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Analysis of influence factors of unconfined compressive strength for composite soil stabilizer-stabilized gravel soil

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Abstract: In order to investigate the effect of some factors on the unconfined compressive strength (UCS) for composite soil stabilizer-stabilized gravel soil (CSSSGS), the orthogonal test is adopted to set up the experimental scheme. Three levels of each factor are considered to obtain the change laws of UCS, in which the binder dosages are 8%, 10%, and 12%; the curing times are 7, 14 and 21 d; the gradation *n* are 0.3, 0.35 and 0.4; and the degrees of compaction are 95%, 97%, and 99%. The range analysis clearly indicates that the influence degree of the four factors on UCS is in such an order: dosage, age, gradation, and degree of compaction. The variance analysis shows that only the composite soil stabilizer dosage can significantly affect UCS. In road construction, the examination of composite soil stabilizer dosage and base-course maintenance should be given much more attention to obtain satisfactory base-course strength, compared with gradation floating and the change of degree of compaction.

Key words: base course; composite soil stabilizer; gravel soil; unconfined compressive strength; orthogonal test
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Cement and crushed stone as base-course materials are commonly used in road construction in China. However, the production of cement and crushed stone has brought serious problems, such as pollution, energy consumption and breaking of the ecological balance. In order to overcome these problems, new alternative materials must be found to ensure the sustainable development of road construction.

Making a full use of local materials can lead to low-cost construction, especially for the local population. Soil-stone mixture is a common geological body, which can be seen everywhere in China. Natural gravel soil is widely distributed in China, especially in the southwest area of China, such as Guangxi, Sichuan and Yunnan provinces[1]. If natural gravel soil, a local material, can be used as a base or sub-base course material, it will save much construction funds, and reduce the use of good-quality crushed stone[2].

Cement and lime are commonly used to improve the engineering properties of soils, which exhibit significant changes in behavior under fluctuating environmental conditions. Unfortunately, the production of cement and lime needs to consume a large amount of energy and releases the high levels of greenhouse gases, poisonous gases, and dust. Therefore, supplementary cement-materials, such as fly ash, slag, and cement kiln dust, have been investigated to replace cement and lime to stabilize soils or granular materials. Existing research shows that the addition of fly ash to cement-stabilized soil, replacing 10% cement, can achieve the same stabilizing effect of soils[3-5]. Furthermore, the engineering properties of soils and crushed stone can also be significantly improved by cement-lime-fly ash. On the other hand, polymers have been studied to enhance soils, and the stabilizing effect is obvious[6-7]. Some polymers used for road construction can improve the hydrophilia of clay particles and stabilize the clay particles by filling the void of soil particles and connecting the soil particles as a whole[8].

In general, the unconfined compressive strength (UCS) is used as an indicator for designing the material mixtures of the road base or sub-base course in China. The base course should have sufficient strength to support the surface course, especially when the pavement is subject to traffic loads and fluctuating environmental conditions (i.e., moisture and temperature). Many factors can affect the UCS of the base course, such as the binder content, curing time, and degree of compaction, which relate to mixture design and road construction. The UCS of cement-stabilized fly ash-soil mixtures increased with the increase of curing time[9]. The variations in UCS of the stabilized fly ash bases were studied, considering curing conditions and other factors, namely, cement content, curing period, immersion, unit weight, water content, and methods of curing adopted during climatic seasons[10]. For cement-treated aggregate base materials, the

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effects of different aggregates (recycled concrete and crushed limestone), gradations, cement contents and curing times on UCS were investigated[11]. Previous studies indicated that the density has a significant impact on the UCS of cementitiously stabilized pavement materials, but the effect of different compaction methods, such as proctor and gyratory compaction methods, on UCS is not obvious[12]. The variables, namely cement content, curing time, moisture content, and dry density, can affect the development of UCS of soil-cement mixtures[13]. From the existing research, there are many factors that can affect the UCS development. However, the relative degrees of importance of these factors are not clear.

With the purpose of reducing the use of cement, the composite soil stabilizer (CSS) containing cement clinker, quick lime, fly ash and polymer is adopted in this study to stabilize natural gravel soil. However, for composite soil stabilizer-stabilized gravel soil (CSSSGS), the influence of these factors and the relative degrees of importance of these factors are not completely clear.

The factors affecting UCS of CSSSGS mainly involve the content of composite soil stabilizer (A), graduation (B), curing time (C) and degree of compaction (D) during base-course mixture design and construction. This paper presents a laboratory investigation of these factors on UCS of CSSSGS based on the orthogonal test. The experimental data are processed by the range analysis and variance analysis. By the analysis of the results of orthogonal experiment, the changes in UCS of CSSSGS due to various factor levels are obtained and the relative degrees of importance of these factors are established. In addition, the results and conclusions can be used for guiding the mixture design and construction of the road base.

