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Review

Study on the Mechanical Properties of Loess Improved by Lignosulfonate and Its Mechanism Analysis and Prospects

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Abstract: As an organic material with large reserves and environmental protection, the application of lignin in loess improvement can greatly improve the engineering properties of loess, such as water loss disintegration and water collapsibility. This paper summarizes the main achievements of lignosulfonate in improving loess over the past five years and discusses and analyzes its microstructure, mechanical properties, and mechanism of action. The microscopic results show that the incorporation of lignosulfonate produces a three-dimensional network structure, which can effectively cement loess particles and improve soil strength and impermeability, and the Quantity of this network structure depends on the amount of lignosulfonate. An excessive amount of lignosulfonate preferentially combines with itself due to its cohesive and chelating properties, resulting in an increase in soil porosity and a decrease in the improvement effect. Based on the macroscopic and microscopic tests, it was concluded that the optimal dosage reference range of lignosulfonate-improved loess is mostly between 1% and 1.5%. However, considering the limited number of references in this paper, the differences in physical properties of the experimental loess used in the literature, and the different curing ages, the optimal dosage needs to be further studied. The discussion and analysis in this paper provide a reference for research on lignosulfonate-improved soil, as well as new knowledge and information for more efficient engineering applications of lignin-improved loess.

Keywords: lignin; lignosulfonate; loess; curing agent; mechanical properties; microstructure; improvement mechanism

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1. Introduction

Loess is a special soil that is widely distributed in the arid and semi-arid regions of northwestern China. It is dominated by silt, has a loose structure, is macroporous, and has no bedding and developed vertical joints. It has strong water sensitivity and collapsibility [1]. Due to its specific material composition, the natural loess is subjected to gravity during the natural deposition process, forming a unique structural state. Under the action of external loads, such as water and earthquakes, loess displays uneven subsidence, local collapse, liquefaction, etc. [2], which seriously affects the safe use of buildings; therefore, the improvement of loess has always been a hot issue in the geotechnical engineering community.

The traditional physical reinforcement methods are usually compacted piles and dynamic compaction, where compaction treatment has a good effect on improving the collapsibility of loess with low water dosage [3–7]. However, when the water dosage of loess is greater than 24%, the saturation is greater than 65%, or the water dosage is very uneven, the compaction pile method is prone to necking, hole collapse, loose fracture of the pile body, and other defects during construction [8]. The dynamic compaction method also leads to a poor local treatment effect and rubber soil situation [9], and there are problems such as limited effective reinforcement depth and large noise [10,11]. Although the physical method is widely used in practical engineering, there are still some limitations.

The curing agent is the product of the combination of new materials and new technologies in the field of engineering and construction. It is widely used in today's geotechnical reinforcement and geological disaster management [12]. The improvement of curing agents is mainly divided into inorganic, biological, and organic types. Inorganic curing agents, such as cement, lime, and fly ash, have a good curing effect and low cost, but they are used in large quantities and often cause damage to the loess structure and cause environmental pollution [13]. The brittle failure is mainly caused by tensile cracking. The lime-improved soil is easily softened when in contact with water and generates a lot of dust during construction. The fly-ash-improved soil has low early strength and poor water stability and requires strict humidity and alkaline conditions control. The biological curing agents have the advantages of less pollution and low cost, but the design life of its improved soil is low, the strength is reduced after immersion in water, and the catalysis of biological enzymes is greatly affected by environmental conditions, and thus, it has poor applicability to soils in some cold regions [14,15]. Most of the organic curing agents are liquid, and they are mainly prepared from one or more combinations of modified water glass, epoxy resins, polymer materials and ions, etc. [14], in which lignin as an environmentally friendly polymer organic curing agent has received close attention in recent years.

With the rapid development of China's social economy, environmental problems have become one of the important factors restricting development. The research on improving loess in a green economy has become a new topic in the field of geotechnical engineering. Lignin is widely present in plant xylem, accounting for 15–35% of the typical dry lignocellulosic biomass [16]. The Chinese paper industry produces about 50 million tons of lignin per year, and the output will continue to increase [17,18]. Lignosulfonate is based on lignin as raw material and the principle of the sulfite pulping process. It is the most abundant industrial lignin that is currently available. It has the advantages of stability, large reserves, environmental protection, and low cost. This paper summarizes the literature published on lignosulfonate-improved loess in recent years and provides the optimal dosage of lignosulfonate-improved loess by analyzing its physical properties, mechanical properties, and engineering properties in order to provide a reference for the study of lignosulfonate-improved loess.

2. Lignin

2.1. Physical Properties

Lignin accounts for about 30% of the organic carbon in the biosphere [19] and can also be regenerated by photosynthesis, with a regeneration rate of about 50 billion tons per year [20], making it a potential renewable biomass resource. Lignosulfonate is obtained using a sulfite pulping process and is one of the main by-products of the paper industry. It is mainly divided into sodium lignosulfonate and calcium lignosulfonate, which are brown or yellow-brown powders with an aromatic odor and are easily soluble in water.

2.2. Structure and Composition

Lignin is mainly distributed in the cell walls of vascular tissues [19], especially in the wood fibers and vessel molecules that constitute a large number of secondary xylem tissues, and it forms a three-dimensional spatial cross-linking structure with cellulose and hemicellulose [21] (see Figure 1). Lignin contributes to the strength and rigidity of the cell wall structure and is a natural adhesive and enhancer. Its phenylpropane macromolecular structure has good water stability and hydrophobicity [22–24]. According to the differences in structural units, it is divided into three types, as shown in Figure 2.

