International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 12 Issue 3 ǁ March 2024 ǁ PP. 63-69

Experimental Study on Physical and Mechanical Properties of Shanghai Clay Cured by Different Biopolymers

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Abstract

In recent years, biopolymers have attracted much attention in the field of sustainable geotechnical engineering, and studies have shown that biopolymers can effectively improve the mechanical properties of soils, but there is a lack of comparative research results on the physico-mechanical properties of different biopolymers in cured soils. In view of this, this paper adopts xanthan gum, chitosan and guar gum biopolymers to treat Shanghai clay, and carries out liquid-plastic limit, compaction and unconfined compressive strength tests to discuss the effects of biopolymer types and biopolymer content on the basic physical properties and compressive strength of cured soils. The results showed that the liquid-plastic limit of biopolymer-cured soils increased with the increase of biopolymer content; the liquid-plastic limits of different biopolymer-cured soils in descending order were guar gum-cured soils > xanthan gum-cured soils > chitosan-cured soils > uncured soils. As the biopolymer content increased, the optimal moisture content of the cured soil increased and the maximum dry density decreased; the maximum dry density of different biopolymer-cured soils was in descending order: guar gum-cured soil<xanthan gum-cured soil<chitosan-cured soil<uncured soil, and the optimal moisture content was in descending order: guar gum-cured soil>xanthan gum-cured soil>chitosan-cured soil>uncured soil. The compressive strength of the biopolymer-cured soils increased significantly compared to the uncured soils, and the xanthan gum-cured soils had the highest compressive strength; the compressive strength of the biopolymer-cured soils increased as the biopolymer content increased.

Keywords: *Shanghai clay, biopolymer, liquid-plastic limit, compaction, unconfined compressive strength.*

Date of Submission: 25-02-2024 Date of acceptance: 05-03-2024

I. INTRODUCTION

Biopolymers are natural polymers produced by organisms such as plants and organisms in their natural environment and are widely used in the food sector. Since biopolymers are hydrophilic, adhesive, and environmentally friendly, they can be used to reinforce soil instead of traditional materials such as cement and lime [1]. Compared with traditional soil consolidation materials (cement, lime, etc.), biopolymers are effective in soil consolidation and have the advantage of significantly reducing carbon emissions in the process of obtaining and consolidating soil, which is estimated to generate up to 2 billion tons of carbon dioxide annually due to the production of cement [2]. In recent years, many researchers have carried out experimental studies on the mechanical properties of biopolymer-cured soils. Sujatha et al. investigated the compaction properties of xanthan gum-cured soils, and the results showed that as the dosage of xanthan gum increased, the maximum dry density of the soil decreased and the optimum water content increased [3]. Chang et al. investigated the effects of junction cold glue and agar glue on improving the mechanical strength of clay, and the results showed that The compressive strength of the clay treated with the two gums increased significantly compared to that of the untreated clay [4]. Ni Jing et al. investigated the effect of β-glucan on the shear strength of soil, and the results showed that β-glucan could effectively improve the internal friction angle and cohesion of soil, and enhance the shear strength [5]. In addition, Chang et al. found that the compressibility of soils treated with xanthan gum increased significantly [6]. Biopolymers achieve the effect of improving soil engineering properties through various physical and chemical interactions with pore fluids and soil particles (e.g., increasing the viscosity of pore fluids, filling the inter-particle pores, increasing the contact area between particles, and inducing cohesion or flocculation of clay particles through hydrogen bonding and ionic bonding, etc.) [7-13].

In summary, the current domestic and international research on biopolymer-cured soils mainly focuses on the effect of a specific biopolymer on the soil properties, and there are fewer research results comparing the properties of cured soils for a variety of biopolymers. Different functional groups carried by different types of biopolymers can combine with different positions of clay particles through chemical bonding, changing the arrangement and microstructure of soil particles, which may produce different curing effects, but there are few relevant reports.

