Optimization of Cement Admixture and Performance Enhancement of Loess Roadbase

Bo Sha [1, a], Wenhui Cao [1, b], Shumin Du [1, c], Yu Zheng [1, d], Zhihong Wang [2, e], Bangxin Zhang [2, f, *]

[1] Xin Jiang Road & Bridge Construction Group Co., Ltd. Wulumuqi 830000, China;

[2] China Merchants Chongqing Communications Technology Research & Designinstitute Co.,Ltd. Chongqing 400067, China.

[a] 121641235@qq.com, [b] 245742156@qq.com, [c] 3112014384@qq.com, [d] 2217894817@qq.com,

[e] 1119064256@qq.com, [f] 3114529982@qq.com

Abstract. Based on the practical difficulties in filling the roadbed of a highway in loess area, cement-reinforced loess was used as the roadbed filling material according to the geological conditions and filler distribution of the project. The mechanism of cement-reinforced loess was analyzed, and the linear fitting relationship between compaction of reinforced soil and *CBR* of bearing ratio was investigated by indoor tests with different cement dosage. Combined with the specification requirements for roadbed bearing ratio and modulus of resilience, the cement dosing of cement-reinforced loess for the project was determined. The study shows that: (1) cement as an admixture for loess roadbed improvement can significantly improve the mechanical properties of loess, and the dosage and the size of performance are linearly related. (2) The *CBR* and E_0 meet the specification requirements when the cement doping is 5% and 96% of the minimum compaction required for the upper roadbed is met; (3) The *CBR* value meets the specification requirements when the cement doping is 3% and 96% of the minimum compaction required for the upper embankment is met; (4) A cement doping of 4% is recommended, which achieves a good transition between the upper roadbed and the embankment, and meets the specification requirements for the lower roadbed;(5)The results of the study can provide a reference for the design and construction of cement-reinforced loess roadbeds.

Keywords: Loess roadbed; Mechanism of action; Bearing ratio; Cement.

1. Introduction

Wet subsided loess is widely distributed in the economically developed and densely populated eastern region of China, which brings great difficulties to the engineering construction in this region. In the highway construction along the loess area, especially when the roadbed is being constructed, subject to the constraints of sand and gravel resources, economy, environmental protection and other factors, the improvement of roadbed filling materials has become an important technical problem. Experts and scholars at home and abroad have carried out many researches[1-3], Jin Mingliang et al.[4] studied the construction effect of cement-improved soil roadbed under the action of ordinary roller and large excitation roller by comparing with the on-site heavy-duty compaction test; Ge Fei et al.[5] analyzed the characteristics of the changes in shear strength indexes of loess improved by cement and silica micropowder; Bu Xiaobin et al.[6] investigated the influence of different factors on the deformation characteristics of cement-improved loess and remolded loess under the action of cyclic loading; Fan Jiangtao et al.[7] improved and validated the EDTA titration method for cement-amended loess; Jiang Yingjun et al.[8] investigated the influence of cement dosage, compaction coefficient, and age of maintenance on the coefficient of water stability, dry and wet residual strength ratio, and freeze-thaw residual strength ratio of amended loess. Existing research exists field experimental conditions are limited by the site, environment, equipment and other factors, the test results may have errors or uncertainty; improvement methods have limitations, the current commonly used methods of wet subsidence loess improvement, such as cement improvement, silica micropowder improvement, etc., although it can improve the mechanical properties and stability of loess to a certain degree; the long-term evaluation of the improvement effect is insufficient, the existing research mainly focuses on the improvement of short-term mechanical properties and stability of loess, and the improvement effect is not enough. The existing research mainly focuses on the short-term mechanical properties and stability of improved loess; the deformation characteristics under cyclic loading are insufficiently studied, and the comprehensive consideration of environmental protection and economic benefits is insufficient.

Given that most of the existing research is partial to theoretical analysis, and less detailed cases in the actual engineering applications, the relevant experimental data and the improvement effect of the relevant targeted research is insufficient, this paper takes a high speed loess roadbed as the research object, analyzes the function mechanism of cement reinforcing roadbed and determines the optimal mixing amount of cement, which provides an important reference for solving the actual roadbed reinforcing engineering problems.