1 Laboratory Experiments

1.1 Raw materials

The composite soil stabilizer used in this study contains 45% cement clinker, 15% quicklime, 30% fly ash and 10% polymers (by weight), as shown in Fig. 1. The technical indices in Ref. [14] are determined, and the test results are shown in Tab. 1.

Fig. 1 Composite soil stabilizer

Tab. 1 Basic technical properties of composite soil stabilizer

Property	Requirement in Ref. [14]	Test result	Test method
Appearance		Gray powder	
Fineness/%	≤15	0.8	Ref. [15]
Loss of UCS in initial setting time/%	≤10	7.2	Ref. [16]
Soundness	No crack	Qualified	Ref. [14]

The natural gravel soil used in these tests is taken from the city of Yulin, Shaanxi Province. Sieve analysis of the natural gravel soil is conducted according to Ref. [17], and the results are shown in Fig. 2. Other technical indices are determined according to Refs. [17 − 18], and the testing results show that the classification of the natural gravel soil is GC, as shown in Tab. 2.

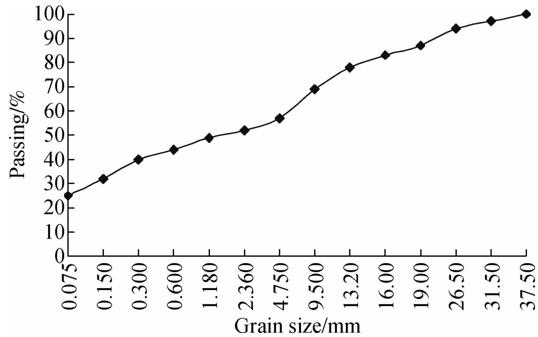

Fig. 2 Grain-size distribution curve of the natural gravel soil

Tab. 2 Technical indices of the natural gravel soil

Crushing value/%	Liquid limit/%	Plastic limit/%	Plasticity index
27.3	20.3	14.7	5.6

In this study, the stabilized material has a maximum size of 37.5 mm. Gradation was selected as one factor, and three gradations were designed in this study, which should meet the requirements of Ref. [19] for the gradation range of gravel soil, as shown in Fig. 3. The gradations are calculated by

$$P = 100\left(\frac{d}{D}\right)^n \tag{1}$$

where P is the percentage passing d sieve; d is the size of the current sieve; D is the maximal size of aggregate; n is the exponent of the equation. Usually, when n ranges

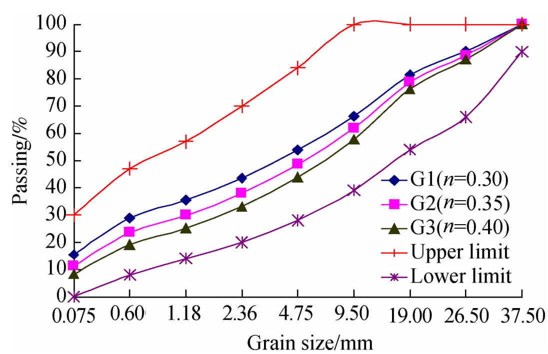

Fig. 3 Three gradations designed for natural gravel soil

from 0.3 to 0.5, the higher compactness of the mixture can be obtained[20]. In order to make a full use of fines in natural gravel soil, 0.3, 0.35 and 0.4 are adopted for n, and three gradations are designed, namely, G1, G2 and G3 (see Fig. 3).

1.2 Experimental scheme

There are four factors considered for UCS in this study, and the orthogonal test is used to find the main controlled factors and their influence law. According to Ref. [19], the UCS requirement of low grade highway is 3 to 5 MPa, and the target UCS is designated as 4 MPa. Based on G1, the optimal dosage of the composite soil stabilizer is 10%. Therefore, three binder contents (8%, 10% and 12%) are adopted. According to Ref. [19], the minimum requirements of curing time and degree of compaction are 7 d and 97%. Consequently, considering the actual construction, nine groups tests according to the orthogonal table are arranged, as shown in Tab. 3.

Tab. 3 Scheme of orthogonal test

Group number	Content of CSS/%	Graduation	Curing time/d	Degree of compaction/%
1	8	G3	7	95
2	8	G2	14	97
3	8	G1	21	99
4	10	G3	14	99
5	10	G2	21	95
6	10	G1	7	97
7	12	G3	21	97
8	12	G2	7	99
9	12	G1	14	95

According to the scheme of the orthogonal test and Ref. [16], the optimum moisture content (OMC) and maximum dry density (MDD) are determined, and the results are shown in Tab. 4.