In this paper, three different ionic biopolymers, i.e. xanthan gum, chitosan, and guar gum, were used to treat Shanghai clay and carry out the liquid-plastic limit, compaction test, and compressive strength test, to investigate the effects of biopolymer types on the basic physical properties and compressive strength of the cured soil.

II. TEST MATERIALS AND TEST PROGRAM

2.1 Test Materials

The test soil was taken from a residential pit under construction in Jiangpu Community, Yangpu District, Shanghai, with a depth of 7.17-8.55 m. The soil layer at this depth belongs to the Holocene Q4 sedimentary layer, which is dominated by clayey soil, and the soil locally contains a small amount of organic matter, mica, and thin layers of silt, and its basic physical properties are shown in Table 1. According to the Standard for Engineering Classification of Soil (GB/T 50145-2007), it can be seen that the soil is a low liquid limit clay.

Xanthan gum used in this study was provided by Ordos Zhongxuan Biochemical Co. Ltd, which consists of D-glucose linked by β-1,4 glycosidic bond, and every two glucose contains a trisaccharide side chain (D-mannose-D-glucuronic acid-D-mannose), and the furthest mannose from the backbone contains pyruvic acid group[14] , which has an anionic nature. Chitosan used in this study was provided by Shandong Qingdao Honghai Biotechnology Co., Ltd, which consists of a binary linear polymer of 2-acetamido-2-deoxy-D-glucose and 2-amino-2-deoxy-D-glucose linked by β-1,4 glycosidic bonds[15] and has cationic properties. Guar gum used in this study was provided by Beijing Guar Run Technology Co. Ltd, which consists of D-mannosyl units linked by β-1,4 glycosidic bonds, and D-galactosyl residues linked by α-1,6 glycosidic bonds as side chains [16], and is a nonionic biopolymer.

Table 1:Basic physical and mechanical properties of Shanghai soft clay

Basic physical indexes Numerical	Values
Maximum dry density(g/cm^3)	1.64
Optimum water content (%)	19.73
Pore ratio	1.21
Specific gravity	2.72
Liquid limit (%)	32.8
Plastic limit (%)	20.8
Natural saturation(%)	96.0
Heaviness(kN/m^3)	17.56

2.2 Pilot program

Liquid-plastic limit test: After the soil was dried (drying temperature 105 ℃), crushed and sieved through 2 mm sieve, the soil was stirred with chitosan, xanthan gum and guar gum powder respectively, and each of them was added with water to form a homogeneous mixture with different water content of 3 portions, and then left to stand in a sealed humidified cylinder for 24 h. The cone depth of cone meter was measured by using the GYS-2 Digital Soil Liquid-Plastic Limit Combined Determination Instrument with different water content. The water content of the sample was taken as the horizontal coordinate, and the cone depth was taken as the vertical coordinate, 3 data points were marked in double logarithmic coordinates, and the relationship curve between the cone depth and the water content was plotted; the water content corresponding to the cone depth of 17 and 2 mm was determined as the liquid limit and the plastic limit, respectively.

Compaction test: According to the results of the plastic limit test, the optimum water content of different biopolymer cured soils can be roughly determined. A total of 5 different water contents were taken near the plastic limit with a gradient of 2% water content, and the mixtures were prepared according to the method in the liquid-plastic limit test. The mixtures were loaded into a compactor in 3 layers and each layer was compacted 25 times by the free fall of a hammer. After the completion of the determination of the moisture content and dry density of the compacted soil samples, the moisture content as the horizontal coordinates, dry density as the vertical coordinates, marking five data points and plotting the compaction curve, the peak point of the curve corresponding to the longitudinal coordinate for the maximum dry density, the corresponding horizontal coordinate for the optimal moisture content.

Compressive strength test: take the optimum moisture content, make samples according to the maximum dry density, repeat each test condition 3 times to make test pieces, and take the average value of strength as the representative value of strength. The average strength is taken as the representative value of strength. The compressive strength test is carried out after 14 days of maintenance at room temperature of 25 ℃ and relative humidity of 50%.