2. Mechanism of cement-amended loess

2.1 Loess characteristics

The remarkable properties of loess, with its main component of chalk, include porosity, moisture hypersensitivity, abundance of soluble salts, high water permeability, and development of vertical joints, which together give loess its unique geological and engineering properties.China's eastern loess covers a large area, located in the scope of wet subsidence loess engineering geology I area, with significant wet subsidence characteristics, with more than 10m thick layer of loess, which is large and wet subsidence, wet subsidence sensitive and rapid development.The major highway diseases caused by this characteristic include instability and deformation of road graben, embankment or slope, and loess traps (dark gullies, dark holes and dark caves formed by erosion and dissolution of loess). It has high strength and low compression in dry state, but when it is wetted by water, the soil will sink and deform rapidly, leading to foundation instability.This wet subsidence has important implications for construction and highway building. The engineering properties of loess are significantly affected by the unique geomorphology and genesis, showing significant diversity and grade variation in wet subsidence, and because of its high salt content, it is prone to compounding with saline soils, which further increases the complexity and risk of engineering and construction.

2.2 Mechanism of action

Loess improvement is through the loess add admixture and chemical reaction with the loess and the moisture in it, using the reaction product to change the composition and structure of the soil, and then realize the improvement of soil properties. At the present stage of the project commonly used mixing materials such as lime, fly ash and cement. As far as cement improved loess is concerned, it is formed by adding a certain amount of cement and water in loess, fully mixed, compacted, maintained, mixed as the complex physicochemical effects of cement and loess, effectively improving the physical and mechanical defects of loess, obtaining higher strength and water stability, et al.[9-11] . In recent years, scholars try to add modified materials in natural loess, such as bentonite, kaolin and other clay-like substances, as well as anti-sloughing force curing agent and so on. These modified materials themselves have specific physical properties that can change the composition and physical structure of loess particles. By increasing the content of clay particles, it improves the bonding between particles within the loess, and causes tiny clay particles to fall into the overhead pores between the loess particles, further densifying the soil body. This physical modification method can significantly improve the strength of loess and reduce its permeability.

The mechanism of action of cement in improving loess is as follows:

(1) Ion exchange and agglomeration

After contacting with water, loess is in colloidal state, and SiO_2 reacts with pore water to produce silicate colloidal particles, which are attached to cations such as Na^+ or K^+ . In the curing of cement soil, the free Ca^{2+} in the hydration product of cement will adsorb and exchange with Na^+ or K^+ and other cations, which makes the original dispersed soil particles coalesce and transform into larger soil clusters, which makes the soil particles more compact, and the strength of the soil body is improved as a whole.

(2) Hard-coagulation reaction

As the reaction intensifies and the concentration of Ca^{2+} produced by the reaction is greater than that required for the ion-exchange reaction, the minerals AlO_3 , SiO_2 and Ca^{2+} in the loess react chemically under higher pH conditions to continuously produce chemically more stable hydrates:

$$SiO_2 + Ca(OH)_2 + nH_2O \rightarrow CaO \cdot SiO_2 \cdot (n+1)H_2O \quad (1)$$

$$Al_2O_3 + Ca(OH)_2 + nH_2O \rightarrow CaO \cdot Al_2O_3 \cdot (n+1)H_2O \quad (2)$$

Hydrate continues to solidify under the action of pore water and air, improving the strength of the soil. The hydrated soil formed has a compact structure, is not easily eroded by water, and has good water stability.

(3) Carbonation

During consolidation, $Ca(OH)_2$ reacts with CO_2 in the air to form $CaCO_3$, which is insoluble in water.

$$Ca(OH)_2 + CO_2 + nH_2O \rightarrow CaCO_3 \downarrow + (n+1)H_2O \quad (3)$$

The $CaCO_3$ generated by the reaction makes the soil particles more compact, and the strength and stability of the soil body are enhanced. In the cement hydration and hydrolysis reaction that occurs in the process of cement-improved loess, a large amount of $Ca(OH)_2$ is generated, but there are differences in the degree of reaction between different types of soils and $Ca(OH)_2$, so under the same amount of cement mixing, the soil body shows different reinforcing effects, which is mainly manifested in the difference of strength.

Combining the above physicochemical effects, mixed with an appropriate amount of cement loess soil mixture can form a composite whole, the strength and integrity has been greatly improved, so as to achieve the role of cement reinforced loess [12-15] .

3. Cement-amended loess for a highway

3.1 Project overview

Wet subsidence loess is widely distributed along a highway, the main type is Holocene alluvial loess and upper Pleistocene wind-accumulated loess, with a thickness of 5-20m, homogeneous structure, loose soil structure, vertical joints and holes development, with wet subsidence. According to the ground investigation data, I (slight) non-self-weight ~ IV (very serious) self-weight wet subsidence site accounted for 74% of the total length of the route, of which each grade is shown in Table 1.

