Analysis of Mechanical Properties of Loess with Cement Incorporation Ratio

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Abstract: Taking loess as the research object, the influence of cement content on mechanical properties of loess was studied. Firstly, the basic physical parameters of loess were obtained through laboratory physical index test, and improved by using Portland cement. Secondly, under different incorporation ratios (3%, 5%, 7%, 9%), heavy compaction test and liquid-plastic limit test were carried out respectively to obtain mechanical parameters of cement-improved loess. Finally, the shear strength parameters and compressive strength of the improved soil samples are obtained by unconsolidation undrained triaxial shear test and unconfined compressive strength test. The results show that the liquid limit, plastic limit and plastic index of loess improved by adding cement increase compared with the original soil sample, indicating that the binding force between soil particles is improved and the plasticity is enhanced. The variation range of dry density and water content has no obvious relationship with the content of cement. At the same time, the compressibility of soil is reduced and the collapsibility of soil is eliminated. With the increase of age, the strength of cement-modified soil also increases. Through unconsolidated and undrained triaxial shear tests and unconfined compressive strength tests, the strength of loess improved significantly after adding cement, and the strength of soil-cement increased with the increase of cement content, and water stability was obviously improved.

Keywords: Loess; Cement incorporation ratio; Mechanical properties.

1. Introduction

Loess refers to the yellow silt deposits transported by wind during the Quaternary Geological Age. There is a certain regularity in geographical distribution, mainly distributed in Shaanxi, Henan, Gansu and other regions. In soil classification, loess is often classified as "special soil", which is mainly attributed to two aspects. On the one hand, loess not only has strong hydrophilicity, adheres to the particle skeleton, but also has swelling and shrinking properties. Due to water swelling, the soil structure is softened, and the bonding capacity between particles is weakened, which improves the compressibility and strength of the soil. reduce. On the other hand, loess in its natural state has the characteristics of large void ratio and low density. When it encounters water, it will collapse rapidly, drop in strength, and increase in deformation[1].

Loess is widely distributed in China, especially in collapsible areas. Once it meets rain weather, a large amount of water penetrates into the soil, making the pore water pressure in the soil rise continuously, while the strength of the soil decreases continuously, which is easy to induce landslides, road subgrade collapse, uneven settlement of the foundation and other engineering accidents. Therefore, a large number of scholars have carried out research on the mechanical properties of loess. Du Jingfang[2] studied the variation rules of compression characteristics, shear strength and permeability of loess under dry-wet cycle through direct shear test. The experimental results show that the shear strength and its parameters decrease with the increase of the number of drying and wetting cycles and moisture content, and increase with the increase of moisture content. Wei Yao et al.[3] analyzed the influence of freezing temperature on mechanical properties of freezing-thawing loess by testing its unconfined compressive strength, shear strength and compressibility under different freezing temperatures. The test results show that the unconfined compressive strength of loess with different moisture content decreases after freezing-thawing at different freezing temperatures, and the cohesion of soil with different moisture content decreases with the decrease of freezing temperature. Fei Xiaoou et al.[4] conducted experimental studies on mechanical properties such as pore pressure dissipation and different water content in order to study the failure mechanism of loess foundation in the dump of open-pit coal mine under large area loading. The results show that the shear strength of loess decreases greatly with the increase of water content, and the change of water content and cohesion is log-linear. The dissipation degree of pore water pressure decreases with the increase of confining pressure, and the dissipation coefficient increases with the increase of water content, and presents the embrittlement failure phenomenon at low confining pressure. Shoubang Sun et al.[5] compared the vertical and horizontal shear strength differences of intact Q_4 loess samples through triaxial and direct shear tests. The results show that the shear strength of surrounding rock of Q_4 loess has obvious anisotropy. The internal friction angles of loess are basically the same in different directions. The vertical strength is generally greater than the horizontal strength. Leng Yanqiu et al.[6] studied the variation rules of structural strength, deformation modulus and strength parameters of intact loess under different moisture content through measuring instrument test and triaxial shear test. It is found that the yield stress, initial deformation modulus and cohesion of structure are sensitive to the water content. With the increase of initial water content, the yield stress, initial deformation modulus and cohesion of structure decrease by power function or exponential function. Kui Liu et al.[7] studied the effects of dry density and water content on mechanical properties of loess through shear strength and compressibility tests, and the results showed that: the lower the water content, the greater the impact of dry density change on cohesion. With the same dry density, the internal friction Angle of compacted loess decreases with the increase of water content. Xiangtian Xu et al.[8] studied the influence of water content on strength, stiffness and damage characteristics of frozen loess through triaxial compression and cyclic loading and unloading tests. The test results show that moisture content of frozen soil is an important factor affecting damage parameters during deformation. The effects of confining pressure on mechanical and damage properties of frozen loess are sensitive, indicating that the effects of water content and confining pressure are coupled. Taking loess as the research object, Shi Chang 'an[9] studied the influence of freezing-thawing cycle on mechanical properties of loess through triaxial test. The results show that the strength of soil decreases with the increase of the number of freezing-thawing cycles, and the influence on the strength decreases with the increase of the number of freezing-thawing cycles. When the water content is constant, the cohesion of loess decreases and the internal friction Angle decreases with the increase of freezing-thawing cycles.

