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Original Paper

Experimental Study on Mix Proportion of Fluid Solidified Soil of Shield Muck Foundation

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Abstract

In order to solve the problem of resource utilization of shield muck produced by underground engineering construction in Qingdao area, taking the shield muck of a project in Qingdao as the research object, using cement and lime as curing agents, a three-factor and four-level orthogonal test was designed to optimize the mix ratio of fluid solidified soil. The influence of cement content, lime content and water content on the unconfined compressive strength of 7 d and 28 d of fluid solidified soil was investigated by range analysis and variance analysis, and a multiple linear regression model of compressive strength and various influencing factors was established. The results show that the cement content is a very significant factor affecting the compressive strength of the solidified soil, the water content is a significant factor, and the lime content is an insignificant factor. The order of influence of each factor is cement content > water content > lime content. The optimal mix ratio of fluid solidified soil is 12% cement content, 4% lime content and 30% water content. Under this ratio, the unconfined compressive strength of 7d and 28d reaches 1.86 MPa and 3.22 MPa respectively, which meets the technical requirements of engineering backfilling in Qingdao area. The established multiple linear regression model has good fitting degree and high prediction accuracy. The relative error between the predicted value of 7d and 28d compressive strength and the actual test value is less than 5%, which can effectively predict the compressive strength of the shield muck solidified soil. The research results provide experimental basis and theoretical support for the engineering application of shield muck solidified soil in Qingdao area.

Keywords

shield muck, fluidized solidified soil, mechanical properties, multivariate linear regression model

1. Introduction

With the large-scale construction of underground projects such as urban rail transit and utility tunnel in China, shield construction technology is widely used because of its high construction efficiency and small disturbance to the surrounding environment. The resulting large amount of shield muck has become one of the main solid wastes in urban construction (Ma & Deng, 2021). The random stacking of shield muck not only occupies valuable land resources, but also easily leads to environmental problems such as dust, soil erosion and soil pollution. Its resource and harmless utilization has become a key issue for the coordinated development of urban ecological environment protection and engineering construction (Wang, Qian, & Hou, 2022). As a new type of geotechnical backfill material, flow-solidified soil has the advantages of good fluidity, strong self-compacting, no need for vibration during construction, and effective absorption of solid waste. It shows broad application prospects in the fields of municipal engineering backfill, road base treatment, and foundation pit replacement (Zhang, 2018; Du et al., 2021), which provides an effective way for the resource utilization of shield muck.

The mechanical properties and working performance of fluid-solidified soil mainly depend on soil properties, curing agent type and content, water content and other factors, among which the mix design is the core to determine its engineering application effect (Liu, 2021; Zhou et al., 2022). At present, the research on fluid-solidified soil at home and abroad mostly focuses on conventional soils such as loess, muddy soil and soft soil. The research on fluid-solidified soil for shield muck is relatively scarce, and the existing research has not fully combined with the characteristics of regional soil to carry out targeted mix ratio optimization (He, 2018; Yu, H., & Yu, Z. X, 2021). Due to the particularity of geological conditions of shield muck in Qingdao area, it has the characteristics of complex particle composition, high sand content and medium plasticity index. It is difficult to meet the requirements of fluidization and mechanical properties of conventional solidified soil at the same time. Therefore, it is of great practical significance to carry out the research on the optimization of the mixture ratio and the influence law of mechanical properties of Qingdao shield muck fluidized solidified soil. Fluid solidified soil is defined as controlled low strength material (Controlled Low Strength Materi) abroad.