Table 1. The wetting of loess table

Wet sink rating	Percentage of route length	Total Wet Depression (Δs)	Self-weight wetting amount (Δzs)	Thickness of wetted soil layer
Class I (minor)	2.18%	51.00～78.00mm	54.00～64.80cm	2.00m
non-self-loading ClassII (medium)	63.56%	67.50～ 500.10mm	76.68 ～ 351.00mm	2.0～(> 10.5)m
deadweight ClassIII (severe)	30.38%	337.50～ 678.62mm	394.2～660.96mm	10.40～12.20m
deadweight ClassIV (severe)	3.86%	710.80～ 876.40mm	491.40～831.60mm	12m

As can be seen from Table 1, loess development along the project route,wet subsidence loess distribution range is more, grade I ~ IV uneven development, of which III, IV wet subsidence loess proportion is higher, the degree of wet subsidence is more serious, along the loess nature of the big difference. Along the project line, there are more filling roadbase, embankment filling needs to consume a lot of earth,but along the line of gravel yard, lime yard and clay yard lack of a large number of borrowing is not economic and not feasible, embankment filling consider in situ use of excavation of loess, mixing and a certain dose of cement for improvement after filling.

3.2 Test methods and results

In order to find out the specific cement mixing amount of cement-amended loess, in-situ samples were taken in the project area for geotechnical tests. This project mainly addresses the use of cement-amended loess for roadbed filling, focusing on whether the filling meets the requirements of the corresponding structural layer of roadbed in the specification for highway roadbeds. According to the "Highway Geotechnical Test Specification" (JTG E40-2007), the test items include: standard compaction test, boundary moisture content test, soil bearing ratio test. The test samples are in-situ soil at the project site, and the cement is P.C32.5R. The main instruments and equipments are: oven, electronic balance, electronic scale, electric compactor, pavement strength meter, *CBR* cylinder, and percentage meter.

By reviewing the relevant information, the cement dosage of 3%, 4% and 5% was selected for the test, and the test data table 2.

Table 2. Physical characteristics of unadulterated loess

Maximum dry density(g/cm^3)	1.84
Optimum moisture contentt(%)	15.5
Liquid limitt(%)	45.7
Plastic limitt(%)	36.7
plasticity index	9

Table 3. Bearing capacity ratio (*CBR*) of soil with the same cement dosage

Form	Cement Admixture	Unadulterated	3%	4%	5%
30 hits	Carrying ratio(%)	2.6	9.1	15.8	26.0
	Expansion (%)	0.19	0.21	0.22	0.18
50 hits	Carrying ratio(%)	3.5	12.4	18.7	31.3
	Expansion (%)	0.15	0.16	0.15	0.16
80 hits	Carrying ratio(%)	4.9	21.9	27.8	42.3
	Expansion (%)	0.12	0.11	0.12	0.11

The above table shows that the *CBR* value for 98.4% compaction is 4.9% when no ash is mixed; the *CBR* value for 98.9% compaction is 21.9% when 3% cement is mixed; the *CBR* value for 99% compaction is 27.8% when 4% cement is mixed; and the *CBR* value for 99% compaction is 42.3% when 5% cement is mixed. From this, the linear fitting equation of compaction (%) and *CBR* value (%) can be derived when the penetration amount is 2.5mm:

Unadulterated vegetative soil:

$$CBR = 0.0257\lambda^2 - 4.5711\lambda + 205.86 \quad (4)$$

When cement is mixed at 3%:

$$CBR = 0.0977\lambda^2 - 17.098\lambda + 757 \quad (5)$$

At 4% cement mixing:

$$CBR = 0.1738\lambda^2 - 31.461\lambda + 1439.3 \quad (6)$$

At 5% cement mixing:

$$CBR = 0.159\lambda^2 - 28.228\lambda + 1278.8 \quad (7)$$

3.3 Design of cement-amended loess for roadbed fillers

Highway roadbed filler needs to meet the specification requirements of compaction and *CBR* indicators according to its filling position, according to the "highway roadbed design specification", each layer of filler indicator requirements such as Table 4.

Table 4. Indicators of normative requirements

Filling position	Minimum *CBR*	Minimum compaction
road bed	8%	96%
lower bed	5%	96%
embankment	4%	94%
lower embankment	3%	93%

From the experimental data in Table 4 and its linear fitting formula, it can be seen that when the compaction degree is 93%, the *CBR* value corresponding to plain soil is 3.027%, which basically meets the requirement of minimum *CBR* (3%) of the lower embankment. When the compaction degree is 94%, the *CBR* value of soil is 3.262%, which can't reach the requirement of minimum *CBR* (4%) of upper embankment and can't be used as the upper embankment filler directly. When the cement mixing amount is 3%, the *CBR* value is 13.0656% when the compaction degree is 94%, which can satisfy the requirement of minimum *CBR* (4%) of upper embankment.