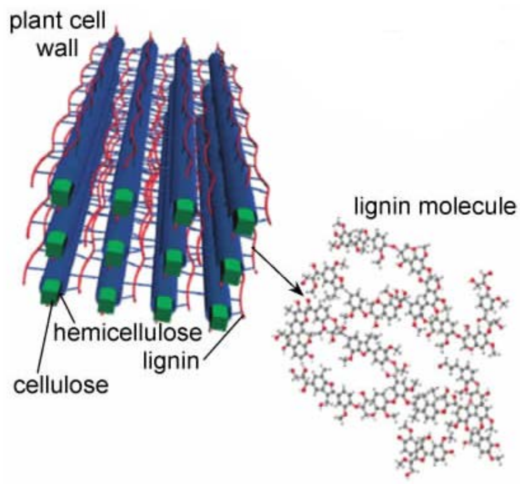
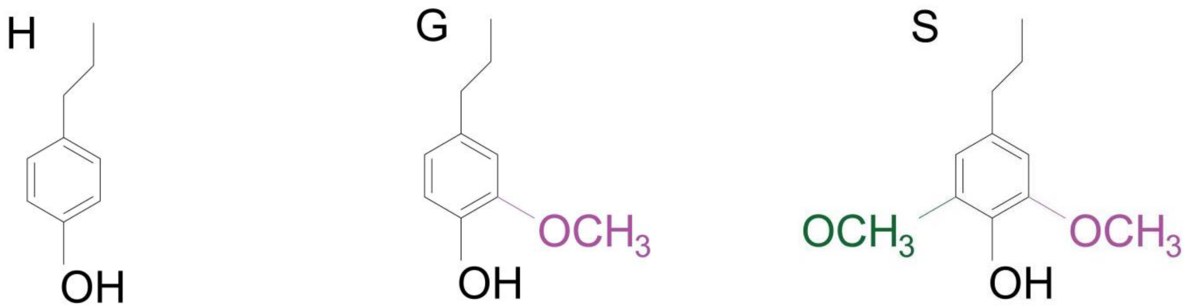


Figure 1. Strctural representation of lignin with cellulose in a plant cell, reproduced with permission from [21].



(**a**) (**b**) (**c**)

Figure 2. Three types of C_6C_3 monomer units in lignin [25]. (**a**) p-Hydroxyphenyl unit(H); (**b**) Guaiacyl unit (G); (**c**) Syringyl unit (S).

2.3. Properties and Applications of Lignosulfonates

Lignosulfonate has strong dispersibility, cohesion, and chelation. The abundant phenolic hydroxyl groups endow lignin with excellent antioxidant, antibacterial and UV protection properties [26], these active sites are beneficial for the preparation of composite materials [27–29]; Polar functional groups such as hydroxyl and carboxyl can weaken the surface force when compounding with other materials [22,30–32]; sulfonic acid groups have good water solubility. The natural degradation process of lignin is very slow. At present, only white-rot fungi have been found to completely degrade lignin; therefore, the durability of lignosulfonate can be guaranteed after being incorporated into loess [33,34].

Because of their surface activity, lignosulfonates are often used in other fields, such as dyes, the coal industry, and the construction industry, such as in clay pavement reinforcement [35] and as a concrete water reducing agent [36,37], adsorbent [38], dispersant [39–41], catalyst [42], etc. In recent years, research on improving loess with lignosulfonates has gradually increased. In 2017, He et al. [43] found that when the amount of lignosulfonates was too large, agglomeration occurs, which affects the soil improvement effect. This phenomenon is directly related to the molecular weight of lignosulfonate [44], and the relative molecular weight of lignosulfonate is larger than other types of lignin [45]; therefore, there is the problem of optimal dosage of lignosulfonate to improve loess in theory.

3. Analysis of the Lignosulfonate Reinforcement Mechanism

3.1. Mineral Composition Analysis

X-ray diffraction tests show that the diffraction peaks of lignosulfonate-modified loess and plain soil are basically the same and their mineral compositions are basically the same [46–48], as shown in Figure 3.