Tab. 4 Results of compaction test

Group number	OMC/%	MDD/(g · cm^{-3})	Group number	OMC/%	MDD/(g · cm^{-3})
1	7.1	2.231	6	7.6	2.188
2	7.3	2.203	7	7.4	2.222
3	7.4	2.197	8	7.5	2.191
4	7.2	2.226	9	7.7	2.181
5	7.4	2.195			

1.3 Specimens preparation and testing procedures

Initially, the air-dried gravel soil was mixed with the predetermined quantity of water, and then the mixture was put into plastic bag for infiltrating about 4 h. Next, the predetermined quantity of composite soil stabilizer was added to the mixture and thoroughly mixed. Cylindrical specimens (150 mm in diameter and 150 mm in height) were prepared by the static compaction method according to Ref. [16] with 95%, 97% and 99% MDD. The specimens were manufactured under strain-control at a loading speed of 1 mm/min. All the specimens were demoulded 2 h after the completion of compaction and stored in a curing room (maintained at (20 ± 2) ℃, no less than 95% RH) wrapped in plastic bags. The curing time were 7, 14 and 21 d.

At the end of curing times, the specimens were soaked in water for 24 h. Afterwards, the specimen was put on the test machine to determine the UCS. The UCS test was carried out by a testing machine under strain-control at a loading speed of 1 mm/min according to Ref. [16]. The specimens and testing apparatus for UCS test are shown in Fig. 4. UCS is calculated by

$$R_c = \frac{P}{A} = \frac{4P}{\pi D^2} \tag{2}$$

where R_c is the UCS; P is the maximum pressure at failure; and D is the diameter of the specimen. Each set includes thirteen specimens, and the average value is adopted as the test value.

Fig. 4 Specimens and testing apparatus

2 Results and Discussion

2.1 Unconfined compressive strength

Tab. 5 shows the results of UCS tests with various influence factors.

Tab. 5 Results of UCS tests

Group number	$\overline{R_c}$/MPa	Standard deviation/MPa
1	4.3	0.56
2	4.6	0.51
3	4.8	0.58
4	5.7	0.68
5	5.7	0.74
6	4.7	0.49
7	6.5	0.90
8	5.6	0.73
9	5.5	0.61

2.2 Range analysis

Although range analysis is rough, the operation is convenient and simple. From the range analysis results, two important information points can be obtained: 1) The importance of different factors; 2) The influence law of factor levels on the evaluation index[21]. The range analysis results are shown in Tab. 6.

Tab. 6 Range analysis results of orthogonal test

Group number	Content of CSS/%	Graduation	Curing time/d	Degree of compaction/%	$\overline{R_c}$/MPa
1	8	G3	7	95	4.3
2	8	G2	14	97	4.6
3	8	G1	21	99	4.8
4	10	G3	14	99	5.7
5	10	G2	21	95	5.7
6	10	G1	7	97	4.7
7	12	G3	21	97	6.5
8	12	G2	7	99	5.6
9	12	G1	14	95	5.5
I_j	13.7	16.5	14.6	15.5	
II_j	16.1	15.9	15.8	15.8	
III_j	17.6	15.0	17.0	16.1	
$\mathrm{I}_j/3$	4.6	5.5	4.9	5.2	
$\mathrm{II}_j/3$	5.4	5.3	5.3	5.3	
$\mathrm{III}_j/3$	5.9	5.0	5.7	5.4	
R_j	1.3	0.5	0.8	0.2	

In Tab. 6, I_j is the sum of UCS values for level 1 in j ($j = 1, 2, 3$ or 4) column. II_j and III_j are similar to I_j. R_j is the differences between the maximum and minimum value of $\mathrm{I}_j/3$, $\mathrm{II}_j/3$ and $\mathrm{III}_j/3$. $\mathrm{I}_1 = 4.3 + 4.6 + 4.8 = 13.7$, $\mathrm{I}_2 = 4.3 + 5.7 + 6.5 = 16.5$, $\mathrm{I}_3 = 4.3 + 4.7 + 5.6 = 14.6$, $\mathrm{I}_4 = 4.3 + 5.7 + 5.5 = 15.5$, $\cdots$, $\mathrm{III}_1 = 6.5 + 5.6 + 5.5 = 17.6$, $\mathrm{III}_2 = 4.8 + 4.7 + 5.5 = 15.0$, $\mathrm{III}_3 = 4.8 + 5.7 + 6.5 = 17.0$, $\mathrm{III}_4 = 4.8 + 5.7 + 5.6 = 16.1$. $R_1 = 5.9 - 4.6 = 1.3$, $\cdots$, $R_4 = 5.4 - 5.2 = 0.2$.