In recent years, loess is the foundation of the industrial development in northwest China, as well as the source and basic conditions of building materials for highway transportation, water conservancy facilities and civil and industrial construction. In order to improve the strength of loess and meet the characteristics of compressibility, permeability and durability, the improved method is often used to meet the needs of practical engineering[10]. Therefore, a large number of scholars have carried out research on soil improvement. Wang Yimin et al.[11] analyzed the physical and mechanical properties of cement-improved loess based on the strict requirements for filling of high-speed railway roadbed and laboratory tests, and studied the influence of different cement content and curing age on strength growth. The results show that the maximum dry density and compression coefficient of Q_3 cement-improved loess decrease with the increase of incorporation ratio, and the unconfined compressive strength increases with the increase of incorporation ratio. In dry-wet cycle, 5% cement-improved loess has the best stability. Ma Xuening et al.[12] studied the compaction characteristics, compression characteristics, strength characteristics and influencing factors of cement-improved loess through a large number of geotechnical tests and theoretical analysis. The results show that the shear strength and unconfined compressive strength of cement-improved loess are affected by density, mass ratio and age, and the strength value increases with the increase of mass fraction of cement content. Zhang Yabin et al.[13] studied the compaction characteristics, strength characteristics and dry-wet cycling effects of cement-improved loess through a large number of laboratory tests. The results show that with the increase of cement content, the optimal water content of cement-improved loess increases and the maximum dry density decreases. When the cement content is low, the strength of cement-modified loess increases obviously. The strength growth rate of cement-improved loess slows down when the cement content is higher. With the increase of the number of dry and wet cycles, the strength of cement-improved loess will slightly decrease or slightly increase, but the range of change is not drastic, and its strength tends to be stable. Jia Ding Wang et al.[14] studied the influence of cement mixing ratio on the dynamic characteristics of cement-improved loess through dynamic triaxial test. The results show that with the increase of cement content, the dynamic characteristics of modified loess become better, and there is no optimal cement content. Taking loess as the research object, He Xiaoliang et al.[15] used GDS dynamic triaxial apparatus to conduct progressive triaxial test on loess after cement improvement, and studied the variation law of cement improvement loess deformation with cement ratio under locomotive vibration load. The results show that with the increase of cement proportion, the vibration subsidence of loess decreases obviously. The vibration subsidence of cement-improved loess increases gradually with the increase of vibration times. When the vibration times exceeds 3000 times, the vibration subsidence basically becomes stable. Guo Xing et al.[16] took loess as the research object and carried out cement soil improvement test on it. The test results show that the maximum dry density, optimal water content and compression coefficient of the improved soil are affected by the cement content. With the increase of cement content, the maximum dry density and compression coefficient decrease while the optimal water content increases. Lang Weijun et al.[17] took highway subgrade in Loess region of Qinghai as the research object and analyzed water content, compactness and settlement observation of cement improved subgrade through tests. The results show that 6% cement-soil ratio meets the construction control requirements, indicating that the construction of cement improved roadbed in loess area has good applicability and reliability. Jiang Yingjun et al.[18] studied the influence of cement dosage, compaction coefficient and health preservation age on the stability of cement improved loess subgrade in order to reveal the factors influencing the stability of cement improved loess subgrade. The results show that the compressive strength of the improved loess increases linearly with the increase of cement dosage or compaction coefficient under dry-wet and freeze-thaw conditions, respectively. When the number of dry-wet cycles is more than 15 times, the number of freeze-thaw cycles is more than 12 times, and the cement dose is more than 3%, the compressive strength of the improved loess tends to be stable. Necmi Yarbasi et al. [19] respectively conducted freezing-thawing cycle tests on improved soils mixed with lime, cement and fly ash, and from the test results and data, they believed that the frost resistance and durability of the three improved soils were effectively improved.