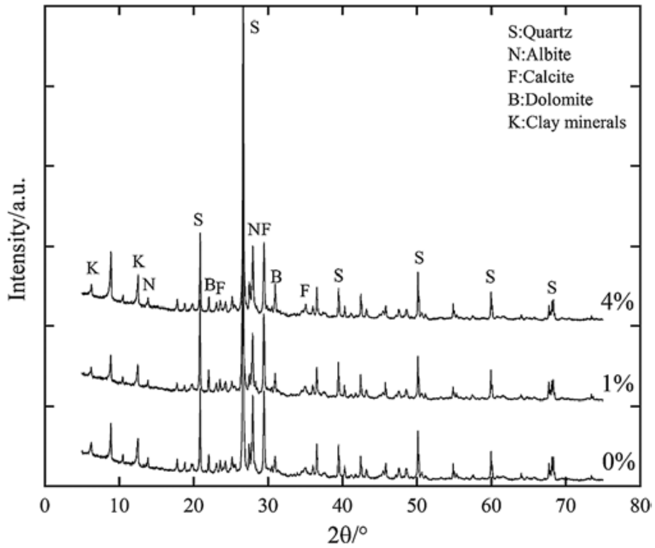


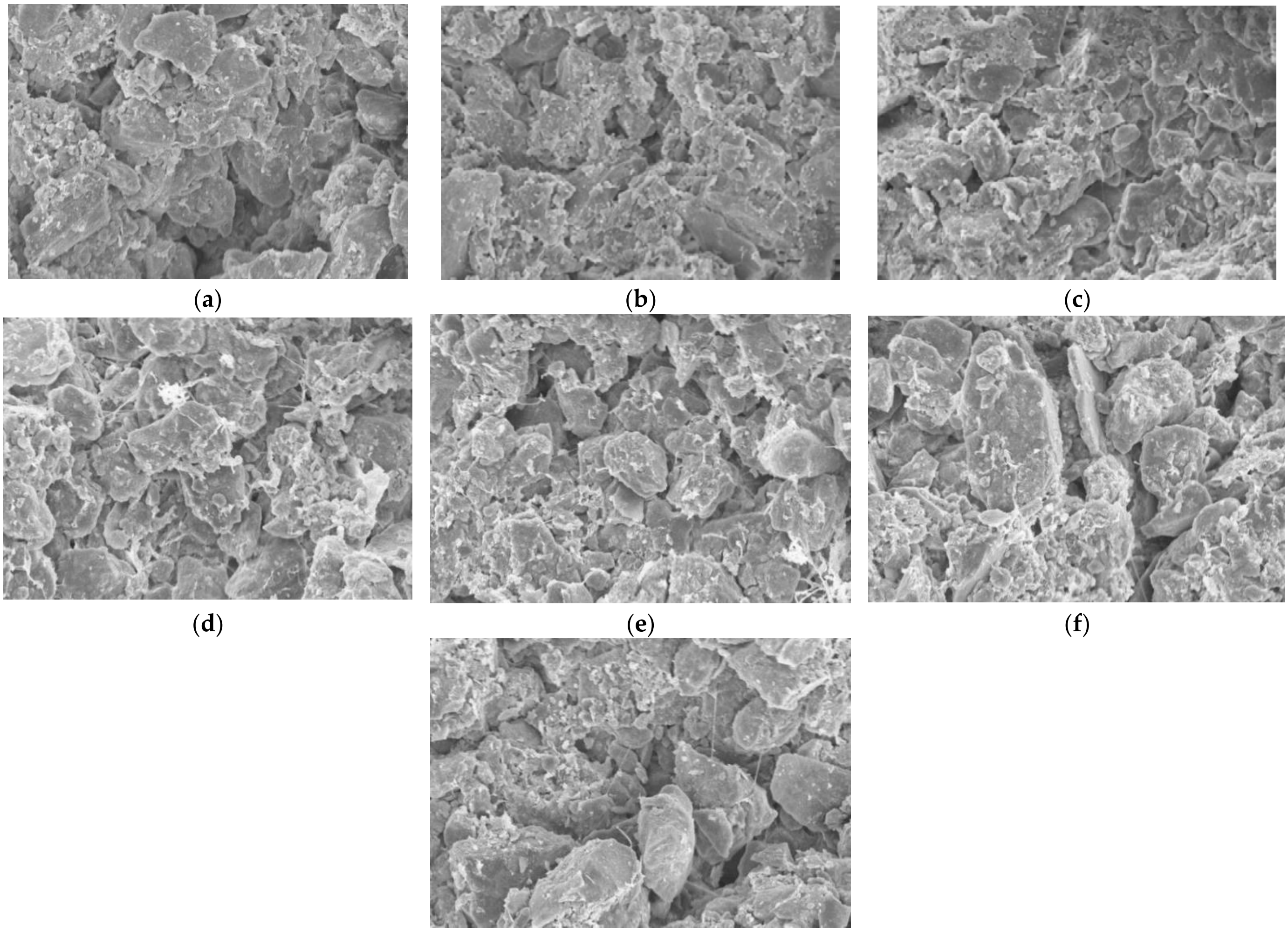
Figure 3. The XRD results of lignosulfonate-modified loess [47].

Liu [46] tested and analyzed the mineral composition of loess modified by calcium lignosulfonate with different dosages and concluded that calcium lignosulfonate and albite ($NaAlSi_3O_8$) in loess undergo decomposition and replacement reactions at the initial stage to form quartz (SiO_2), thereby improving the mechanical properties of the improved soil. Ca^{2+} in calcium lignosulfonate reacts with loess to form calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Carbonate is an inorganic compound with good filling and cementing ability, and its content is the largest when the content of calcium lignosulfonate is 1% to 1.5%. The content of clay minerals increases first and then decreases with the addition of calcium lignosulfonate, and the content is the largest when the dosage of calcium lignosulfonate is 1%. Clay minerals can not only improve the bonding strength between particles but also enhance the water-holding capacity of modified loess due to their hydrophilicity [46].

Hou et al. [49] compared the mineral composition of loess modified with 3% calcium lignosulfonate or 3% sodium lignosulfonate. It was concluded that Na^+ in sodium lignosulfonate produces the clay mineral albite ($NaAlSi_3O_8$) in this reaction. The increase in quartz content can improve certain mechanical properties of the modified soil, but the carbonate in the modified soil does not increase significantly compared with calcium lignosulfonate, the cementation effect on loess is weaker, and sodium lignosulfonate leads to excessive Na^+ in the soil.

