Frontiers in Computing and Intelligent Systems
ISSN: 2832-6024 | Vol. 8, No. 1, 2024

Analysis of Dispersibility and Mechanical Properties of Lignin Modified Dispersive Soil

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Abstract: Dispersive soil is a kind of special soil with water sensitivity, which is easy to produce ravages such as gully and piping when encountering water in engineering. In order to improve the poor engineering properties of dispersive soil, a kind of lignin was selected to improve the dispersibility and mechanical properties of dispersive soil in western Jilin Province. Pinhole test, fragment test, unconfined compressive strength test and resistivity test were carried out on the improved soil samples with different lignin content. The results showed that lignin could significantly reduce the dispersibility of dispersive soil. With the increasing of curing time, the unconfined compressive strength of the improved soil samples increased gradually. With the increase of lignin content, the unconfined compressive strength of the improved soil first increased and then decreased, and the peak strength appeared when the lignin content was 3%. In the resistivity test, the resistivity of the improved soil decreased gradually with the increase of lignin content. Through microscopic analysis of lignin improved soil samples, it can be concluded that lignin fibers play a stereograin-like bridging role in soil, which promotes the formation of larger aggregates, weakens the dispersion of single soil particles, and thus reduces the dispersion of soil mass and improves the strength of soil mass. This study can provide a basis for the improvement of dispersive soil in seasonal freezing area and has practical engineering significance.

Keywords: Dispersive Soil; Lignin; Pinhole Test; Fragment Test; Unconfined Compressive Strength; Resistivity Test; Microscopic Analysis.

1. Introduction

Dispersive soil is a kind of viscous soil which is dispersive and lost because the repulsive force between soil particles exceeds the attractive force under the condition of very low hydraulic slope. Its particles are usually relatively small, the content of clay particles is high, and it is easy to be affected by water erosion. In addition, the surface charge of soil particles is strong, resulting in a large repulsive force between particles, resulting in the dispersion trend of soil. Therefore, weak structural stability is a major feature of dispersive soil. Dispersive soil has poor particle bonding ability and loose soil structure, which affects the bearing capacity and stability of foundation, structure and road. Scattered soil slope is easy to be washed by rain, which leads to slope instability and landslide. The scattered soil after the action of rain and groundwater is easy to settle, which poses a threat to the stability of the foundation of the building. In the area of high rainfall, dispersive soil is easy to be washed by water flow, resulting in local soil erosion and so on. When the dispersive soil is affected by environmental factors such as freeze-thaw cycle, it is more prone to collapse, frost heave and other damage, which causes adverse effects on water conservancy projects such as canals and DAMS. Therefore, in engineering practice, we should pay attention to dispersive soil and seek ways to deal with its bad properties.

The main improvement materials of dispersive soil at home and abroad are lime, cement and fly ash, etc. By increasing the content of cations such as calcium and magnesium in dispersive soil, the original sodium ions are replaced, and the purpose of weakening the dispersion of soil is finally achieved. The mechanism of these methods is roughly the same and the operation is simple, but there are obvious defects. For example, the use of materials such as lime and cement can lead to an increase in the pH of the soil and surrounding water, which can have adverse effects on local soil and groundwater, and increase the risk of brittle damage to building materials. In addition, these traditional inorganic materials will consume a lot of energy and emit a lot of greenhouse gases in the production and application process, thus causing damage to the ecological environment [1], which runs contrary to the current environmental protection concept of sustainable development. Therefore, the research and development of efficient, economical and environmentally friendly amendments is a key issue in the field of dispersive soil.