By summarizing the research results of the above scholars, it is not difficult to find that the improvement of loess with cement can improve its water stability, improve its strength, reduce its permeability, and avoid the occurrence of engineering accidents. At the same time, it has important theoretical and practical significance in engineering. In this paper, the influence of cement content on mechanical properties of loess was studied by compaction test, liquid-plastic limit test, consolidation test, collapsibility test, triaxial test and unconfined compressive strength test.

2. Physical Property

Loess is non-saline soil, and its physical parameters are shown in Table 1 through indoor parameter test. Grade 32.5 ordinary Portland cement is used for cement, and the physical and mechanical indexes are shown in Table 2.

Table 1 Physical parameters of loess

Liquid limit/%	Plastic limit/%	Plasticity index	Maximum dry density/(g/cm^3)	Optimum water content/%
29.2	19.8	9.4	1.880	14.3

Table 2 Physical and mechanical indexes of ordinary Portland cement

Fineness	Ignition loss	Stability	Setting time		Compressive strength/MPa		Flexural strength/MPa	
			Initial set	Final set	3d	28d	3d	28d
≤ 10%	≤ 5.0%	Normal	≥ 45min	≤ 10h	11.0	32.5	2.5	5.5

3. Mechanical Analysis

The methods of loess improvement mainly focus on physical improvement and chemical improvement. Physical improvement is to join the coarse particle in loess and the use of dynamic compaction, the compaction pile method such as physical soil compaction method to change the internal grain size distribution, particle arrangement and contact, increase the contact area between particles and reduce the pore volume, make the internal structure of soil tend to be more compact, thus achieve permeability, such as improving strength improvement purpose. Chemical modification is to improve the stability and strength of loess by adding a certain modifier to the loess, using the effect of modifier and water and the chemical reaction with soluble salt in the loess, to produce cementing material to fill the pores, change the soil particle composition and spatial structure, so as to improve the stability and strength of loess engineering properties. The commonly used improvers are mainly cement, lime, fly ash and other materials [20-23] to reduce the permeability of loess and improve its strength.

Cement as a powdery hydraulic inorganic cementitious material, mixed with water into slurry, hardening in air or hardening in water, and the sand, stone and other materials firmly cemented together. Therefore, cement as a modifier, not only low cost, economic and environmental protection, and significant improvement effect, is widely used in construction engineering, water conservancy engineering and traffic engineering and other special construction in the engineering field. Since this paper studies the influence of cement content on mechanical properties of loess, it will be analyzed through the following tests [24] :

(1) Heavy compaction test and liquid plastic limit test were carried out by adding cement into loess at the rate of 3%, 5%, 7% and 9% respectively.

(2) Improved soil specimens with corresponding density were prepared by pressing 95% compacting method and kept in a constant temperature and humidity curing box (chamber) with a temperature of 20±2℃ and humidity >90%. After keeping in good health, their compression coefficient, compression modulus and collapsibility coefficient were measured.

(3) Modified soil specimens with the corresponding density were prepared by pressing 95% compacty by hydrostatic method. The specimens were kept in a constant temperature and humidity curing box (chamber) with a temperature of 20±2℃ and humidity >90%, and their unconsolidated and undrained triaxial shear strength was measured after 28 days of curing.

(4) 39.1×80 mm specimens were prepared by pressing 95% compactness method, kept in a constant temperature and humidity curing box (chamber) with a temperature of 20±2℃ and humidity >90%, and their water-soaked and unconfined compressive strength without water-soaked for 7 days were measured (water-soaked means that the specimens were taken out one day before they reached age. The specimen was immersed in water at a temperature of 20 ±2℃ for 24h).