3.2. Microstructure Analysis

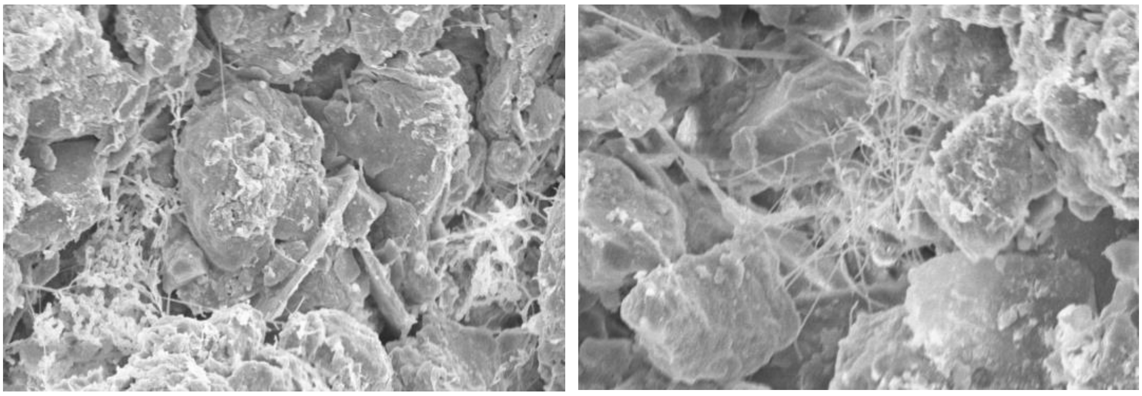
Through SEM experiments, Liu [46] found that the pore types of remodeled loess are mainly large and medium pores, the porosity is high, and the connection between particles is mainly overlapping, where some small particles are attached to the large particles. When the content of lignosulfonate increases from 0 to 1%, the fine particles have the effect of filling the pores in the soil, the large pores are significantly reduced, the medium and small pores become the main pore form, and the total pore area is significantly reduced [50]. Calcium lignosulfonate can reduce the thickness of the bound water film adsorbed on the surface of clay particles, reduce the distance between particles, make the arrangement more compact [43], and form obvious cementing substances with loess particles, which strengthens the soil skeleton structure. The structure type gradually changes from a mosaic structure to a clot-like cemented structure, and the loess particles transition from point contact to surface contact [46,51,52]. When the amount of lignosulfonate increases to 2%, small and medium pores are still the main pore types, the aggregated flocculent cement does not increase significantly, the total pore area does not decrease significantly, and the lignosulfonate particles between particles increase. When the content of lignosulfonate exceeds 2%, some lignin preferentially combines with itself to form aggregates due to cohesiveness and chelation [51], the spacing between soil particles increases, the cementation strength between particles is weakened, and the pore structure type is transformed into a mosaic structure again. Therefore, the continuous increase in the content of lignosulfonate cannot play a role in strengthening loess all the time (see Figure 4).



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**)

Figure 4. SEM images of lignosulfonate-modified loess with the stated percentages of lignosulfonate magnified at 500 times [46]. (**a**) 0%; (**b**) 0.5%; (**c**) 1%; (**d**) 1.5%; (**e**) 2%; (**f**) 3%; (**g**) 4%.

Through experiments, Liu et al. [24,46] and Huang [52] found that when the content of lignosulfonate is 1–2%, the microstructure parameters of the loess modified by lignosulfonate are the smallest, such as porosity and average pore area. It exhibits the optimal structure, which orders the directional arrangement of the improved loess. Liu [46] also observed that a “network structure” was formed in the pores of loess after adding lignosulfonate to loess (see Figure 5). It can not only fill pores and effectively cement soil particles but also acts as a scaffold for the entire soil structure and improve the strength of the skeleton, where the network structure is the most abundant when the content of lignosulfonate is 1–1.5%.



(**a**) (**b**)

Figure 5. Lignosulfonate-modified loess reticular structures at the stated magnifications [46]. (**a**) 500×; (**b**) 800×.

4. Properties of Lignosulfonate-Improved Loess

4.1. Basic Physical Properties

4.1.1. Moisture Dosage Limits

The plastic limit and liquid limit are important indicators of the basic physical properties of soil. Through experiments, Liu [46] and Hou et al. [49] found that the liquid limit (W_L) is inversely proportional to the dosage of calcium lignosulfonate and proportional to the sodium lignosulfonate dosage. The plastic limit (W_P) of the improved soil is proportional to the amount of lignosulfonate. The plasticity index is affected by the mineral composition, particle size, water ion concentration, and the thickness of the bound water film on the surface of soil particles [17,46]; the plasticity index (I_P) of lignosulfonate-modified soil decreases with the increase in the dosage of the lignosulfonate (see Figure 6).

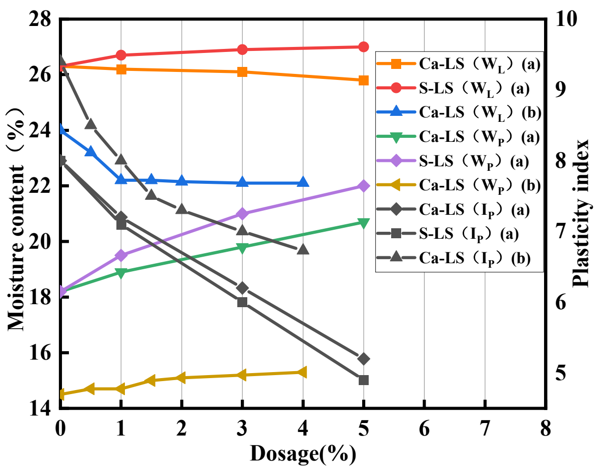


Figure 6. Variation in the moisture content limit with lignosulfonate dosage [46,49]. a: date from Hou et al. b: date from Liu. Ca-LS: calcium lignosulfonate, S-LS: sodium lignosulfonate, W_L: liquid limit, W_P: plastic limit, I_P: plasticity index.

