

Lignin-Improved Soil Research Progress

Xiaojie Chen

Central South University of Forestry and Technology, China

Abstract: As a byproduct of biomass, lignin demonstrates significant potential and application value in the field of soil improvement. Historically, lignin has been utilized to enhance the strength, modulus, and water stability of soils, although its effects and mechanisms on various soil types, such as silt, require further investigation. Research indicates that the efficacy of lignin amendments is influenced by its source, type, and method of application, while environmental factors like soil moisture content, curing conditions, and curing duration also significantly affect the outcomes. Consequently, optimizing the use of lignin, exploring its micro-mechanisms of interaction with soil, and developing efficient lignin amendment strategies are crucial for future research. Additionally, the successful application in engineering projects demonstrates the practicality and eco-friendliness of lignin soil amendment technologies, offering new perspectives for the green and sustainable development of soil engineering.

1. The Application of Lignin in Soil Improvement

Research on lignin as a soil amendment agent has a developmental history spanning several decades, initially used in grouting materials, including sodium persulfate lignin and sodium dichromate lignin. These lignin materials, under the action of catalysts, could generate gels that filled voids between soil particles and bonded them together. However, these gel products typically contained certain amounts of heavy metals, such as chromium and lead, leading to the gradual restriction of this application. Karol was the first to report on the potential use of liquid lignin, a by-product of paper mills, as a soil amendment material, highlighting the potential of lignin as a non-toxic and non-corrosive material. Following this, many scholars internationally have conducted extensive research on by-product lignin, with the majority of studies indicating that lignin can significantly enhance the strength, modulus, and water stability of soils, demonstrating its vast potential in soil improvement applications.

This study focuses on exploring the application of industrial by-product lignin in soil improvement, particularly in enhancing subgrade engineering properties, stabilizing erosion-prone soils, and controlling road dust emissions. Professor Tingle and his team at the U.S. Army Engineer Research and Development Center conducted experimental research on the effects of non-traditional amendments like lignin, resin, and enzymes on the engineering properties of clay and silt soils. They discovered that lignin significantly improves soil strength and water stability, outperforming six other amendment materials. It is noteworthy that the lignin used in these experiments was a commercial product subjected to purification and modification processes, not directly derived from industrial by-products. On another note, Professor Ceylan[1] from Iowa State University investigated the effects of lignin from different sources on subgrade soil improvement; one type of lignin was a dark brown liquid from a Canadian biomass processing plant, and the other was a yellow-brown powder from an ethanol processing plant in Iowa. The findings indicate that both types of lignin effectively enhance the strength of low plasticity clay soils and could potentially replace fly ash as a subgrade soil amendment in certain cases. Professor Indraratna[2] from the University of Wollongong used by-product lignin from paper

mills to improve erodible soils, exploring its erosion resistance under water flow in laboratory model tests. The study found that lignin-amended soils exhibited superior erosion resistance under equivalent critical shear stress conditions compared to cement-amended soils.

Research on the use of industrial by-product lignin for soil improvement is not confined to laboratory settings, with successful applications in actual engineering projects already documented. Specifically, the Argentine National Road Administration implemented a project in Buenos Aires using by-product lignin for subgrade road improvement and dust control. The project's road performance was comprehensively evaluated through two years of field observations, dynamic penetrometer tests, and nuclear density measurements, demonstrating outstanding performance across all test indicators, surpassing six other amendment materials and fully meeting design and usage requirements. Researchers like Kim employed computer software to simulate the impact of lignin-amended subgrade soil on road performance over a 20-year design life under high traffic loads. These simulations revealed that lignin-amended subgrades showed significantly fewer occurrences of cracking and rutting compared to natural subgrades, attributed to lignin's enhancement of soil's elastic modulus and strength. Ceylan and colleagues conducted similar simulations under various climatic conditions, confirming that lignin-amended subgrades outperform natural subgrades across different climates, significantly improving road surface conditions.

In China, research on soil improvement using industrial by-product lignin is relatively sparse, and recycling and reuse technologies are somewhat behind developed countries. Researchers like Liu Songyu from Southeast University pioneered lignin amendment experiments on poor-quality subgrade soils in the southeastern coastal regions and obtained a relevant invention patent, drawing academic and practical attention. Lignin, a diverse natural material, has been applied in various forms, including solid and liquid, for soil amendment. Some studies have proposed a construction technique involving spraying a 30% lignin solution, while others have adopted mixing processes similar to those used with traditional materials like lime. Liquid lignin applications typically involve pre-mixed solutions sprayed using water trucks. Despite demonstrating the potential of lignin for soil improvement, standardized field construction processes for

lignin-amended soils are lacking in China, highlighting the need for further research and practical exploration to apply lignin effectively in engineering practice.

2. Study on the Strength Characteristics of Soil Improved with Lignin

The unconfined compressive strength (UCS) serves as a pivotal metric for assessing the strength properties of improved soil, influenced by a composite of factors including the type and dosage of the improvement agent, soil moisture content, curing conditions, and age. Through a series of indoor experiments, researchers like Hua et al. have delved into the effect of lignin on soil strength characteristics, revealing that the addition of lignin notably increases soil density. Specifically, when the lignin dosage is set at 2.5% with a curing period of 7 days, the maximum UCS of the soil can reach up to 766 kPa. The research also identified that a decrease in soil strength is primarily caused by erosion and the leaching of lignin due to water evaporation. Pengelly and his team explored the effect of calcium lignosulfonate on the improvement of low-traffic volume road base expansive soil, confirming that the improvement measures significantly curb soil expansiveness. Concurrently, Puppala and Hanchanloet[3] investigated the engineering properties such as strength and modulus of elasticity of viscous soil improved with a mix of lignin and sulfuric acid, finding significant enhancements in engineering properties of the lignin-improved soil compared to the unimproved soil. These findings not only showcase the efficacy of lignin improvement technology in enhancing soil engineering performance but also provide valuable insights for further application and research.