As one of the by-products of bioethanol industry, lignin has a wide range of sources and low price, which can improve soil performance and make secondary use of industrial solid waste, and has a good application prospect in improving soil undesirable properties. In recent years, many scholars have made some progress in the field of lignin improving soil properties. Tingle[2] et al., Chen[3] et al added lignin to the sandy silt for improvement, and found that lignin had a significant effect on improving the strength of sandy silt. Liu Yaowu [4] showed that lignin could significantly improve the unconfined compressive strength of carbonate saline soil, but the strength first increased and then decreased with the increase of content. Tests conducted by Wang Enliang et al. [5] showed that lignin could effectively improve the dispersity of dispersive soil, and the erosion resistance of soil could be effectively enhanced with lignin content ≥3% and curing age ≥7d. Chen Cheng et al.[6] used lignin to improve soft clay in a certain area of Tianjin, and found that when the lignin fiber content was 0.75%, the damage strength and cohesion of the improved soil were the maximum, the internal friction Angle was the most stable, and the resistance to freeze-thaw deterioration was the strongest. Wang et al.[7] conducted a dry and wet cycle test on the improved soil with 3% lignin content, and compared it with quicklime improved soil with the same properties such as pH, unconfined compressive strength, appearance and volume stability, and found that the overall stability of lignin improved soil was superior to that of quicklime improved soil.

In summary, this study considered using lignin with dry soil mass of 1%, 2%, 3%, 4% and 5% to improve the poor dispersibility and mechanical properties of dispersive soil, and conducted various tests after curing the improved soil samples for 1d, 7d and 28d, respectively. Pinhole test and fragment test were used to verify the dispersibility of the improved dispersive soil. The unconfined compressive strength test was used to explore the mechanical strength changes of the improved dispersive soil, and the resistivity test was used to test the internal connectivity of the test soil sample, and the mechanical characteristics of the improved soil were verified. Based on the results of various tests, the optimal modifier dosage range was found. Finally, the improvement mechanism of lignin in dispersive soil was revealed by observing the soil microstructure from the perspective of particle bonding and pore structure.

2. Test Materials and Methods

2.1. Test Materials

The dispersive soil in western Jilin was selected as the study object. The dispersive soil used in the test was transported back to the laboratory from the site and prepared for crushing and air drying, and then sealed after 2mm screening. The basic physical and mechanical properties of the dispersive soil were tested, and the basic physical property parameters of the soil sample were shown in Table 1, and it was finally determined that the soil sample in this test was low liquid limit clay (CL).

Table 1. Physical and mechanical properties of soil

Natural moisture content (%)	Liquid Limit (%)	Plastic limit (%)	Plasticity index	Maximum dry density (g·cm-3)	Optimal moisture content（%）	Natural density (g·cm-3)
19.37	35.99	16.87	19.12	1.7625	16.3810	1.9934

Particle analysis test is one of the routine tests of soil. The particle analysis test of soil samples can quantitatively describe the content of each particle group in soil particles, and provide a basis for soil engineering classification and understanding of soil engineering properties. The laboratory laser particle size analyzer was selected to analyze the particle size of the soil sample, and the percentage content of each particle group of the soil sample was shown in Table 2.

Table 2. Particle size composition of soil

Percentage content of each grain group (%)		
San(0.075mm-2mm)	Silt(0.005mm-0.075mm)	Clay(<0.005mm)
15.41	59.96	24.63

Figure 1. Lignin powder

As shown in Figure 1, lignin is a kind of polymer compound composed of aromatic rings, the main components of which include phenylpropane monomer. Phenylpropane monomers form a three-dimensional network structure through the connection of aromatic rings. The basic structure of lignin consists of aromatic ring, side chain and hydroxyl group. The aromatic ring, formed by phenylpropane monomer, is the main supporting structure of lignin. The side chain is connected to the aromatic ring to make the lignin have various structures. The presence of the hydroxyl group in the side chain or aromatic ring gives the lignin some special chemical properties. Lignin is usually a polymer with a relatively high molecular weight, which allows the lignin to form a strong structure in the cell wall, providing the plant with tensile strength and rigidity. Lignin has good physical properties, due to its polymer structure and the stability of aromatic rings, lignin is insoluble in general solvents. At the same time, lignin shows high thermal stability, which makes lignin can withstand extreme temperature environment. In general, lignin plays a key role in industrial applications due to its unique chemical structure and diverse functions.

