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Enzyme-induced Carbonate Precipitation (EICP) Combined with Lignin to Improve the Unconfined Compression Strength (USC) of Shanghai Clay

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Abstract

In order to improve the mechanical properties of high moisture content and low strength of clay particles in Shanghai, the effects of different lignin content on the unconfined compressive strength of EICP-lignin-cured clay were studied by using the method of lignin combined with EICP technology to strengthen the clay by lignin combined with EICP technology. The experimental results showed that EICP-lignin could enhance the unconfined compressive strength of Shanghai clay. With the increase of lignin content, the unconfined compressive strength of clay first increased and then decreased, and there was an optimal content value. The optimal lignin content is 8%.

Keywords

Enzyme-induced Carbonate Precipitation (EICP); Lignin; Unconfined Compressive Strength (UCS).

1. Introduction

Shanghai is situated on the forefront of the Yangtze River Delta, facing the Taihu Plain to the east. The current flat deltaic plain of Shanghai has been formed due to marine regression, tectonic subsidence, and sedimentation from rivers, lakes, and seas during the Holocene. Its unique geological history has resulted in the widespread distribution of natural soft clay foundations in Shanghai. After studying the engineering geological structure of Shanghai, Yan et al. [1] discovered that Shanghai clay exhibits characteristics such as high moisture content, low strength, and high compressibility, making it unsuitable for meeting the requirements of practical engineering construction. Therefore, it is necessary to reinforce and improve the mechanical properties of this clay through treatment to meet the demands of foundation engineering construction.

Enzyme-Induced Carbonate Precipitation (EICP) has emerged as an attractive soil improvement technique and serves as an alternative to Microbially Induced Carbonate Precipitation (MICP). The use of EICP instead of MICP can promote the precipitation of calcium carbonate in fine-grained soils, as the applicability of MICP may be constrained by pore size [2, 3, 4]. Furthermore, fine-grained soils possess larger specific surface areas and more particle-to-particle contacts, where bacteria often attach. These factors can impede bacterial transport in the soil and have adverse effects on MICP treatment [5, 6]. The process of EICP involves the hydrolysis of urea by urease produced from plant sources, including legumes, leaves, seeds, soybeans, and pumpkins. The reaction results in carbonate ions, which precipitate as calcium carbonate (CaCO3) in the presence of calcium ions.

Calcium carbonate precipitation can fill soil pores, encapsulate soil particles as a binding agent, reduce soil permeability, and improve soil strength and stiffness [7, 8]. However, most urease extracted from plants exists in a free state, lacking nucleation sites required for calcium carbonate precipitation. This leads to the formation of small and scattered CaCO3 crystals, reducing the number of contact points within the soil mass, thereby resulting in lower effectiveness of EICP technology for soil improvement compared to microbial-induced calcium carbonate deposition techniques [9.10]. Consequently, researchers have attempted various combinations of materials with traditional EICP to enhance the curing effect. Zhang et al. [11] found that adding lignin in EICP technology effectively enhances the cohesion and internal friction angle of the soil mass. Almajed et al. [12] attempted to improve the compressive strength of sand samples treated with EICP technology by adding an appropriate amount of skim milk powder. Yuan et al. [13] combined EICP technology with sodium-based montmorillonite, effectively improving the mechanical properties of fine-grained soils. In this study, through unconfined compressive strength tests and utilizing lignin and EICP technology as additives, we compare and analyze the impact of EICP combined with lignin on the unconfined compressive strength of Shanghai clay

2. Materials and Methods

2.1. Experimental Material

The soil material used in the experiment was taken from the foundation excavation of a construction site in Yangpu District, Shanghai, at a depth of 4 meters to 5 meters below the ground surface. After retrieving the soil samples, they were dried, crushed, and sieved through a 2 mm sieve. The physical properties of the soil samples were tested according to the Highway Soil Testing Code. The experimental results are presented in Table 1 and Table 2. The plasticity index of the soil sample was determined to be 21.86. According to the "Code for Geotechnical Investigation of Rocks and Soils" (GB 50021-2001), this soil sample is classified as clay.

Table 1. Physical and mechanical properties of the Shanghai clay

Property	Clay
Optimum water content / %	213
Maximum Dry Density / (g.cm^{-3})	1.67
Liquid limit / %	42.32
Plastic limit / %	20.46
Specific gravitys	2.72
Plasticity Index	21.86

Table 2. Particle-size distribution of the Shanghai clay

Particle-size /mm	The content of soil particles / %
0.075	67.5
0.25	88.6
0.5	94.2
1	96.1
2	97.5

The lignin used in this experiment is sodium lignosulfonate. Sodium lignosulfonate is a byproduct of the paper industry, appearing as a dark brown powder. Its aqueous solution ranges in color from light yellow to dark red to black as the lignin content increases, with its viscosity continuously increasing. Lignosulfonate solutions are alkaline, with a pH as high as 11.4 (at a liquid-to-soil ratio of 3:1). Due to its molecular structure containing a large number of phenolic hydroxyl and sulfonic acid groups, sodium lignosulfonate exhibits strong adsorption, water solubility, electronegativity, and surface activity. It is commonly used in industry for synthesizing resins, adhesives, building material additives, and dye dispersants.