When the compaction degree is 96%, the corresponding *CBR* value of plain soil is 3.89%, which is not up to the requirement of minimum *CBR* of roadbed (8% for upper roadbed and 5% for lower roadbed), and it can't be directly used as roadbed fill. For the filling requirements of roadbed, the *CBR* of roadbed and the resilience modulus of the top surface of roadbed as well as the structural layer of pavement are required for the structural layer of roadbed. According to the highway roadbed design specification 3.2.4~3.2.6, the design value of rebound modulus of roadbed E_0 and the value of rebound modulus of roadbed under standard condition MR are calculated as follows:

$$E_0 = K_S K_\eta M_R, (E_0 \geq [E_0]) \quad (8)$$

$$M_R = 17.6 CBR^{0.64} (2 < CBR \leq 12) \quad (9)$$

$$M_R = 22.1 CBR^{0.55} (12 < CBR < 80) \quad (10)$$

For the upper roadbed, at 96% compaction and 5% ash mixing, the *CBR* value is 34.26%, and the rebound modulus of the top surface of the roadbed MR is estimated to be 153MPa, multiplied by the moisture adjustment factor *KS* and the soil discount factor of the roadbed under the condition of wet/dry cycle or freeze-thaw cycle K, the design value of rebound modulus of the roadbed E_0 is 86 Mpa. At 96% compaction and 4% ash mixing, the *CBR* value is 20.78%, and the top surface of the roadbed M is estimated to be 117MPa, multiplied by the moisture adjustment factor and the soil discount factor of the roadbed under the condition of wet/dry cycle or freeze-thaw cycle. Resilience modulus MR estimated value of 117 MPa, multiplied by the humidity adjustment coefficient and wet and dry cycle or freeze-thaw cycle conditions of the roadbed soil discount coefficient, the design value of the resilience modulus of the roadbed E_0 for 66 MPa. All meet the specification for heavy traffic 50 Mpa of the specified value, but should meet the pavement structural layer on which the roadbed can provide to meet the requirements of the top surface of the resilience modulus (more than 75 MPa), so the proportion of ash mixing 5% to meet the requirements. Therefore, the ash mixing ratio is 5% to meet the requirements. For the lower roadbed, because the embankment is not high, in order to realize the good transition between the upper roadbed (5%) and the upper embankment (3%) rigidity, and to meet the *CBR* requirements, the lower roadbed is 4% of the ash mixing.

In summary, the ash blending ratio for this project is shown in Table 5.

Table 5. Percentage of cement-amended loess mixed with ash

Filling position	Ash mixing ratio	Minimum compaction

road bed	5%	96%
lower bed	4%	96%
embankment	3%	96%
lower embankment	3%	95%

4. Conclusion

In this paper, for a highway project in loess area, cement is used to improve loess and then applied to roadbed filling. The indoor test is used to study the physical and mechanical parameters of improved loess with different cement dosage, combined with the mechanical index requirements of different layers of the roadbed in accordance with the specification, to explore the cement dosage of different layers of the roadbed to meet the specification requirements, and to provide engineering examples to support the reinforcement and filling of the roadbed of the highway in loess area . This paper mainly draws the following conclusions:

（1）Uncemented plain loam does not meet the specification requirements for *CBR* for all layers of the roadbed under minimum compaction.

（2）Cement as an improved loess roadbed admixture can significantly improve the mechanical and deformation properties of loess; the degree of improvement is related to the cement admixture, within a certain admixture range, the greater the cement admixture, the greater the mechanical and deformation properties of improved soil.

（3）The *CBR* value, the design value of the modulus of rebound of the roadbed E_0 meets the specification requirements when 96% of the specification's minimum compaction requirements for the upper roadbed are met at a cement admixture of 5%.

（4）The *CBR* value meets the specification requirements for minimum compaction of the upper embankment at 96% of the specification requirements at 3% cement dosing.

（5）In order to achieve a good transition between the upper roadbed and the rigid upper embankment, a cement mix of 4% is recommended and meets the specification's compaction requirements for the lower roadbed.

（6）This paper is based on the loess roadbed filling of a highway, considering the environmental conditions of the project as well as the traffic loading level, cement doping and improvement of loess, and the conclusions formed are really reliable. Other environmental areas and different traffic load levels can be based on the specification of each structural layer of the resilience modulus requirements, the use of different cement mixing.

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