2.2.1 Importance analysis of factors

R_j reflects the fluctuation of data. It can be seen from Tab. 6 that when dosage and age change, the UCS significantly changes. However, the rangeability of UCS is less for gradation and degree of compaction compared with dosage and age. Intuitively, the importance of the factors can be estimated according to the values of R_j: A > C > B > D. It can be concluded that the control of soil stabilizer dosage and maintenance of the base course should be paid more attention to with the purpose of obtaining sufficient strength. In addition, the sorting of test factors is mainly dependent on the selection of factor levels. So, varying the levels of factors can cause the changes in the order of test factors.

2.2.2 Influence of factor levels on unconfined compressive strength

In addition to obtaining the order of test factors, road researchers also hope to understand the impact of the changes of factor levels on the strength index (increase or decrease). Fig. 5 shows the relationship between the factor levels and UCS, based on range analysis.

The UCS increases with the increase of composite soil stabilizer dosage. When the dosage level changes from 1 to 2 (from 2 to 3), the growth rates of UCS are 17.4% (9.3%). The coarser gradation can lead to higher UCS. The UCS also increases with the increase of curing time and degree of compaction. The growth rates of UCS are 8.2% and 7.5%, respectively, when the curing time increases from 7 to 14 d, and from 14 to 21 d. However, when the degree of compaction increases from 95% to 97%, and from 97% to 99%, the growth rates are 1.9% and 3.8%, respectively.

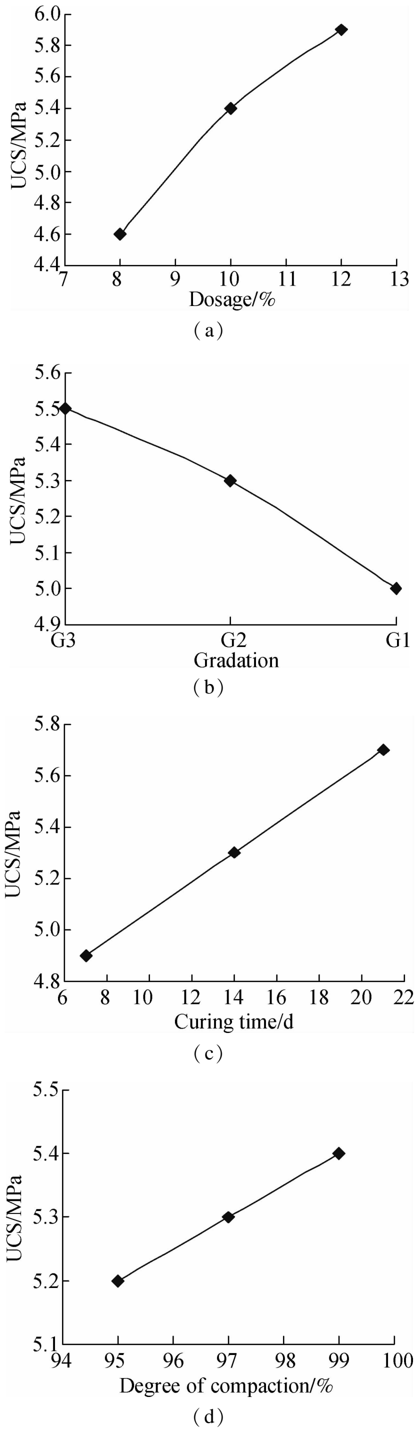

Fig. 5 Range analysis. (a) Relationship between dosage and UCS; (b) Relationship between gradation and UCS; (c) Relationship between curing time and UCS; (d) Relationship between degree of compaction and UCS

2.3 Variance analysis

In this orthogonal test, there are four factors and the orthogonal experiment table $L_9(3^4)$ is adopted. So, there is no error column. The sum of squares of deviations of factor A(B, C or D) shows the effect of factor A(B, C or D) on the total sum of squares of deviations. In order to make variance analysis, the fourth column (factor D) is selected as the error column since the sum of squares of deviations of factor D is the smallest[21]. The results of variance analysis are shown in Tabs. 7 and 8.