3.1 Beating Experiment

Beating experiment is a basic method to study the compactability of fine grained soil in laboratory. The dry density and moisture content of the soil samples were measured by heavy-duty compactor. By changing the moisture content and repeating the test, the compaction curve is obtained and the maximum dry density and optimal water content of soil samples are obtained, among which the maximum dry density and optimal water content are the necessary conditions for controlling the quality of subgrade filling. The results of compaction test are summarized in Table 3.

Table 3 Results of compaction test and liquid plastic limit test

Soil sample	Liquid limit/%	Plastic limit/%	Plasticity index	Maximum dry density/(g/cm^3)	Optimum water content/%	Dry density /(g/cm^3)	Dry unit weight /(kN/m^3)
3% cement soil	35.7	22.7	13.0	1.900	14.3	1.805	17.689
5% cement soil	36.5	22.8	13.7	1.902	14.3	1.807	17.708
7% cement soil	37.1	23.6	13.5	1.880	14.4	1.786	17.503
9% cement soil	39.5	25.8	13.7	1.900	14.3	1.805	17.689

3.2 Liquid Limit-Plastic Limit Joint Test

Liquid limit is the limit water content of soil sample when it transitions from plastic state to flowing state. Plastic limit is the limit water content of soil sample from plastic state to semi-solid state. Liquid and plastic limits are important physical characteristics of clay and reflect the degree of interaction between soil particles and water. In engineering practice, the exact value of liquid-plastic limit index directly affects the determination of soil name and bearing capacity of corresponding soil foundation, and indirectly reflects the engineering properties of soil samples. The liquid limit, plastic limit and plastic index of the modified filler were obtained through the liquid plastic limit test. The results of liquid plastic limit test are summarized in Table 3, in which the dry density is 95% of the maximum dry density.

It can be seen from Table 3 that the change of maximum dry density and optimal water content is not obvious after the loess is mixed with different cement content. The liquid limit and plastic limit of the improved soil increased with the increase of cement content, and both increased compared with the original soil sample, indicating that the adhesion between soil particles was improved and the plasticity was enhanced after the addition of cement. The plasticity of the improved loess with 9% cement content was the strongest.

3.3 Consolidation Test, Loess Collapsibility Test

Consolidation test refers to the compression test to determine the saturated clay sample under the condition of confining pressure. Compressibility of soil is mainly caused by the reduction of pore volume. Therefore, the relationship between pressure and sample deformation or pore ratio is measured through consolidation test, so as to calculate the compression coefficient and compression modulus of soil sample. The test results are shown in Table 4.

Loess collapsibility is the process of loess compression and collapsibility deformation under certain pressure and water immersion. The collapsibility coefficient of loess can be obtained through loess collapsibility test, and the results are shown in Table 4.

Table 4 Results of consolidation test and loess collapsibility test

Soil sample	Degree of compaction /%	Curing age：1d			Curing age：7d		
		Compression coefficient /MPa-1	Compression modulus /MPa	Collapsible coefficient	Compression coefficient /MPa^{-1}	Compression modulus /MPa	Collapsible coefficient
Original soil sample		0.18	10.6	0.026			
Compaction of soil samples	95	0.10	15.0	0.000	0.09	16.2	0.000
3% cement soil	95	0.06	24.9	0.000	0.05	30.2	0.000
5% cement soil	95	0.06	24.9	0.000	0.05	30.1	0.000
7% cement soil	95	0.06	25.1	0.000	0.05	30.9	0.000
9% cement soil	95	0.07	21.3	0.000	0.05	30.2	0.000

It can be seen from Table 4 that, compared with the original soil sample, the compression coefficient of the improved soil sample decreases and the compression modulus increases after adding a certain proportion of cement, indicating that the compressibility of the improved soil sample decreases. Meanwhile, the collapsibility of the improved soil sample is eliminated, and the relationship between the change range and the dosage is not obvious. With the increase of health age, the compression coefficient decreases and the compression modulus increases with the same cement content, indicating that the strength of cement improved soil increases slightly.