After the lignosulfonate is incorporated, its active functional groups and pore water undergo a hydrolysis reaction and the decomposed hydrogen ions break the active alcohol hydroxyl groups of the lignosulfonate, forming a positively charged cement in the soil. Therefore, the cement is closely attracted to the surface of clay minerals due to electrostatic force, thereby neutralizing the negative charge on the surface, resulting in a decrease in the thickness of the electric double layer; the macroscopic manifestation of this is the spacing between soil particles decreases and the plasticity index of the improved soil decreases [49].

4.1.2. Void Ratio

The void ratio is an important physical property index that directly reflects the compactness of the material. The porosity ratio of lignosulfonate-modified soil shows a trend of first decreasing and then increasing with the increase in the lignosulfonate dosage. When the dosage of lignosulfonate is small, the fine particles have a good filling effect and cementing effect such that the porosity of the modified soil decreases. When the dosage is too large, lignosulfonate preferentially combines with itself due to its characteristics, resulting in an increase in porosity.

Huang [52] obtained that the inflection point of the curve is about 1%, and the void ratio at this point is about 29.4% lower than that of plain soil; Liu et al. [50] obtained that the inflection point of the curve is about 1%, and the void ratio at this point is about 42.8% lower than that of plain soil; Liu et al. [24] obtained that the inflection point of the curve is about 2%, and the void ratio at this point is about 38.4% lower than that of plain soil; Wang et al. [48] obtained that the inflection point of the curve is about 4%, and the void ratio at this point is about 25.2% lower than that of plain soil, as shown in Figure 7.

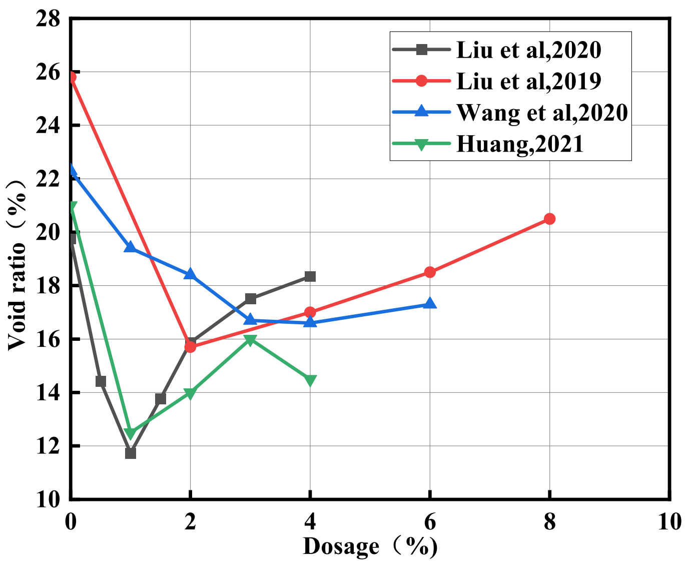


Figure 7. Variation of void ratio with lignosulfonate [24,48,50,52].

Through the comparative analysis in Table 1, the higher the liquid–plastic limit of loess, the more significant the effect of water on the strength of the improved soil is and the weaker the soil cementation is, resulting in a larger optimal dosage of lignosulfonate. The higher the compaction degree, the smaller the optimal dosage of lignosulfonate. In conclusion, variables such as moisture content and compaction degree of the loess in the test lead to the inconsistency of the optimal dosage. In conclusion, the porosity ratio of lignosulfonate is the smallest for a dosage of 1–2%, and the improvement effect is the best.

Table 1. Basic properties of trial loess.

Reference	Density (g·cm^3)	Moisture Dosage (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Proportion	Maximum Dry Density	Optimal Moisture Dosage
Liu [50] Liu [46]	1.35	5.21	24.00	14.50	9.50	2.72	1.78	14.60
Huang [52]		13.92	30.50	20.00	10.50		1.74	19.60
Wang [48]	1.59	13.30	25.60	16.44	9.16	2.71	1.71	16.6

4.2. Static Strength Properties

4.2.1. Tensile Strength

Through experiments, He et al. [43] found that the tensile strength of improved soil increases first and then decreases with the increase in the calcium lignosulfonate dosage. The inflection point is at 1%, which is 26.1% higher than that of plain soil. It decreases slightly in the range of 1–2%; the tensile strength of the improved soil decreases sharply after more than 3%. The results show that calcium lignosulfonate can effectively cement the soil particles and increase the cohesion of the soil under the condition of low dosage, thereby improving the tensile strength of the improved soil. When the dosage of lignosulfonate exceeds 2%, the tensile strength decreases. In summary, the recommended dosage range of lignosulfonate is 1–2%.

4.2.2. Shear Strength

Shear strength is one of the important indicators that are used to characterize the strength characteristics of lignosulfonate-solidified soils. Through experiments, He et al. [43] and Liu [46] found that the cohesion of lignosulfonate-modified soil increases first and then decreases with the increase in the lignosulfonate dosage. The change of cohesion is obvious, which is the main reason for the change in shear strength performance; meanwhile, the change of internal friction angle with different dosages is small, the influence on shear performance is small, and the curing age is proportional to the shear strength of the improved soil.

