, 2004.

[41] X.-n. Gong, *Soil Plasticity*, Zhejiang University Press, Hangzhou, 1999.

[42] Y. Xi, Y. Zhao, and S. Li, "Effects of three kinds of soil amendments on shear strength of aeolian soil," *Acta Pedologica Sinica*, vol. 55, no. 6, p. 1401, 2018.

[43] P. J. Vardanega and M. D. Bolton, "Stiffness of clays and silts: normalizing shear modulus and shear strain," *Journal of Geotechnical & Geoenvironmental Engineering*, vol. 139, no. 9, pp. 1575–1589, 2013.

[44] S. I. Laneuville, S. L. Turgeon, P. Paquin, and C. Sanchez, "Gelation of native β-lactoglobulin induced by electrostatic attractive interaction with xanthan gum," *Langmuir*, vol. 22, no. 17, pp. 7351–7357, 2006.

[45] M. Mahamaya, S. K. Das, K. R. Reddy, and S. Jain, "Interaction of biopolymer with dispersive geomaterial and its characterization: an eco-friendly approach for erosion control," *Journal of Cleaner Production*, vol. 312, article 127778, 2021.