2.2. Test Methods

Firstly, the soil samples used in the test are prepared by crushing, air drying and screening. Add the lignin powder to the soil according to the preset ratio, spray distilled water and stir fully to the optimal moisture content. Stand for 24h until the moisture in the soil is evenly diffused. Then prepare the sample with the required size (ϕ39.1mm × 80mm for unconfined compressive test, resistivity test, etc., with 95% compactness for each sample). The tests were carried out after the cling film was wrapped for a predetermined time under standard curing conditions.

The pinhole test method is mainly in a special test device, the cylindrical sample center is perforated with a diameter of 10mm axial fine hole, and then the seepage test is carried out with pure water (or water required by the test), and the pinhole is observed under different water pressure (water head), the flow rate and color of the water flow, according to which the dispersion performance of the soil is judged.

The test method of fragment test is mainly to cut a square soil block with a bottom length of about 15mm in the middle part of the unconfined compressive strength test soil sample, and place the soil block at the bottom of a beaker containing 250ml water with tweezers to prevent external disturbance. After 2min, 1h and 6h, photos are taken to record the disintegration of the soil sample in water.

3. Test Results

3.1. Pinhole Test

As shown in Table 3, pinhole tests were carried out on lignin improved soil, and the results were shown in the table below. In the pinhole test, when the curing age was 1d, the improved soil samples with 1% and 2% lignin content showed dispersibility, while the other improved soil samples showed transition. When the curing age was 7 days, the experimental soil sample with 3% lignin content showed non-dispersibility, while the other improved soil samples showed transitional property. At the curing age of 28 days, the modified soil samples with 3% and 4% lignin content showed non-dispersibility, while the other modified soil samples with other lignin content showed transitional property. With the increase of curing age, the pore diameter of the soil sample under each content gradient has a tendency to shrink gradually, and the water flow is gradually clear. It shows that the longer the curing time, the more obvious the binding effect of lignin in the soil, the ability of soil to resist erosion and the ability to resist dispersion is gradually enhanced. The results showed that lignin content of 3% was the best in improving soil dispersion.

Table 3. Pinhole test results

Curing age (d)	Lignin content (%)	Water color	aperture (mm)	Discriminant result
1	1	turbid	3	dispersivity
	2	turbid	3	dispersivity
	3	slightly cloudy	1.5	transitivity
	4	slightly cloudy	1.5	transitivity
	5	slightly cloudy	1.5	transitivity
7	1	turbid	1.5	transitivity
	2	slightly cloudy	1.5	transitivity
	3	limpid	1.0	non-dispersion
	4	limpid	1.5	transitivity
	5	slightly cloudy	1.5	transitivity
28	1	slightly cloudy	1.5	transitivity
	2	slightly cloudy	1.5	transitivity
	3	limpid	1.0	non-dispersion
	4	limpid	1.0	non-dispersion
	5	slightly cloudy	1.5	transitivity

3.2. Fragment Test

As shown in Table 4, according to the chip test results, when the curing age is 1d, the experimental group with 1% and 2% lignin content shows dispersibility, while the other improved groups show transitional characteristics. When the curing age was 7 days, 1% lignin showed dispersibility, and the rest of the soil samples showed transition. When the curing age was 28 days, the modified soil samples with 3% lignin content showed non-dispersibility, and the modified soil samples with other lignin content showed transitional. The results showed that lignin content of about 3% had the best effect on soil dispersity, which was basically consistent with the pinhole test.

Table 4. Fragment test results

Curing age (d)	Lignin content (%)	phenomenon		Discriminant result
		Disintegrate or not	Water color	
1	1	disintegration	turbid	dispersivity
	2	disintegration	turbid	dispersivity
	3	disintegration	slightly cloudy	transitivity
	4	unbroken	slightly cloudy	transitivity
	5	disintegration	slightly cloudy	transitivity
7	1	disintegration	turbid	dispersivity
	2	disintegration	slightly cloudy	transitivity
	3	unbroken	limpid	transitivity
	4	unbroken	limpid	transitivity
	5	unbroken	slightly cloudy	transitivity
28	1	unbroken	slightly cloudy	transitivity
	2	disintegration	slightly cloudy	transitivity
	3	unbroken	limpid	non-dispersion
	4	unbroken	limpid	transitivity
	5	unbroken	limpid	transitivity