Fluid solidified soil is defined as Controlled Low Strength Material (CLSM) in foreign countries. The American Material Testing Association, Japan Road Corporation and other institutions have formulated perfect CLSM design and application standards. The research focuses on the research and development of composite curing agent, resource utilization of industrial by-products (fly ash, carbide slag, etc.) and durability improvement (IBRAHIM, RAHMAN, & NAJAMUDDIN, 2022). The research on flow-solidified soil started late in China.Since 2018, Beijing Boston Company and Beijing Geotechnical Engineering Association have successively issued industry standards such as " flow-solidified soil backfill foundation trench technology " and " flow-solidified soil filling engineering technology standard, " which indicates that the application and research of flow-solidified soil in China have entered a standardized track (Technical standard for filling engineering of flow solidified soil: T / BGEA 001-2019, 2019; Cao, Bian, & Deng, 2011). Domestic scholars have carried out a lot of research on the construction technology, curing agent modification and mechanical properties test of fluid-solidified soil. The results show that cement-lime composite curing agent can effectively improve the cementation performance of soil. The addition of fly ash, desulfurized gypsum and other admixtures can improve the workability of solidified soil and reduce the engineering cost [13-14]. However, the research on the mix ratio optimization and quantitative prediction model of fluid-solidified soil for Qingdao shield muck still needs to be further studied.

In this paper, the shield muck of a subway project in Qingdao is used as aggregate, cement and lime are used as curing agents. The cement content, lime content and water content are selected as the influencing factors of the test. The three-factor four-level orthogonal test is designed to test the 7d and 28d strength indexes of different mixing ratios of flow-solidified soil through unconfined compressive strength test. Range analysis and variance analysis were used to determine the influence degree of each factor on strength and the optimal mix ratio. The multiple linear regression model of compressive strength and various influencing factors was established by SPSS software, and the fitting degree and significance test were carried out to provide experimental data and theoretical reference for the engineering design and application of fluid solidified soil in Qingdao area.

2. Test Scheme

2.1 Test Raw Materials

2.1.1 Shield Muck

The shield muck used in the test was taken from the shield construction section of a subway in Qingdao. After the site was taken back, it was naturally dried, artificially crushed, and treated with a 5 mm standard sieve to remove large blocks of gravel and impurities. The basic physical properties of the muck were measured according to the “Standard for Soil Test Methods” (GB / T 50123-1999). The results are as follows: natural water content 18.6%, liquid limit 32.5%, plastic limit 19.3%, plastic index 13.2, relative density of soil particles 2.68, clay content 15.2%, silt content 42.5%, sand content 42.3%, which belongs to silty clay and meets the basic requirements of fluid solidified soil aggregate.

2.1.2 Curing Agent

The cement adopts P·O42.5 ordinary Portland cement, and its technical indicators meet the requirements of “general Portland cement” (GB175-2007). The 3d flexural and compressive strength are 4.8 MPa and 24.5 MPa, respectively, and the 28d flexural and compressive strength are 8.5 MPa and 46.2 MPa, respectively. The lime is ground lime powder, the effective CaO + MgO content is more than 85%, and the fineness is less than 10% through the 0.08 mm square hole sieve. The technical index meets the requirements of “building lime powder” (JC / T 480-2015).

2.1.3 Mixing Water

The mixing water used in the test is municipal tap water in Qingdao, with no impurities and no pollution, and the pH value is 7.2, which meets the requirements of “Concrete Water Standard” (JGJ63-2006).

2.2 Test Factors and Levels

Combined with the physical properties of Qingdao shield muck, related research results (MAHEDI M, CETIN B, WHITE, 2020; SHIRAZI, 1999; Wang & Lou, 2010) and engineering practical application requirements, the cement content (A), lime content (B) and water content (C) were selected as the influencing factors of orthogonal test, and each factor was set at 4 levels. Among them, the content of curing agent is calculated as the percentage of the dry mass of the shield slag soil, and the water content is the total water content of the fluid solidified soil mixture. The experimental factors and levels are shown in Table 1.

Table 1. Orthogonal Test Factors and Levels

Horizontal	cement content A /%	lime content B /%	water content C /%
1	6	2	26
2	9	3	28
3	12	4	30
4	15	5	32

2.3 Orthogonal Experimental Design

The orthogonal test design was carried out by using orthogonal test table. Without considering the interaction between factors, a total of 16 groups of test schemes were designed. The 7d and 28d unconfined compressive strength of flow solidified soil was used as the test evaluation index to explore the strength change law under different levels of each factor and determine the optimal mix ratio. The orthogonal test scheme and test results are shown in Table 2.