The shear strength parameters are related to the soil particle morphology, degree of cementation, pore distribution, water content, and clay mineral content [53,54]. Calcium lignosulfonate can fill the pores at the initial stage, effectively cementing the soil particles to strengthen the skeleton structure [55], and the cohesion of the soil increases. The internal friction angle may be related to particle occlusion and the content of clay. Fine lignosulfonate particles are gradually embedded in the pores, and the interlocking effect with the particles enhances the occlusion force between particles, resulting in a small increase in the internal friction angle [46]. The shear strength index of the improved soil with the calcium lignosulfonate dosage of 1.0% is the highest, and the shear strength of the soil begins to decrease after the dosage is higher than 1% due to its characteristics. When the dosage is higher than 3%, the shear strength of the improved soil drops sharply. In conclusion, the recommended dosage range of lignosulfonate is approximately 1%.

4.2.3. Compressive Strength

Through experiments, Liu [46] and He et al. [43] found that the unconfined compressive strength of improved loess shows a trend of first increasing and then decreasing with the increase in lignosulfonate dosage under non-freeze–thaw cycles. The inflection point of lignosulfonate dosage in each curing age is 1%, the compressive strength drops sharply when the lignosulfonate dosage exceeds 1.5%, and the curing age should not be less than 7 d.

Under the premise of ensuring the degree of compaction, the moisture content should be lower than the optimal moisture content. Under the condition of a certain moisture content, the compressive strength of the improved soil is related to the internal cohesion and porosity of the soil. With an increase in lignosulfonate, the cohesive polymer on the surface of loess particles increases and its porosity decreases. When the amount of lignosulfonate is too high, it preferentially combines with itself, and the skeleton structure between soil particles is destroyed, resulting in an increase in the void ratio and a decrease in soil cohesion. Therefore, the recommended dosage range of lignosulfonate is about 1%.

4.3. Water Sensitivity

4.3.1. Impermeability

Through a penetration test, He et al. [43] found that the impermeability coefficient of the improved loess is basically inversely proportional to the calcium lignosulfonate dosage.

When the dosage of calcium lignosulfonate increases from 0 to 0.5%, its permeability coefficient decreases the most. When the dosage is increased to 3%, the permeability coefficient of the improved soil is one order of magnitude lower than that of the plain soil. Under the same conditions, prolonging the curing period can further reduce the permeability coefficient. Huang [52] found that the impermeability of the soil is similar when the dosage of calcium lignosulfonate was 2% and 4%, and the impermeability of the improved soil is the best when the dosage of calcium lignosulfonate is 3%.

Through a charge test of soil samples, Huang [52] found that with an increase in lignosulfonate, the charge in the soil changes from positive to negative and increased continuously, which causes the thickness of the water film in the soil to increase. Therefore, the effective pore radius is reduced and the permeability of loess is reduced; therefore, the recommended dosage range of calcium lignosulfonate is 3%.

4.3.2. Water Stability

The wet disintegration test is used to study the disintegration form and disintegration rate of soil in still water. He et al. [43] found that remolded soil disintegrates within half an hour, the modified soil is stable with dosages of calcium lignosulfonate ranging from 0.5% to 3%, and the modified soil with the 1% dosage is the best; when the dosage of calcium lignosulfonate reaches 5.0%, it shows severe disintegration at 3 d. Liu [46] found that the water stability of the modified loess with a dosage of 1% to 2% is stable, and the modified soil with a dosage of 2% has the best performance; when the dosage exceeds 3%, the cementation effect of lignosulfonate decreases and the water stability of the improved soil is poor.

The disintegration rate of loess is mainly related to the degree of particle cementation and pore structure [43]. In conclusion, when the lignosulfonate dosage is 1–2%, it can effectively cement the soil particles and fill the pores. Its structure type changes from a mosaic pore structure to a clot-like cemented structure; after the optimal dosage is exceeded, lignosulfonate preferentially combines with itself due to its characteristics and the cementation becomes weaker, resulting in poor water stability. Therefore, the recommended dosage range of lignosulfonate is 1–2%.

4.3.3. Water-Holding Capacity

The influencing factors of the soil–water characteristic curve are complex and are usually expressed using empirical formulas. The VG model has a good fitting effect on the soil–water characteristic curve of lignosulfonate-improved loess [56]. Referring to the soil–water characteristic test data of Liu [46], the VG model was used to nonlinearly fit the change trend curves of volumetric water content and the matrix suction by origin.

When the substrate suction is less than 5 kPa, the volumetric moisture content of the improved loess remains basically unchanged and the volumetric moisture content of the plain soil is the largest. When the matrix suction is higher than 5 kPa, the volumetric water content of the improved loess shows a decreasing trend, and the loss rate decreases after adding lignosulfonate. When the dosage is 1% to 2%, the curve is the smoothest and the loss of volumetric water content is small; the water holding capacity of the modified loess with the dosage exceeding 2% decreases, as shown in Figure 8. The soil–water characteristic curve is related to the internal water-based mineral content and pore structure of the soil [50]. After lignosulfonate is incorporated into loess, a certain amount of clay minerals is produced and its hydrophilicity improves the water-holding capacity of the improved soil. When the amount of lignosulfonate is too high, it preferentially combines with itself, resulting in an increase in the porosity of the improved soil and a decrease in the water-holding capacity. Therefore, the recommended amount of lignosulfonate is in the range of 1–2%.