3.3. Unconfined Compressive Strength Test

The unconfined compressive strength of the original soil has been measured in the previous test as 68.89kPa. The unconfined compressive strength test results of the improved soil under different lignin content and different curing days are shown in the figure 2. With the increase of curing age, the unconfined compressive strength corresponding to the improved soil sample with different lignin content increased gradually. Taking the improved soil sample with 2% lignin content as an example, the unconfined compressive strength after curing for 1d was 110.89kPa, and after curing for 7d was 133.18kPa, which increased by 20.1%. The unconfined compressive strength after curing for 28d was 146.32kPa, which was only 9.8% higher than that of the sample after curing for 7d, and the strength improvement rate slowed down significantly.

With the gradual improvement of curing age, the unconfined compressive strength increases obviously. Lignin plays a binding role in the soil, gradually combines from the loose powder in the addition into a three-dimensional grid structure, and fills the internal pores of the soil, and the water diffused more evenly in the soil. Under the comprehensive effect, the porosity of the soil decreases and the structure is significantly enhanced. However, during the curing time of 7d-28d, the rate of soil strength improvement was slightly lower than that of the previous period, so it can be inferred that the structure of the improved soil sample had basically formed within 7d, and increasing the curing days had limited influence on the soil strength improvement.

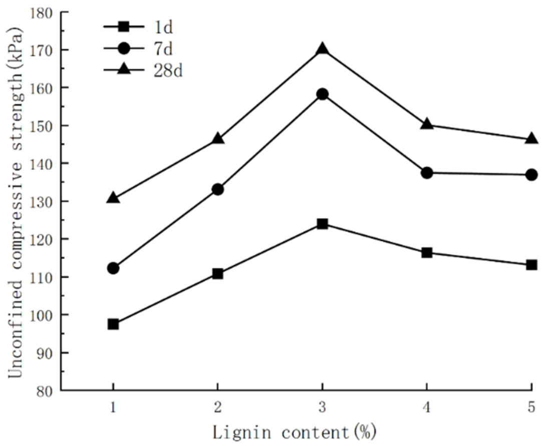

Figure 2. Unconfined compressive test results

By observing one of the curves separately, it can be found that in the five gradients, the unconfined compressive strength of soil increases significantly in the interval of 1%-3% lignin content, and the strength begins to decline gradually after the strength peaks at about 3%. Among all lignin contents, the improvement effect of unconfined compressive strength was the most significant in the 3% content range. In this range, lignin-bound water had the best ability to bind soil particles, and the improved soil had the strongest structure. Among them, the lignin-modified soil sample with 3% content obtained the maximum unconfined compressive strength of 170.12kPa after curing for 28d. About two and a half times that of plain soil. After the lignin content exceeds 3%, the unconfined compressive strength of soil begins to decrease gradually with the gradual increase of lignin content, which indicates that there is a certain optimal range of lignin content during the addition process, and exceeding or insufficient lignin content may affect the strength improvement effect. Combined with the results of dispersive identification test, the optimal lignin content was 3%.

3.4. Resistivity Test

The main purpose of resistivity test on soil sample is to evaluate its electrical conductivity, so as to reflect the improvement effect of lignin on soil properties. There is a certain relationship between the resistivity of the soil sample and the unconfined compressive strength. The higher the strength of the soil sample, the better the structure, the more uniform the water diffusion, the lower the resistivity. Resistivity tests were carried out on the improved soil samples with each lignin content at each curing age of 28d at the frequency of 2kHz and 50kHz, and the resistivity test results were shown in Figure :

The analysis of the test results shows that the resistivity test results at different frequencies are basically the same. With the increase of lignin content, the resistivity of the samples decreased first and then increased, and the resistivity of the samples decreased obviously in the range of 1%-3% lignin content. In the range of 3%-5%, the resistivity base of the sample increases slightly. This is consistent with the results of the unconfined compressive strength test. When the lignin content is in the range of 1%-3%, the unconfined compressive strength of soil gradually increases, the structure and internal connectivity of the improved soil sample are gradually enhanced to become stable, and the water diffusion in the soil sample is also very uniform, and the structure of the soil-water-lignin composite system is stable. Indirectly, the effective cross-sectional area of the conductor on the cross section inside the sample increases, and the resistance value decreases, resulting in the decrease of the resistivity of the sample. When the lignin content is greater than 3%, too much lignin hinders the diffusion of water between particles, and changes the arrangement of soil particles due to extrusion, resulting in an increase in the resistivity of the sample.