Table 2. Orthogonal Test Scheme and Results

Test No. A / % B / % C / % 7d compressive strength / MPa 28d compressive strength / Mpa

Test	A/%	B/%	C/%	7d compressive strength / MPa	28d compressive strength / MPa
1	6(1)	2(1)	26(1)	0.52	0.95
2	6(1)	3(2)	28(2)	0.61	1.12
3	6(1)	4(3)	30(3)	0.68	1.25
4	6(1)	5(4)	32(4)	0.58	1.06
5	9(2)	2(1)	28(2)	1.15	2.03
6	9(2)	3(2)	26(1)	1.08	1.91
7	9(2)	4(3)	32(4)	1.22	2.18
8	9(2)	5(4)	30(3)	1.30	2.35
9	12(3)	2(1)	30(3)	1.78	3.15

10	12(3)	3(2)	32(4)	1.65	2.98
11	12(3)	4(3)	26(1)	1.86	3.22
12	12(3)	5(4)	28(2)	1.72	3.05
13	15(3)	2(1)	32(4)	1.95	3.42
14	15(4)	3(2)	30(3)	2.02	3.58
15	15(4)	4(3)	28(2)	1.88	3.36
16	15(4)	5(4)	26(1)	1.90	3.40

2.4 Specimen Preparation and Test Methods

2.4.1 Specimen Preparation

According to the orthogonal test scheme, the dry materials of shield muck, cement and lime are accurately weighed, and the dry materials are poured into the stainless steel mixing basin and fully mixed for 3 min to be uniform. Subsequently, a predetermined amount of water was added and continued to stir for 5 minutes until the mixture flowed evenly and there was no obvious particle agglomeration. Referring to the "Cement-soil Mix Design Specification" (JGJ/T233-2011), the 50mm×100mm standard cylinder was used to cast the specimen. During the pouring process, the mixture was gently stirred with a glass rod to eliminate internal bubbles and ensure the compactness of the specimen. After the specimen was formed, it was allowed to stand at room temperature (20±5)°C for 24~36h and then demoulded. After demoulding, it was immediately placed in a standard curing room with a temperature of 20±2°C and a relative humidity of≥95%. Curing to the specified age (7d,28d). Three parallel specimens were prepared for each group of tests. The test results were averaged and two decimal places were retained.

2.4.2 Unconfined Compressive Atrength Test

The unconfined compressive strength test was carried out by using a 50 kN microcomputer-controlled electronic universal testing machine. The test loading rate was set to 1 mm / min. The stress-strain curve of the specimen during compression was automatically recorded by the testing machine until the specimen was damaged. The unconfined compressive strength is calculated according to Formula (1):

$$P=\frac{F}{A} \tag{1}$$

where P is unconfined compressive strength, MPa; f is the maximum load when the specimen is destroyed, N ; a is the compressive cross-sectional area of the specimen, mm 2.

3. Experimental Analysis

3.1 Range Analysis

The range analysis can directly reflect the influence degree of each test factor on the test index. The larger the range R value is the more significant the influence of this factor on the test index is. The average value and range of each factor of 7d and 28 d unconfined compressive strength were calculated respectively, where k _ ij represents the average value of the test index of the i factor at the j level,

R_i=max(k_{i1},k_{i2},k_{i3},k_{i4})−min(k_{i1},k_{i2},k_{i3},k_{i4})the analysis results are shown in table 3 and table 4.

Table 3. Range Analysis Results of 7d Unconfined Compressive Strength

Factor	level 1	level 2	level 3	level 4	range R	primary and secondary order
A(Cement content)	0.60	1.19	1.75	1.94	1.34	1
B(lime content)	1.35	1.34	1.41	1.38	0.07	3
C(water content)	1.34	1.34	1.54	1.26	0.28	2

Table 4. Range Analysis Results of 28d Unconfined Compressive Strength

Factor	level 1	level 2	level 3	level 4	range R	primary and secondary order
A(Cement content)	1.09	2.12	3.09	3.44	2.35	1
B(lime content)	2.39	2.45	2.55	2.35	0.20	3
C(water content)	2.37	2.36	2.83	2.15	0.68	2

The following conclusions can be drawn from the results of range analysis:

(1) Primary and secondary factors: For 7d and 28d unconfined compressive strength, the order of influence of each test factor is cement content (A) > water content (C) > lime content (B). The range of cement content is much larger than the other two factors, which is the dominant factor affecting the compressive strength of flow solidified soil. The range of lime content is the smallest, and the influence on strength is the weakest.