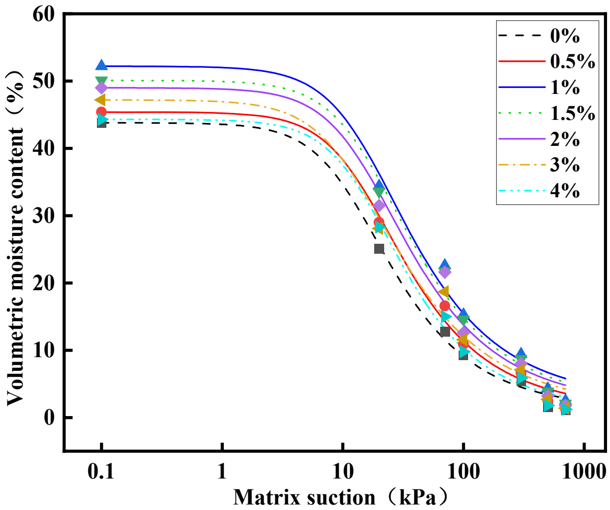


Figure 8. Soil–water characteristic curves of lignosulfonate-improved loess [46].

4.4. Dynamic Characteristics

4.4.1. Dynamic Elastic Modulus

The fitted curve shows that the dynamic elastic modulus of the improved loess is inversely proportional to the lignosulfonate dosage, and the dynamic elastic modulus reaches the maximum when the dosage is 1%, which is about 60% higher than that of reshaped loess. When the dosage is more than 3%, the dynamic elastic modulus of the improved loess decreases significantly, but it is still better than that of plain soil, as shown in Figure 9. The dynamic elastic modulus is affected by the average pore diameter and apparent porosity, and the incorporation of lignosulfonate can effectively reduce the porosity at the initial stage to enhance the deformation resistance of loess under dynamic loads. When the amount of lignosulfonate is too high, it preferentially combines with itself and the effect on the soil changes from “cementation” to “lubrication”. In summary, the recommended amount of lignosulfonate is 1–1.5%.

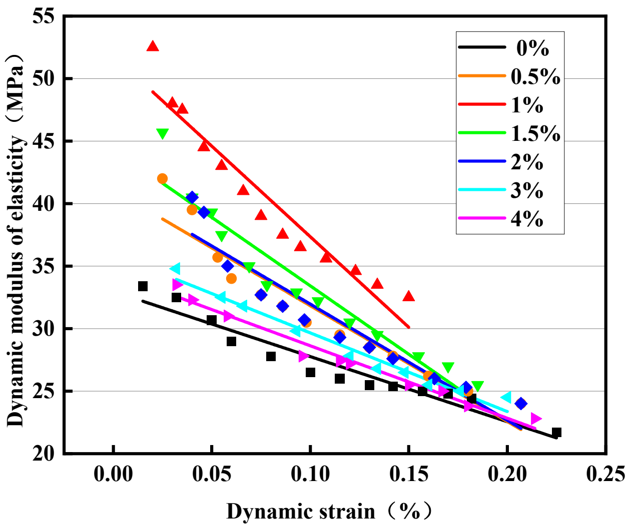


Figure 9. Variation of the dynamic elastic modulus with dynamic strain [47].

4.4.2. Damping Ratio

The damping ratio of the improved soil shows an upward trend with the increase in dynamic strain, and the damping ratio is the smallest when the dosage of lignosulfonate is 1% to 2%, as shown in Figure 10. The damping ratio of soil represents the energy consumed by the internal action of the material when the soil is deformed under a dynamic load [40,46].

The incorporation of lignosulfonate plays the role of filling pores and cementing soil particles. The relative sliding between soil particles is reduced, and the energy loss caused by particle friction is also reduced, and thus, the damping ratio is reduced. In summary, the recommended dosage of lignosulfonate is 1–2%.

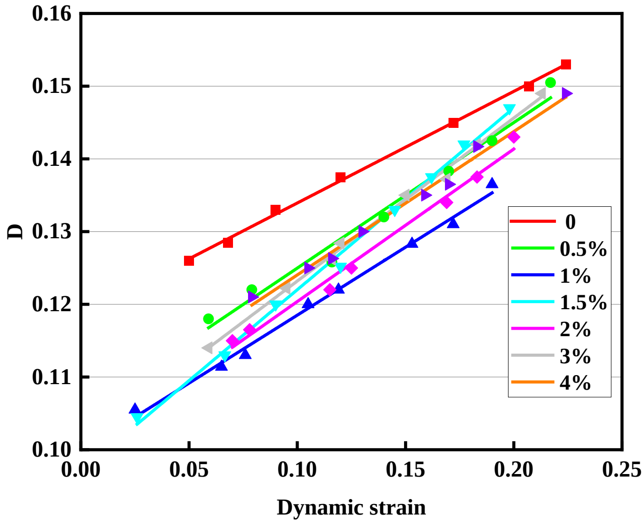


Figure 10. Variation of damping ratio with dynamic strain [47].