3.4 Unconsolidated and undrained triaxial shear test

The unconsolidated and undrained shear test, also known as the fast shear test, does not allow the sample to drain during the process of applying confining pressure and increasing axial pressure until the specimen is broken. The shear strength parameters, namely c and φ, can be obtained through the test. The index parameters of soil shear strength are an important index to determine the bearing capacity of soil. Therefore, it is of great significance to accurately measure the index parameters of soil shear strength for engineering design and construction. The results of unconsolidated and undrained triaxial shear test are summarized in Table 5.

It can be seen from Table 5 that the modified loess specimen prepared by pressing 95% compaction was kept in a curing box (chamber) with a temperature of 20±2℃ and humidity >90% for 28 days, and the internal friction Angle and cohesion increased with the increase of cement content. Among them, the shear strength parameters of the modified loess with 9% cement content were the maximum.

Table 5 Results of unconsolidated and undrained triaxial shear test

Soil sample	Degree of compaction/ %	Curing age/d	Internal friction angle/ (°)	Cohesion/ (kPa)
Original soil sample			31.2	21
Compaction of soil samples	95	28	35.6	34
3% cement soil	95	28	34.3	214
5% cement soil	95	28	30.5	437
7% cement soil	95	28	42.4	442
9% cement soil	95	28	44.7	553

3.5 Unconfined Compressive Strenght Test

The unconfined compressive strength test is a special case of the triaxial test, that is, the soil sample is subjected to the pressure test under the condition of no lateral limitation, so as to obtain the ultimate strength of resisting axial pressure, that is, the unconfined compressive strength. The unconfined compressive strength test results are summarized in Table 6.

Table 6 Unconfined compressive strength test results

Soil sample	Degree of compaction/%	Curing age/ d	Unconfined compressive strength during immersion/kPa	Unconfined compressive strength without flooding /kPa	Strength degradation /%
Original soil sample			0	100	100
Compaction of soil samples	95	7	0	387	100
3% cement soil	95	7	816	1360	40
5% cement soil	95	7	999	1461	32
7% cement soil	95	7	1341	1651	19
9% cement soil	95	7	1559	1919	19

As can be seen from table 6, under the condition of 95% compaction degree, the unconfined compressive strength of cement-improved soil under standard curing, dry-wet cycle and saturation conditions for 7 days increases significantly with the increase of cement content, and the attenuation rate of strength decreases gradually, that is, the water stability gradually increases. After soaking for 24h, the unconfined compressive strength attenuates by 19% ~ 40%, except that the strength attenuating rate of the modified soil mixed with 3% cement is slightly higher, the other attenuation rates are relatively small. Among them, the improved soil sample with 9% cement content has the maximum unconfined compressive strength and the minimum strength attenuation, both after soaking and without soaking, indicating the strongest water stability.

4. Conclusion

In this paper, loess is taken as the research object. Firstly, the basic physical parameters of loess are obtained through laboratory physical parameter test. Secondly, the loess was modified by adding different doses of cement (3%, 5%, 7%, 9%). The mechanical parameters of the loess were measured by compaction test, liquid-plastic limit test, consolidation test, collapsibility test, triaxial test and unconfined compressive strength test. Finally, the influence of cement content on mechanical properties of loess is studied through data analysis. The results show that:

(1) The liquid limit, plastic limit and plastic index of the loess improved by adding cement increased compared with the original soil sample, indicating that the binding force between soil particles was improved and the plasticity was enhanced. The variation range of dry density and water content had no obvious relationship with the content of cement.

(2) After adding cement to loess, the compressibility of soil is reduced and the collapsibility is eliminated; With the increase of age, the strength of cement-modified soil also increases.

(3) The unconsolidated and undrained triaxial shear test shows that the strength of loess improved significantly after adding cement, and the strength of soil-cement increases with the increase of adding cement.

(4) The unconfined compressive strength test shows that the water stability of loess improved by adding cement is obviously improved.

In conclusion, after adding a certain proportion of ordinary Portland cement into the loess, the properties of the soil are greatly improved, which can improve the strength and water stability of the soil, reduce the compressibility of the soil, and eliminate the soil collapsibility.

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