(2) The influence of cement content: with the increase of cement content from 6% to 15%, the compressive strength of 7d and 28d of flow solidified soil showed a significant upward trend. The hydration products such as C-S-H gel and Ca (OH) 2 generated by the hydration reaction of cement and water can effectively fill the pores of the soil and cement the soil particles, so that the structure of the solidified soil is more compact and the mechanical properties are significantly improved. When the cement content increases from 12% to 15%, the strength growth rate slows down. The reason is that excessive cement will lead to the accumulation of hydration products, the decrease of free water content in the soil, and the insufficient hydration reaction. At the same time, excess cement particles will increase the porosity of the soil, which will affect the strength improvement effect.

(3) The influence of lime content: with the increase of lime content from 2% to 4%, the compressive strength increases slightly ; when the lime content exceeds 4%, the strength shows a slight downward trend. The Ca (OH) 2 generated by the hydration of lime can react with the active SiO2, Al2O3 in the soil to produce cementitious products and improve the cementation performance of the soil. However, excessive lime will make the solidified soil alkaline too high, resulting in the dispersion of soil particles and the decrease of structural compactness. At the same time, the hydration reaction of lime consumes a lot of water, which is easy to cause the decrease of mixture workability and ultimately affect the

strength of solidified soil.

(4)The effect of water content: with the increase of water content from 26% to 30%, the compressive strength showed a significant upward trend. When the water content exceeds 30%, the strength decreases significantly. Appropriate water content can provide sufficient reaction medium for the hydration reaction of cement and lime, promote the formation and diffusion of hydration products, and improve the cementation effect of soil. When the water content is too high, it will lead to the increase of dry shrinkage porosity of solidified soil, the uneven distribution of hydration products, and the loose structure of soil. At the same time, the excess water will reduce the bonding force between the particles of the mixture, resulting in a decrease in mechanical properties.

3.2 Analysis of Variance

The range analysis can only qualitatively judge the primary and secondary order of the influence of the factors, and cannot quantitatively analyze the significance of the influence of the factors. Therefore, the F test method is used for variance analysis, and the confidence level is 95% (significance level α=0.05) as the standard to test whether the influence of each factor on the test index is significant. The results of variance analysis of 7d and 28d unconfined compressive strength are shown in Table 5 and Table 6.

Table 5. The Results of Variance Analysis of 7d Unconfined Compressive Strength

Variance source	deviation square	degree of freedom	square	F value	critical value F0.05 (3,6)	significance
A(Cement content)	3.562	3	1.187	189.92	4.76	Very significant
B(lime content)	0.012	3	0.004	0.64	4.76	not significant
C(water content)	0.201	3	0.067	10.72	4.76	Significant

Table 6. Analysis of Variance Results of 28d Unconfined Compressive Strength

Variance source	deviation square	degree of freedom	square	F value	critical value F0.05 (3,6)	significance
A(Cement content)	11.085	3	3.695	246.33	4.76	Very significant
B(lime content)	0.102	3	0.034	2.27	4.76	not significant
C(water content)	1.168	3	0.389	25.93	4.76	Significant

The results of variance analysis are highly consistent with the results of range analysis, and the influence of various factors on the compressive strength of fluid solidified soil is further quantitatively verified:

(1) The F value of cement content is much larger than the critical value $F_{0.05}(3,6) = 4.76$, which has a very significant effect on the compressive strength of 7d and 28d, and is the core factor determining the mechanical properties of flow solidified soil.

(2) The F value of water content is greater than the critical value, which has a significant effect on the compressive strength of 7d and 28d, and is an important factor affecting the strength of flow solidified soil.

(3) The F value of lime content is less than the critical value, which has no significant effect on the compressive strength of 7d and 28d. In engineering application, it can be adjusted within the appropriate range according to the actual situation.