2.2. Specimen Preparation

The preparation process involves four steps: urease solution preparation, reaction solution preparation, specimen making and specimen curing.

Urease solution preparation: The simplified steps for preparing crude urease from soybeans, referencing previous studies [14], are as follows:

(1) Dry fresh soybeans in an electric oven at 40°C.

(2) Grind the dried soybeans in a grain mill several times to achieve a fine powder consistency. The finer the grinding, the higher the utilization rate.

(3) Sieve the ground soybean powder through a 50-mesh screen to remove residual bean husks and obtain soybean fine powder. If the grinding in step 2 is thorough enough, there should be minimal residual bean husks on the sieve.

(4) Add deionized water and a magnetic stir bar to a beaker, place the beaker on a magnetic stirrer, and turn on the switch. Using deionized water for urease preparation can reduce the cost compared to using chemical solutions.

(5) Weigh the required amount of soybean fine powder and slowly add it to the stirring beaker, ensuring that the powder dissolves evenly in the deionized water without clumping. Continue stirring for 30 minutes. Then, refrigerate the soybean fine powder solution at 4°C for 24 hours to allow for thorough soaking and dissolution of urease from the bean powder into the solution.

(6) After the solution has settled, remove it from the refrigerator and stir it evenly using a magnetic stirrer. Filter the solution through a 100-mesh cloth to remove bean powder and obtain a light yellow solution. The soybean fine powder solution can be stored in the refrigerator for later use.

(7) Pour the fine powder solution into a centrifuge tube and centrifuge it at 4000 rpm for 15 minutes.

(8) After centrifugation, the soybean powder solution will separate into distinct layers. The upper clear liquid is the crude soybean urease solution needed for the experiment, while the solid sediment at the bottom consists of solid impurities from the bean powder solution. Use a cloth to filter out any creamy soybean oil floating on the surface of the upper clear liquid to obtain the finished crude urease solution.

Reaction solution preparation: Mix calcium chloride and urea in a 1:1 ratio to prepare the reaction solution. The optimal concentration is 0.75 mol/L, and the optimal pH is 8 [15]. Then, add the urease solution to the reaction solution to form a mixed solution. Since soybean urease activity may be weak and decline rapidly, this step should be carried out 1-2 days after the preparation of the urease solution.

Specimen making: First, the soil collected from the site is dried, crushed, and sieved to meet the experimental requirements. Lignin is added to the soil at weight ratios of 0%, 2%, 4%, 6%, 8%, and 10%. Then, the liquid mixture is added to the solid. The mixed solution consists of a 1:1 volume ratio of urease to reaction solution. Under the conditions of the six lignin mass fractions (20.2% (0+% lignin), 19.1% (2% lignin), 18.1% (4% lignin), 15.3% (6% lignin), 13.6% (8% lignin), and 13.4% (10% lignin)), the amount of mixed solution added is determined based on the optimal soil moisture content. Subsequently, the soil, lignin, and mixing solution are uniformly mixed to prepare specimens with a diameter of 39.1 mm and a height of 80 mm. The compaction density of the specimen should reach 95%. In the third step, the soil samples are covered with plastic film and wet towels for 12 hours to ensure uniform soil moisture content. Then, the samples are demolded and tightly wrapped with plastic wrap to prevent changes in moisture content during the curing process. Additionally, experimental errors can be avoided.

Specimen curing: The specimens are placed in a constant temperature curing chamber at (20±2)°C and humidity (relative humidity greater than 95%) for 7, 14, or 21 days.

2.3. Test Method

Unconfined compressive tests: The experiment utilizes the PY-3 type strain-controlled unconfined compression tester produced by the Nanjing Soil Instrument Factory to test the unconfined compressive strength of the completed and cured specimens. The displacement range is 30 mm, and the load range of the force gauge is 600 N. A loading rate of 1 mm/min was adopted.During the testing process, any ice film possibly adhering to the surface of the low-temperature specimens should be removed. For high-temperature specimens, they should be cooled to room temperature in a dry environment after being taken out of the overiment to ensure the repeatability of the test results.The test process was carried out in strict accordance with the standard for geotechnical testing method GB/T 50123-2019 (China Planning Press 2019).

3. Results and Discussions

3.1. The Strength Index Variation with Lignin Content

Figure 3 and Figure 4 show the effect of lignin content on the unconfined compressive strength (UCS) and elastic modulus of modified clay after 14 days of curing. Both UCS strength and elastic modulus increase with increasing lignin content, reaching a maximum value at a lignin content of 6%. In the absence of lignin content, it indicates that the soil has only undergone EICP treatment. The UCS strength of the EICP-treated soil is 115 kPa, approximately 1.4 times higher than that of untreated clay (82 kPa). The elastic modulus of the EICP-treated soil is 5 MPa, approximately 2.5 times higher than that of untreated clay (2.01 MPa). When the lignin content is 6%, lignin exhibits the best improvement effect on UCS strength (330 kPa) and elastic modulus (13.1 MPa). When the lignin content exceeds 6%, the influence of modification on UCS strength and elasticity weakens.