III. TEST RESULTS AND ANALYSIS

3.1 Liquid-plastic limit test

The liquid and plastic limits of uncured and biopolymer-cured soils are shown in Table 2. The results show that the liquid-plastic limits of the biopolymer-cured soils (except in some cases) increased with increasing biopolymer content, but the liquid limit increased more significantly. For example, the liquid limit of 0.5%, 1.0%, 1.5%, and 2.0% xanthan gum cured soil was 35.64%, 40.9%, 43.93%, and 49.42%, respectively, which increased by 8.67%, 24.70%, 33.93%, and 50.67%, respectively, compared with the uncured soil. Comparing the liquid limit of different biopolymer-cured and uncured soils, there was a significant difference in the change of liquid limit of Shanghai clay by different biopolymers. The anionic xanthan gum and nonionic guar gum had significant effects on increasing the liquid limit of the soil, for example, in the case of 2.0% biopolymer-cured soil, the liquid limit wL increased from 32.80% to 49.42% and 62.58%, which were 51% and 89% higher, respectively; in contrast, the cationic chitosan had little effect on the liquid limit of the soil, and when chitosan content was increased from 0 to 2.0%, the liquid limit increased from 32.8% to 32.87% only. When the chitosan content increased from 0 to 2.0%, the liquid limit increased from 32.8% to 32.87%. Analyzing the reasons, there may be the following points: (i) the surface and edges of the clay particles were negatively and positively charged, respectively, and the anionic xanthan gum attached to the edges of the clay particles through electrostatic attraction, inducing the formation of flocculation structure between the clay particles, resulting in a porous soil, which could adsorb more water; (ii) the cationic chitosan attached to the surface of the clay particles through electrostatic attraction, inducing the formation of cohesive structure between the clay particles, which resulted in fewer pore spaces in the soil for the adsorption and storage of water. In addition, cationic chitosan exchanges cations with ions in the diffusion layer of clay particles, which can lead to a thinning of the thickness of the diffusion layer [17,18]. Therefore, although chitosan also contains hydrophilic group hydroxyl group (-OH), the combination of the above three effects of chitosan has little effect on the soil liquid limit; (iii) nonionic guar gum can increase the soil liquid limit to a greater extent is due to its large number of hydroxyl groups (-OH), through the formation of hydrogen bonds with water to adsorb more water [19]. In summary, the physical and chemical interactions that exist between the biopolymer-water-viscous particles, leading to changes in the arrangement of soil particles, pore space, hydrophilicity and thickness of the diffusion layer are the main reasons for the differences in the liquid-plastic limit of different ionic biopolymer-cured soils.

3.2 Friction testing

The optimum moisture content as well as the maximum dry density of the unconsolidated and biopolymer-consolidated soils are shown in Table 2. Overall, the addition of biopolymers resulted in an increase in the optimum moisture content and a decrease in the maximum dry density of the Shanghai clay. Comparing different biopolymers treated Shanghai clay, it can be found that the biopolymers increased the optimum water content of the soil to different degrees, which is closely related to the fact that polysaccharide biopolymers contain hydrophilic groups, for example, the optimum water content of 1.0% biopolymer-treated Shanghai clay was the highest for the guar gum-cured soil (21.46%), followed by xanthan gum-cured soil (21.03%), and the smallest for the chitosan-cured soil (20.36%). 20.36%). In addition, the optimum water content of biopolymer-cured soils increased with the increase of biopolymer content. The reason for the above phenomenon may be that different biopolymers have different viscosities, as the greater the pore fluid viscosity, the more the soil particles are hindered from moving, more water needs to be added in order to achieve the purpose of reducing the pore fluid viscosity, promoting the sliding of the particles, and discharging the inter-particle gases [20], it is known that the viscosity of guar gum (8,000 cP) > viscosity of xanthan gum (1,500 cP) > viscosity of chitosan (75 cP). Due to the addition of biopolymers to increase the percentage of water per unit volume, the maximum dry density of cured soils decreases compared to uncured soils [21], which is manifested by the fact that the higher the optimum moisture content, the lower the maximum dry density.