Tab. 7 Calculation process of variance analysis

Group number	Content of CSS/%	Graduation	Curing time/d	Degree of compaction/%	$\overline{R_c}$/MPa	Square
1	8	G3	7	95	$Y_1=4.3$	$Y_1^2=18.49$
2	8	G2	14	97	$Y_2=4.6$	$Y_2^2=21.16$
3	8	G1	21	99	$Y_3=4.8$	$Y_3^2=23.04$
4	10	G3	14	99	$Y_4=5.7$	$Y_4^2=32.49$
5	10	G2	21	95	$Y_5=5.7$	$Y_5^2=32.49$
6	10	G1	7	97	$Y_6=4.7$	$Y_6^2=22.09$
7	12	G3	21	97	$Y_7=6.5$	$Y_7^2=42.25$
8	12	G2	7	99	$Y_8=5.6$	$Y_8^2=31.36$
9	12	G1	14	95	$Y_9=5.5$	$Y_9^2=30.25$
I_j	13.7	16.5	14.6	15.5	$K=47.4$	$W=253.62$
II_j	16.1	15.9	15.8	15.8		
III_j	17.6	15.0	17.0	16.1		
U	$U_A=252.22$	$U_B=250.02$	$U_C=250.60$	$U_D=249.70$	$P=249.64$	
Q	$Q_A=2.58$	$Q_B=0.38$	$Q_C=0.96$	$Q_D=0.06$		

Tab. 8 Results of variance analysis

Factors	Dispersion	Degree of freedom	Mean square deviation	F-value
A	$Q_A=2.58$	2	$S_A^2=Q_A/2=1.29$	$F_A=S_A^2/S_E^2=43$
B	$Q_B=0.38$	2	$S_B^2=Q_B/2=0.19$	$F_B=S_B^2/S_E^2=6.3$
C	$Q_C=0.96$	2	$S_C^2=Q_C/2=0.48$	$F_C=S_C^2/S_E^2=16$
D(considered as error)	0.06	2	0.03	
Error	$Q_E=0.06$	2	$S_E^2=Q_E/2=0.03$	
Total	$Q_T=3.98$	8		

$$K=\sum_{i=1}^{9} Y_i,\quad P=\frac{1}{9}K^2,\quad W=\sum_{i=1}^{9} Y_i^2$$
$$U_A=1/3[(I_1)^2+(II_1)^2+(III_1)^2]$$
$$U_B=1/3[(I_2)^2+(II_2)^2+(III_2)^2]$$
$$U_C=1/3[(I_3)^2+(II_3)^2+(III_3)^2]$$
$$U_D=1/3[(I_4)^2+(II_4)^2+(III_4)^2]$$
$$Q_A=U_A-P\quad Q_B=U_B-P\quad Q_C=U_C-P$$
$$Q_D=U_D-P\quad Q_T=W-P$$

where Y_i is the average value of UCS for each group; Q_T is the total sum of squares of deviations.

For $\alpha=5\%$, $F_\alpha(2,2)$ is 19. So, F_A is higher than $F_\alpha(2,2)$, while F_B and F_C are less than $F_\alpha(2,2)$. This indicates that factor A significantly affects strength index and factors B, C and D have no significant effect on strength index.

3 Conclusions

1) The order of importance of factors affecting the UCS are dosage, curing time, gradation, and degree of compaction. Therefore, it is important to control composite soil stabilizer dosage and base-course curing time in road construction.

2) The UCS increases with the increase of composite soil stabilizer dosage, curing time and degree of compaction. However, the growth rate is clearly not the same, and for composite soil stabilizer dosage, the maximum growth rate of UCS is 17.4%. The coarser gradation can result in higher UCS.

3) By variance analysis, it is found that composite soil stabilizer dosage can significantly influence the UCS, and curing time, gradation and degree of compaction have no obvious effect on UCS.

4) For a road construction project, composite soil stabilizer dosage and curing time should be paid much more attention to compared with the changes in gradation and the degree of compaction. In other words, composite soil stabilizer dosage detection and base-course curing work should be carried out strictly.

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复合型土壤固化剂稳定碎石土无侧限抗压强度影响因素分析

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摘要:为明晰多种因素对复合型土壤固化剂稳定碎石土基层强度的影响情况,采用正交试验,研究了当固化剂剂量为8%,10%,12%,养护时间为7,14,21 d,级配粗细n为0.3,0.35,0.4及压实度为95%,97%,99%时无侧限抗压强度的变化规律.极差分析结果表明,上述4个因素对无侧限抗压强度的影响程度由大到小为:剂量、养护时间、级配粗细、压实度;方差分析结果表明,只有固化剂剂量能够显著影响基层无侧限抗压强度.因此,在该基层施工过程中,相对于级配和压实度,应加强施工过程中固化剂剂量的控制以及基层养护,以获得满意的基层强度.

关键词:道路基层;复合型土壤固化剂;碎石土;无侧限抗压强度;正交试验
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