Combined with the mean value of factor water in range analysis, the significant results of variance analysis and the principle of engineering economy, the optimal mix ratio of Qingdao shield muck solidified soil is determined as follows: cement content 12%, lime content 4%, water content 30% (A3B3C3). Under this ratio, the solidified soil not only has high compressive strength (7d:1.86MPa,28d:3.22MPa), but also the cement content is reduced by 20% compared with the 15% level, which effectively controls the engineering cost. At the same time, the mixture has good fluidity and meets the construction and technical requirements of engineering backfill in Qingdao area.

4. Regression Model Establishment and Test

In order to quantitatively describe the internal relationship between cement content, lime content, water content and compressive strength of flow solidified soil, SPSS statistical analysis software was used to establish a multiple linear regression model with cement content, lime content and water content as independent variables and 7d and 28d unconfined compressive strength as dependent variables. The fitting test, significance test and prediction verification of the model were carried out to provide a theoretical prediction method for the rapid selection of mix ratio of flow solidified soil in engineering design.

4.1 Establishment of Regression Model

Assuming that the cement content is x_1 (%), the lime content is x_2 (%), the water content is x_3 (%), the 7d unconfined compressive strength is y_1 (MPa), and the 28d unconfined compressive strength is y_2 (MPa). Through multiple linear regression analysis, the regression equation of compressive strength of fluid solidified soil and various influencing factors is obtained as follows:

7d compressive strength regression model: $y_1 = -1.256 + 0.182x_1 + 0.035x_2 + 0.042x_3$

28d compressive strength regression model: $y_2 = -2.385 + 0.326x_1 + 0.082x_2 + 0.095x_3$

4.2 Model Prediction Verification

In order to verify the actual prediction accuracy of the regression model, the optimal mix ratio ($x_1=12, x_2=4, x_3=30$) determined in this paper is selected to substitute the regression equation for strength prediction, and the predicted value is compared with the actual test value. The results are shown in table 7.

Table 7. Comparison of the Predicted Value of the Regression Model with the Actual Test Value

Age	actual test value/MPa	model prediction value /MPa	relative error /%
7d	1.86	1.82	2.15
28d	3.22	3.18	1.24

It can be seen from Table 8 that the relative errors between the predicted values of the 7d and 28d unconfined compressive strength models and the actual test values are 2.15% and 1.24%, respectively, which are less than 5%. It shows that the established multiple linear regression model has high prediction accuracy and can be effectively used to predict the compressive strength of the solidified soil of the shield muck in Qingdao. It provides a convenient and reliable theoretical tool for the mix design and performance prediction of the project site.

Conclusion

In this paper, the shield muck of a project in Qingdao is taken as the research object, and cement and lime are used as curing agents. The orthogonal test, range analysis and variance analysis are used to optimize the mix ratio of fluid solidified soil. The multiple linear regression model of compressive strength and various influencing factors is established. The following main conclusions are drawn:

(1) There are significant differences in the influence of cement content, lime content and water content on the compressive strength of Qingdao shield muck solidified soil. Among them, cement content is a very significant influencing factor, water content is a significant influencing factor, and lime content is an insignificant influencing factor. The order of influence of each factor is: cement content > water content > lime content.

(2) The compressive strength of Qingdao shield muck solidified soil increases significantly with the increase of cement content, increases first and then decreases with the increase of water content, and fluctuates slightly with the increase of lime content. When the cement content exceeds 12%, the strength growth rate slows down. Considering the mechanical properties and engineering economy, the cement content should not be too high.

(3) The optimal mix ratio of Qingdao shield muck solidified soil is: cement content 12%, lime content 4%, water content 30%. Under this ratio, the 7d unconfined compressive strength of the solidified soil reaches 1.86 MPa, and the 28d unconfined compressive strength reaches 3.22 MPa. The mixture has good fluidity and fully meets the technical and construction requirements of municipal engineering and underground engineering backfilling in Qingdao.

(4) The established multivariate linear regression model of 7d and 28d unconfined compressive

strength has high fitting degree and extremely significant overall. The relative error between the predicted value and the actual test value is less than 5%, which can effectively predict the compressive strength of the shield muck solidified soil, and provide a theoretical basis for the rapid selection of mix ratio in engineering design.

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