Table 2: Liquid plastic limit and compaction test results

Style	Liquid limit（%）	Plastic limit（%）	Optimum water content （%）	Maximum dry density(g/cm^3)
Uncured	32.80	20.80	19.73	1.64
0.5%Xanthan gum	35.64	19.7	20.58	1.62
0.5%Chitosan	30.76	18.6	19.56	1.65
0.5%Guar gum	45.62	21.4	21.05	1.58
1.0%Xanthan gum	40.90	20.1	21.03	1.60

1.0%Chitosan	31.70	20.4	20.36	1.63
1.0%Guar gum	58.10	23.4	21.46	1.57
1.5%Xanthan gum	43.93	21.1	21.42	1.55
1.5%Chitosan	32.85	20.8	20.89	1.61
1.5%Guar gum	60.08	23.7	22.46	1.53
2.0%Xanthan gum	49.42	22.0	21.58	1.53
2.0%Chitosan	32.87	21.5	21.26	1.58
2.0%Guar gum	62.58	23.9	23.75	1.52

3.3 Compressive strength test

The compressive strengths of uncured soil and biopolymer-cured soil with different contents are given in Figures 1 to 4, respectively. The study comparing Figures 1~4 shows that in general (except in some cases), the compressive strength of biopolymer cured soils is greater than that of uncured soils. Xanthan gum had the most significant effect on increasing the compressive strength of Shanghai clay. When the xanthan gum content was increased from 0 to 0.5%, 1.0%, 1.5%, and 2.0%, the compressive strength of the cured soil was 3.51 MPa, 4.79 MPa, 5.8 MPa, and 7.24 MPa, which were 72.9%, 135.9%, 185.7% and 256.6%. The low content (0.5%-1.5%) of chitosan and guar gum was not ideal for increasing the compressive strength of Shanghai clay, when the content was increased to 2.0%, the strength of chitosan-cured and guar gum-cured soils were 3.76 and 2.71 MPa, respectively, which were increased by 85.2% and 33.5% compared with the uncured soils. The biopolymer can increase the compressive strength of the soil, which is due to the gel formed by the biopolymer can fill the pores in the soil structure, form a bridge between the coarse particles (such as sand and powder particles), and induce the cohesion and flocculation of clay particles and the formation of agglomerates; with the increase of the maintenance time, the gel hardens, so that the bond between the particles is further strengthened [22], and the strength of the cured soil is increased.

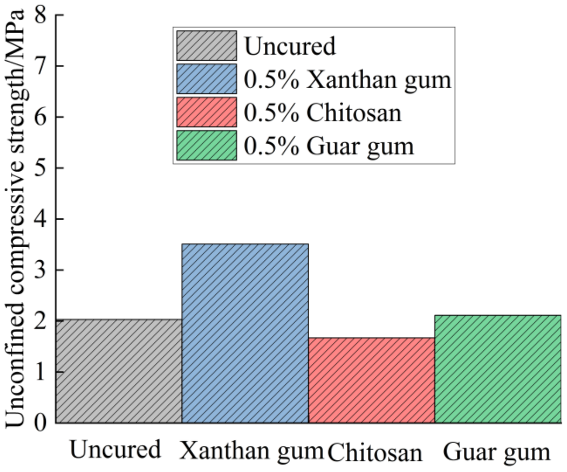

Fig.1: Compressive strength of biopolymer solidified soil with different 0.5% content