For sandy soil samples with a height of 152mm and a diameter of 102mm, lignin-improved soil exhibited significant strength increase under a 5% moisture content condition. At a temperature of 22.2°C and a relative humidity of 40%, the strength of the soil after a 28-day curing period was approximately twice that after a 7-day curing period. Analysis of the curing effects at lignin dosages of 2.9%, 5.0%, and 8.0% determined that a 5% dosage is optimal. UCS tests conducted after 28 days of curing demonstrated that lignin-improved soil, both in low plasticity clay (CL) and high plasticity clay (CH) samples, showed notable strength improvements, particularly in low plasticity clay samples. A comparison of dosages at 3.4%, 5%, and 8% under 40% relative humidity confirmed 5% as the optimal lignin dosage. The study on low plasticity clay revealed that lignin A significantly enhances soil solidification strength under low moisture content conditions, whereas lignin B shows superior improvement effects under high moisture content conditions. Experiments across different lignin dosages observed the highest strength in soil treated with a 12% dosage after 7 days of curing, thus recommending 12% as the optimal lignin dosage. Collectively, these results indicate a marked increase in soil strength following lignin improvement. Within the experimental scope, only a 2% improvement ratio resulted in soil strength comparable to that of unimproved soil, thereby validating the effectiveness of lignin in enhancing soil strength without negative impacts.

Experiments conducted at the U.S. Army Engineer Research and Development Center on lignin-improved soil UCS revealed key insights. For sandy soil, the comparative analysis of compressive strength before and after lignin

improvement indicated a notable strength enhancement in clay samples, whereas the strength increase in sandy soil samples was relatively modest. Notably, when the lignin dosage exceeded 5%, the compressive strength of sandy soil showed a decreasing trend. Conversely, clay samples exhibited superior performance post-lignin improvement compared to other improvement agents, with detailed analysis of 3.4%, 5.0%, and 8.0% dosages leading to a recommendation of 5% as the optimal lignin dosage. It is important to note that the lignin used by researchers like Tingle was a specially processed commercial lignin product, which is significant for understanding and applying these results.

Ceylan[1] and his team conducted improvement studies on low plasticity roadbase soil using industrial by-product lignin from two different sources, exploring the impact of dosage, compaction moisture content, and curing time on soil compressive strength. The findings indicated that soil improved with lignin A exhibits higher strength under lower moisture content conditions, while lignin B improved soil shows greater strength under higher moisture content conditions. Although lignin's improvement effect is slightly less compared to that of fly ash, its strength improvements are still significant compared to unimproved soil. Notably, when the lignin A dosage exceeds 12%, soil compressive strength tends to decline, a phenomenon not observed with fly ash samples. This discovery underscores the importance of precise dosage control in lignin soil improvement to ensure optimal results.

Diverging from other studies, findings by researchers like Blanck on using lignin to improve sludge revealed some discrepancies. Their UCS tests showed that at lignin dosages of 2.5% and 5.0%, the improved sludge strength was actually lower than that of unimproved sludge; only at a 2.0% dosage did the strength of improved sludge align closely with that of the untreated counterpart, and the strength increase was minimally dependent on the curing period. Hence, Blanck and his team concluded that lignin's effectiveness in enhancing sludge strength is nearly negligible, with inappropriate dosages potentially leading to a decrease in soil strength. However, the existing literature lacks detailed descriptions regarding the source and specific types of lignin used, nor does it delve into the mechanisms behind these observations. Thus, these findings suggest the uncertain efficacy of lignin in improving sludge and highlight the need for further research and validation to more comprehensively understand the potential mechanisms of lignin in soil improvement.

3. Summary and Prospects

Based on the current literature overview, the strength characteristics of silt improved with lignin follow these key patterns:

(1) Under identical experimental conditions, lignins of different origins and types have varied effects on the unconfined compressive strength (UCS) of silt. Studies have ranged from commercial-grade lignins to those derived from various industrial by-products. While all types of lignin have to some extent increased the strength of silt, differences in additive amounts, moisture content, and curing periods have led to variations in the optimal addition rates for different lignins.

(2) Lignin's effect on soil improvement varies across different soil types. While lignin can effectively enhance the strength of sandy soil and low plasticity clay, its application

in silt may reduce its strength, showing a negative effect. Therefore, further experiments and studies are needed to explore the potential effects of lignin on the improvement of other soil types.

(3) The UCS of improved soil is significantly affected by factors such as moisture content, curing conditions, and curing period; however, these factors seem to have a negligible impact on determining the optimal addition rate. Thus, in-depth studies on the influence of lignin addition ratios and curing periods on silt strength, clarifying the fundamental mechanisms by which lignin improves the engineering properties of silt, and exploring the intrinsic connections between different engineering properties of improved soil, are key directions for future research.

References

- [1] CEYLAN H, GOPALAKRISHNAN K, KIM S. Soil stabilization with bioenergy coproduct [J]. *Transportation Research Record*, 2010,2186(1): 130-137.
- [2] INDRARATNA B, MUTTUVEL T, KHABBAZ H. Modelling the erosion rate of chemically stabilized soil incorporating tensile force–deformation characteristics[J]. *Canadian Geotechnical Journal*, 2009,46(1): 57-68.
- [3] PUPPALA A J, HANCHANLOET S. Evaluation of a new chemical (SA-44/LS-40) treatment method on strength and resilient properties of a cohesive soil: Proc., *Transportation Research Board Annual Meeting*[C]: Transportation Research Board Washington, DC., 1999.