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ARTICLE

Experimental Study on Improvement Effects of Completely Weathered Phyllite Using Red Clay and Cement for High-Speed Railway Embankments

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ABSTRACT

Completely weathered phyllite (CWP) has the characteristics of difficult compaction, low shear strength after compaction and large settlement after construction. The traditional improvement method using a single agent of red clay or cement for CWP satisfies the subgrade requirements for ordinary railway, but cannot meet the requirements of immediate strength and long-term post-construction settlement of high-speed railway at the same time. A series of experimental investigations were undertaken for the blended CWP soils, with three additives used. The first additive was red clay, the second was cement and the third was a combination of both red clay and cement at various portions. Results of consolidation test and shear strength test carried out for the treated CWP soils show that: 1) The effect of cement on improving the compression modulus of CWP is much better than that of red clay; 2) The settlement of an embankment of 10 m high formed by blended soil of CWP with 3% cement can be controlled within 15 mm, while the settlement will be 25.15 mm for the same embankment of blended soil of CWP with 40% red clay; 3) The shear strength and ultimate bearing capacity of CWP improved by red clay are much better than those of 5% cement; 4) The ultimate bearing capacity of CWP improved by 40% red clay is 3.42 times of that by 3% cement and 2.95 times by 5% cement. Furthermore, the bearing capacity of CWP when improved by red clay can meet railway subgrade requirements immediately after compaction, while cement improved CWP needs a curing time of 1 day or longer. This is an impediment to rapid construction process. The improvement mechanism of red clay is mainly filling effect and grading improvement effect, while the improvement mechanism of cement is mainly hardening reaction, which produces high strength material to cement. It is found that 40% red clay and 3% cement treated CWP, which is considered to be optimum, can meet the subgrade requirements of both immediate bearing capacity and long-term post-construction settlement for the high-speed railway.

KEYWORDS

Completely weathered phyllite (CWP); red clay; cement content; immediate strength; post-construction settlement; high-speed railway

1 Introduction

The completely weathered phyllite (CWP) is widely distributed in the north of Jiangxi Province, China. Because the hardness of CWP is very soft, most of it is transformed into fine-grained soil in the process of subgrade compaction layer by layer. Therefore, the CWP can be studied according to the engineering properties of fine-grained soil. Weathered phyllite has the characteristics of high liquid limit [1–2], difficulty in compaction [3], and large deformation of subgrade filling when it is socked after compaction [4–6]. Many scholars have systematically analyzed the factors affecting the basic physical properties of weathered phyllite from microstructure and mineral composition perspectives [7–9].

Due to the low strength of weathered phyllite, it is not suitable to be used as subgrade fill without treatment. Cement or lime is often used as an agent for improvement of the shear strength of the weathered phyllite [10–12]. Cement or lime improvement belongs to a kind of chemical improvement, and the cementation process usually needs a period of time to be fulfilled [13–15]. This is often not desirable for rapid subgrade construction using locally won soils. For example, if the finished surface of each compacted subgrade layer cannot meet the ultimate bearing capacity requirement as a temporary construction access for moving vehicles, then the construction program will have to be extended to allow the layer to gain strength, leading to an increase in the overall project construction cost.

Red clay is also widely distributed in Jiangxi Province and is a kind of special soil with the characteristics of high liquid limit and high water sensitivity [16–18]. After dry-wet cycles, it is easy to produce drying shrinkage cracks [19–21]. In order to reduce the water sensitivity of red clay, many scholars and engineers have added cement and lime to increase the stability of red clay after soaking or reduce fissure rate [22,23].

According to previous studies, weathered phyllite and red clay as subgrade fill have some engineering property deficiencies. However, red clay has high shear strength due to iron cementation in the case of low saturation [24–26], and the high cohesion of red clay can be used for specific improvement of CWP. The research shows that the shear strength of blended soil increases with the increase of red clay blending ratio, and the improvement method can also reduce the expansibility of CWP and the fissure rate of red clay undergo dry-wet cycles [27,28].

The traditional methods of improving weathered phyllite with cement or lime mainly consider the long-term strength and long-term stability of subgrade fill, but a significant amount of cement or lime is required to achieve this [9,10]; Using red clay to improve CWP soil mainly considered the immediate strength [27], and the method can not only reduce the expansibility of CWP, but also reduce the fissures in red clay [29]. However, this type of improvement method is only suitable for ordinary railway subgrade applications but cannot satisfy the subgrade requirements for the high-speed railway. In this paper, the shear strength tests and consolidation tests of a variety of improved CWP soils using red clay, cement, and both have been carried out in the laboratory, and the influence of red clay blending ratio, curing period, cement content and other factors on the foundation coefficient (K_{30}), ultimate bearing capacity, compression modulus has also been studied. The research results show that the CWP treated with both red clay and cement can not only meet the requirements of the ultimate bearing capacity of subgrade as temporary access platform, but also the long-term settlement of subgrade after construction. The results of this study have provided a useful basis for the full utilization of undesirable CWP and red clay materials and minimization of unsuitable material disposals for major civil engineering projects, hence reducing the cement and/or lime consumption, resulting in significant environmental benefits and overall project cost savings.