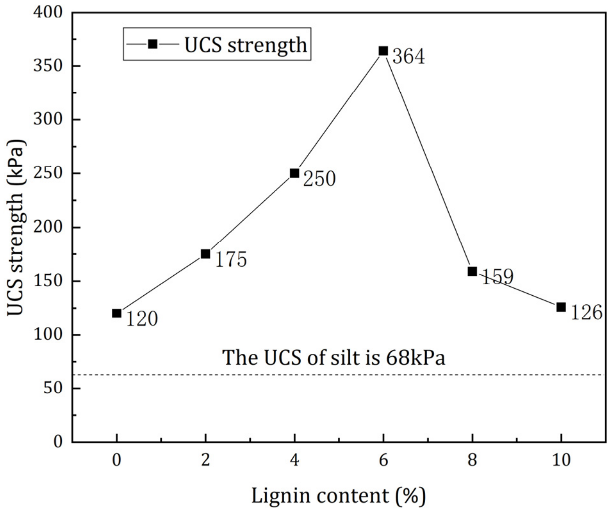

Figure 1. Curve of UCS

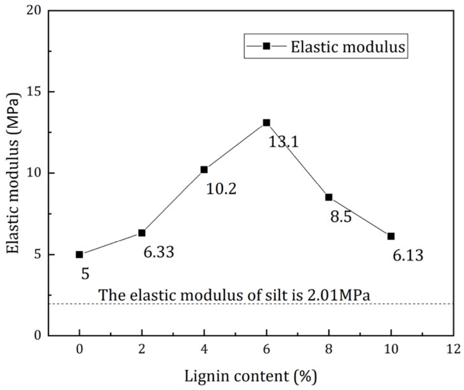

Figure 2. Curve of elastic modulus.

3.2. Typical Stress–strain Behaviors

Figure 3 illustrates the stress-strain characteristics of soil samples treated with different lignin content. From Figure 3, it can be observed that the axial stress of clay specimens increases continuously with increasing axial strain under different lignin content, initially increasing and then decreasing. The stress at the vertex of the curve represents the unconfined compressive strength of the specimens under the corresponding conditions. The compressive strength of each specimen increases first and then decreases with the increase of lignin content, indicating that there is an optimal lignin content that maximizes the unconfined compressive strength of the clay specimens.

The slope of the soil in the elastic deformation stage is greater than that of the clay specimens with lignin added, indicating the brittleness of Shanghai clay. Compared to the soil without lignin, the strains at failure of the clay specimens with lignin added are increased, indicating that the combination of lignin and EICP enhances the ductility of the soil mass, effectively inhibiting the deformation of the soil mass.

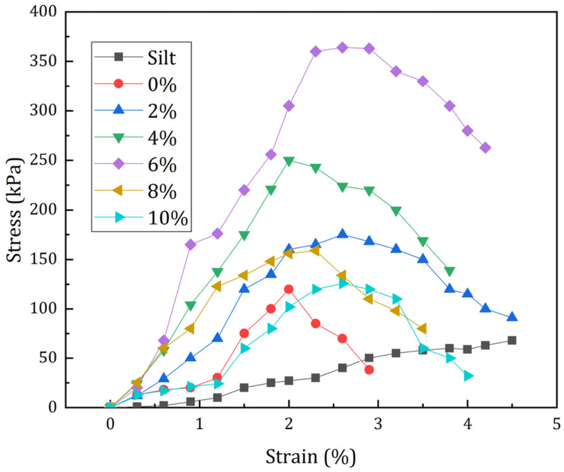

Figure 3. Typical stress–strain curves for the treated soils.

4. Conclusion

The study investigated a novel method combining enzyme-induced carbonate precipitation (EICP) with lignin to improve the unconfined compressive strength (UCS) of Shanghai clay. UCS tests were conducted on the silt samples treated with EICP-lignin, leading to the following conclusions:

（1） The novel soil treatment method, EICP-lignin treatment, exhibits superior improvement in the mechanical properties of Shanghai clay compared to single treatments of EICP or lignin alone. EICP-lignin treatment represents an environmentally friendly approach with promising applications in construction projects in the Shanghai region.

（2） Sodium lignosulfonate can enhance the unconfined compressive strength of Shanghai clay and suppress soil deformation. With increasing lignin content, the unconfined compressive strength of the clay initially increases and then decreases. The optimal strengthening effect is achieved when the lignin content is 8%.These findings suggest that the combination of EICP and lignin presents a promising strategy for enhancing the strength and stability of Shanghai clay, with potential practical applications in construction and geotechnical engineering projects.

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