4.5. Thermal Conductivity

Hou et al. [49] found that the thermal conductivity of lignosulfonate-modified soil is basically inversely proportional to the dosage. When the dosage of calcium lignosulfonate ranges from 0 to 3%, the thermal conductivity decreases significantly, and the improvement effect is better than that of calcium lignosulfonate. The thermal conductivity of soil is a function of the dry bulk density, moisture content, and temperature, and is related to the soil mineral composition and structure. The heat of the sample is mainly conducted by the contact between the soil particles and the water in the lignosulfonate. The incorporation of lignosulfonate absorbs a certain amount of water in the soil, reduces the water film between the soil particles, and reduces the connectivity of the soil [57], and thus, the thermal conductivity decreases.

5. Discussion of the Optimal Dosage

When the dosage of lignosulfonate is increased to 1%, lignosulfonate can effectively cement the soil particles. The cement makes the loess particles transition from point contact to surface contact, the void ratio is the lowest, the soil skeleton is stable, and its internal cohesion is the largest. The macroscopic performance is presented as the static strength characteristics of the improved soil all reaching the peak value when the lignosulfonate dosage is 1%. When the lignosulfonate dosage increases to 3%, the static strength of the improved soil is still higher than that of the plain soil, but the relative improvement is not large. When the dosage of lignosulfonate is higher than 3%, part of lignosulfonate preferentially combines with itself to form agglomerates due to cohesiveness and chelation, the bonding strength between particles is weakened, and the pore type changes to mainly large mesopores; as such, lignosulfonate can no longer play a role in strengthening the soil, and thus, recommended amount of lignosulfonate is 1%.

In the early stage of lignosulfonate incorporation into loess, its tiny particles play a role in filling the pores of the soil body, and the void ratio of the soil body decreases. See Table 2 for details. When the lignosulfonate dosage reaches 3%, the permeability coefficient is the lowest; when the dosage of lignosulfonate ranges from 1% to 2%, the water stability of the improved loess is stable, the soil–water characteristic curve is the smoothest, and the loss of volumetric water content is small. When the dosage exceeds 2%, the water-holding capacity of the improved soil decreases, and thus, the recommended dosage of lignosulfonate is 1–2%; however, in practical applications, the impermeability needs to be further considered.

Table 2. Recommended optimal dosage of lignosulfonate-improved loess.

Sample			Test Optimal Dosage (%)	Recommended Dosage (%)
Lignosulfonate-improved loess	Static Strength Properties	Tensile strength	1–2	1
		Shear strength	1	
		Compressive strength	1	
	Water sensitivity	Impermeability	3	1–2
		Water stability	1–2	
		Water-holding capacity	1–2	
	Dynamic characteristics	Dynamic elastic modulus	1–1.5	1–1.5
		Damping ratio	1–2	
	Thermal conductivity	Thermal conductivity	-	-

When the dosage of lignosulfonate is in the range of 1–2%, the structure type of loess gradually changes from a mosaic structure to a clot-like cemented structure. The fine pores are transformed into micropores, the average pore diameter is small, the pores of the soil are densely arranged, and the relative sliding of the soil body is reduced [54,55]; the macroscopic performance is presented as the improvement of the dynamic deformation characteristics of the improved soil. When the dosage of lignosulfonate is more than 2%, part of the lignosulfonate is preferentially combined with itself, and the pore structure type is transformed into a mosaic structure again. Therefore, the recommended amount of lignosulfonate is 1–2%.

By summarizing the basic physical properties, static strength properties, water sensitivity, and dynamic properties of lignosulfonate-improved loess, we concluded that lignosulfonate has a good curing effect. The recommended dosage is shown in Table 2. The improved mechanism of lignosulfonate in soil can be attributed to ion exchange, hydrogen bonding, covalent bonding, and electrostatic attraction. A polymer with consolidation properties is formed between lignosulfonate and clay minerals, which improves the structural stability of soil [17]. After lignosulfonate is added to loess, a “network structure” is formed in the pores of the loess, which can effectively fill the pores and strengthen the internal structure of the soil. The content of this structure is the largest when the content of lignosulfonate is 1–1.5%, which may be the reason why the optimal content of lignosulfonate to improve the mechanical properties of loess is basically between 1% and 1.5%.

6. Challenges

Li et al. [58] studied the improvement of loess with lignosulfonate under the condition of freezing and thawing and compared it with traditional curing agents (quicklime and sodium silicate) at the same dosage. The test results show that lignosulfonates have wide application potential in cold loess regions. At present, there are few studies on the improvement of loess using lignosulfonates during freeze–thaw cycles. We still lack the optimal dose range for lignosulfonate-modified loess under freeze–thaw conditions.

Considering the limited number of references in this paper, the characteristics of the experimental loess, and the different curing ages, the optimal amount of lignin fluctuated within a certain range. Therefore, the specific optimal dosage of lignin to improve loess needs to be further studied.

7. Outlook

Lignosulfonate is environmentally friendly and has great research prospects in the application of improved loess. This paper only discusses the improvement effect of lignosulfonate on loess and does not discuss whether lignosulfonate is used with other materials (such as lime) to improve the compatibility with loess, thereby improving the improvement effect. Kaveh Roshan et al. [59,60] used lignosulfonate and polypropylene fiber to improve clay sand, Amir Hossein Vakili et al. [61,62] used lignosulfonate and polypropylene fiber to improve marl and disperse clay, and Lu et al. [63] used lignosulfonate and polypropylene fiber to improve disperse soil, and all these authors achieved good results. This shows that polypropylene (PP) fibers can theoretically be used with lignosulfonates to improve loess, which will become the future research direction of lignin-improved soils.

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