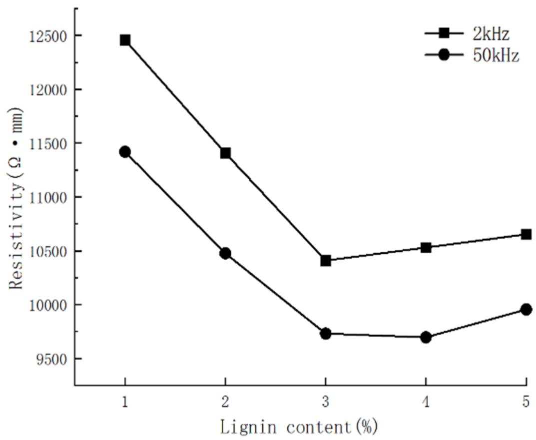

Figure 3. Resistivity test results

4. Micro Analysis

As shown in Figure 4, the microscopic mechanism of lignin improved dispersive soil was analyzed by scanning electron microscopy. The image is a scanning electron microscope image of lignin modified soil enlarged by 2050 times. Analysis of the image shows that lignin plays a role in pulling and connecting soil particles inside the soil, forming a similar three-dimensional grid structure, which enhances the bonding effect between soil particles. The fundamental reason for the dispersion of clay soil is that the repulsive force between particles is greater than the gravitational energy, and the repulsive force between particles leads to the dispersion of clay particles in water and the formation of colloidal suspension. Lignin can act as a bridge material between soil particles to induce particle aggregation, improve the internal structural integrity of soil and thus improve soil strength. Lignin fiber plays a three-dimensional grid bridging role in the soil. This bridging effect promotes the formation of larger aggregates, reduces the dispersion of single soil particles, and thus reduces the dispersion of soil and improves the strength of soil [8].

Figure 4. Electron microscope photo of lignin modified soil

At the microscopic level, lignin molecules can interact with soil particles through van der Waals force, hydrogen bonding and electrostatic interaction, which helps to stabilize the soil structure and reduce the movement and dispersion of particles. Lignin can be adsorbed on the surface of soil particles to form a hydrophobic film and change the surface properties of soil particles, thereby reducing the penetration rate of water and enhancing the stability and erosion resistance of soil, etc. Such surface modification will affect the wettability and surface charge characteristics of soil particles and reduce their dispersion trend.

5. Conclusion

1) Adding lignin to dispersible soil can effectively reduce the dispersibility of dispersible soil. At the curing age of 28 days, in the pinhole test, the lignin modified soil with 3% and 4% content changed from dispersive to non-dispersive, and the other modified soil also changed from dispersive to transitional. In the chip test, the lignin modified soil with 3% content changed from dispersive to non-dispersive, and the other modified soil also changed from dispersive to transitional.

2) Lignin can significantly improve the mechanical properties of dispersive soil. The unconfined compressive strength of lignin improved soil at different curing ages and with different modifier gradients increased to different degrees. Among them, the lignin improved soil sample with 3% content obtained the maximum unconfined compressive strength of 170.12kPa after curing for 28d, which was about 2.5 times that of plain soil. The results of resistivity test also proved that lignin can improve soil properties effectively.

3) Scanning electron microscopy (SEM) test found that lignin fiber played a stereograin-like bridging role in the soil, which promoted the formation of larger aggregates, reduced the dispersion of single soil particles, and improved the density of the soil, thereby reducing the dispersion of the soil and improving the strength of the soil.

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