2 Laboratory Investigations

2.1 Test Materials

The completed weathered phyllite (CWP) soil and red clay in this study were obtained from Nanchang city, Jiangxi province, China. According to the *Code for Soil Test of Railway Engineering (TB 10102-2010)*

[30], the liquid-plastic limit test and compaction test were carried out, and the basic physical indexes of the test materials are shown in Table 1.

Table 1: Basic physical properties of test materials

Type of soil	Liquid limit (%)	Plastic limit (%)	Plastic index	Relative density	Maximum dry density (g/cm^3)	Optimum moisture content (%)	Natural moisture content (%)
CWP	43.3	28.9	14.4	2.76	1.64	19.2	8.48
Red clay	48.4	26.4	22.0	2.69	1.75	17.8	22.31

2.2 Red Clay Blending Ratio and Cement Content Design

If the dry mass of CWP is m_0 and the dry mass of red clay is m_1, the blending ratio of red clay is denoted as λ, $\lambda = m_1/(m_0 + m_1)$, and expressed as a percentage. When the blending ratio is 0%, 20%, 40%, 60% and 100%, the corresponding mass ratios of CWP to red clay are 5:0, 4:1, 3:2, 2:3 and 0:5, respectively, in which 0% represents pure CWP and 100% represents pure red clay.

In order to further improve the water stability and strength of the mixed soil and reduce the post-construction settlement, 3% and 5% cement (425# Ordinary Portland Cement, Hailuo brand, Nanchang) were added into the blended soil of CWP with red clay respectively. The cement content is the ratio of cement mass to the total mass of CWP and red clay blended soil.

2.3 Consolidation Test

Consolidation test can be used to measure the deformation of ring cutter specimen under the action of a vertical load under the condition of sample soaking, and then calculate the compression modulus of soil, which is an important index to calculate the settlement of subgrade after construction. NT.YJZ-1 type triple consolidation instrument was used for consolidation test, in which the sample diameter is 61.8 mm, the height is 20.0 mm, and the loads were applied in stages at 50 kPa, 100 kPa, 200 kPa, 300 kPa, 400 kPa, respectively.

According to the compaction test of blended soil with different blending ratio, the maximum dry density varies from 1.64 g/cm^3 to 1.75 g/cm^3, and the optimal moisture content varies from 17.8% to 19.2%. Considering that the cement content is small, it has little impact on the max dry density. For this study, the maximum dry density of 1.70 g/cm^3 has been adopted for all samples of blended soils with the corresponding optimal moisture content of 18.0%. Based on the requirement of high-speed railway, a compaction coefficient of 93% was adopted, and the bulk density for every sample was set to be 1.866 g/cm^3.

2.4 Direct Shear Test Method

Direct shear test is usually used to measure the shear strength index of soil. DJY-4L type four-way direct shear instrument was used for this study, and the shearing rate was set at 8 mm/s. The direct shear specimen was prepared in the same manner as the consolidation test. The normal pressure (σ) for each sample group was set as 50, 100, 150 and 200 kPa, respectively, and the shear strength (τ) of each sample was calculated using the recorded shear force at the time of failure.

The direct shear strength tests of the blended soil samples were carried out for samples with water soaking and without soaking. The non-soaking test can represent the strength of the embankment after compaction. The soaking test is carried out after soil samples were soaked in water for 24 h, which can simulate the embankment shear strength in Nanchang City after continuous rainfall.

3 Consolidation Test Results and Post-Construction Settlement Analysis

Compression modulus is an important index for settlement assessment. The higher the compression modulus, the smaller the compressibility of soil is, and the smaller the post-construction settlement of subgrade is. The compression modulus of the same kind of soil changes with the range of consolidation pressure. In order to facilitate the comparison of compression modulus of different kinds of soil, compression modulus under the consolidation pressure range of 100–200 kPa is generally taken as the compression modulus (E_{s1-2}, unit: MPa) in the *Code for Design of Building Foundation (GB50007-2011)* [31]. The calculation method is shown in Eq. (1).

$$E_{s1-2} = \frac{(1+e_0)(p_2-p_1)}{e_1-e_2} = \frac{0.1\times(1+e_0)}{e_1-e_2} \quad (1)$$

where, e_0, e_1, e_2 are the pore ratios at consolidation pressure of 0 kPa, 100 kPa and 200 kPa, respectively; p_1 and p_2 are 100 kPa and 200 kPa, respectively.