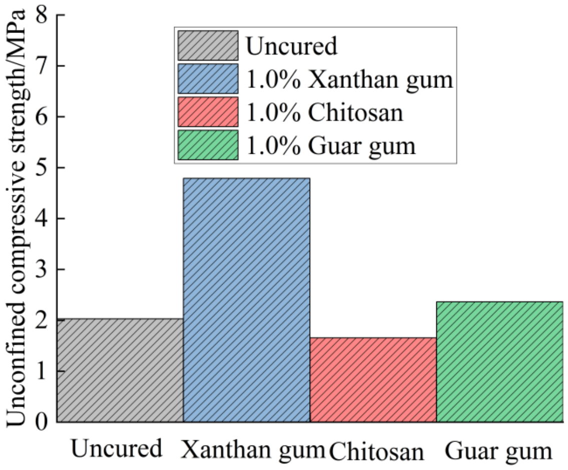

Fig.2: Compressive strength of biopolymer solidified soil with different 1.0% content

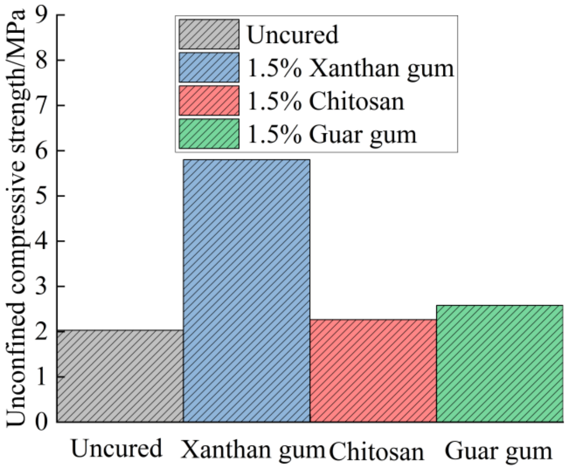

Fig.3: Compressive strength of biopolymer solidified soil with different 1.5% content

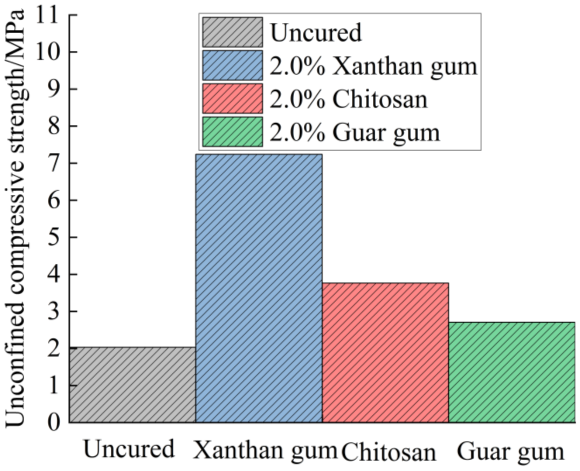

Fig.4: Compressive strength of biopolymer solidified soil with different 2.0% content

IV. CONCLUSION

In this paper, liquid-plastic limit (LPL), compaction and unconfined compressive strength tests were carried out on different biopolymer-treated Shanghai clays to study the effects of biopolymer type and content on the basic physical properties and compressive strength of Shanghai clays, and the following main conclusions were obtained:

(1) The liquid-plastic limit (LPL) of Shanghai clay increased with the increase of biopolymer content; the LPL of different biopolymer-cured soils in descending order were: guar gum-cured soil > xanthan gum-cured soil > chitosan-cured soil > uncured soil.

(2) With the increase of biopolymer content, the optimal moisture content of the cured soil increased and the maximum dry density decreased; the maximum dry density of different biopolymer-cured soils was in descending order: guar gum-cured soil < xanthan gum-cured soil < chitosan-cured soil < uncured soil; the optimal moisture content was in descending order: guar gum-cured soil > xanthan gum-cured soil > chitosan-cured soil > uncured soil.

The compressive strength of xanthan-cured soil was the highest compared to uncured soil, and the compressive strength of chitosan-cured soil as well as guar gum-cured soil increased slightly; the compressive strength of biopolymer-cured soil increased as the biopolymer content increased.

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