3.1 Influence of Cement Content on Compression Modulus

After adding cement to the blended soil of CWP and red clay, the cement hydrolyzes and reacts with the minerals in the mixed soil to form cementitious materials, thus reducing the compressibility of the soil. The variation law of soil compression modulus with cement content based on the test results is shown in Fig. 1.

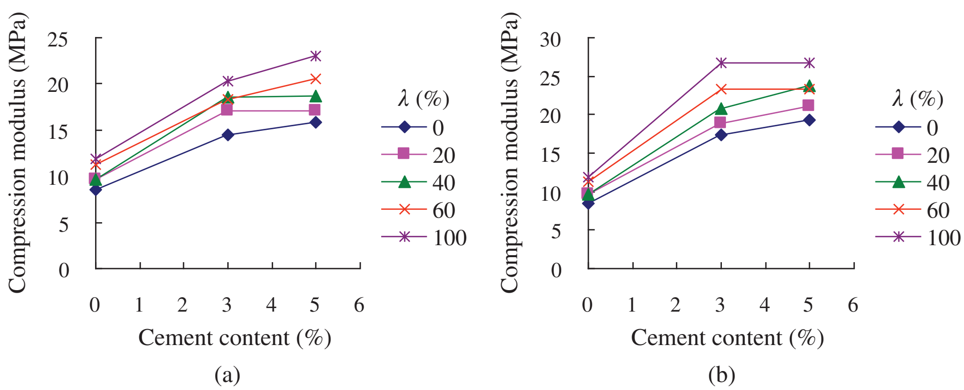


Figure 1: Variation of compression modulus with cement content (a) Curing period is 7 days (b) Curing period is 28 days

It can be seen from Fig. 1 that the compression modulus of the mixed soil increases with the increase of cement content after the curing period of 7 days or 28 days. It is readily found that the increase rate of compressive modulus of mixed soil with cement content increasing from 0% (no cement added) to 3% is much greater than that of cement content increasing from 3% to 5%, with some of mixed soil samples showing little increase in compression modulus with cement content increase from 3% to 5%. For example, the compression modulus of the mixed soil with 40% of red clay has increased by 11.23 MPa after 28 days of curing, as shown in Fig. 1b when the cement content is increased from 0% to 3%, while the compression modulus has increased by only 2.45 MPa when the cement content is increased from 3% to 5%. It can be seen that the relative growth rates is 116.7% with cement content from 0% to 3% and 25.4% from 3% to 5%, respectively. Therefore, if the post-construction settlement can meet the requirements of the high-speed railway, then the use of 3% cement content is more economical than that of 5%.

3.2 The Effect of Red Clay Blending Ratio on the Compression Modulus

The compression modulus, as shown in Fig. 2, will increase with the increase of blending ratio of red clay, irrespective of the percentage of cement added.

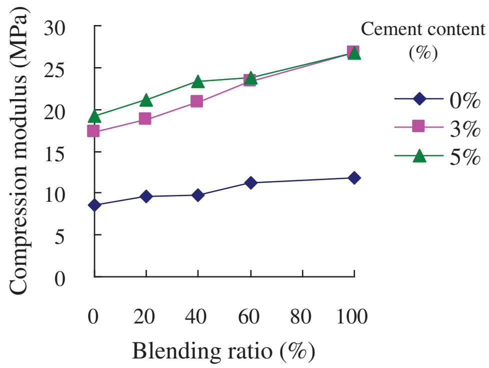


Figure 2: Variation of compression modulus with red clay blending ratio

It can be seen from the analysis in Fig. 2, taking pure CWP as an example, that when the blending ratio is 20%, 40% and 60%, the compression modulus value is 9.63 MPa, 9.69 MPa and 11.28 MPa, respectively, which has increased by 12.91%, 13.61% and 32.3% compared with that of pure CWP. The increase rate of compression modulus with blending ratio of mixed soil with cement ratio at 3% or 5% is higher than that for pure CWP (0% cement).

This study has found that the compression modulus of CWP can be improved by adding red clay or cement. It is found from the test results, for example, that the compression modulus is increased by 214.0% when cement content is 3%, while the compression modulus is increased by 32.3% when red clay blending ratio is 60%. It can be inferred that the effect of cement on improving the compression modulus and reducing the compressibility of soil is much greater than that of red clay at a given blending ratio.

3.3 The Effect of Curing Period on Compression Modulus

When cement is added into the mixed soil, the minerals in the cement and the water in the soil have strong hydrolysis and hydration reactions. At the same time, $Ca(OH)_2$ is decomposed from the solution and other hydrates are formed to produce hardened materials, so as to improve the compressive modulus of the mixed soil. With deepening of cement hydration reaction, a large amount of Ca^{2+} is precipitated from the solution. When the amount of Ca^{2+} exceeds the demand of ion exchange, it will react with SiO_2 and Al_2O_3, which are part of clay minerals, in an alkaline environment to form stable crystalline minerals that are insoluble in water. This further improves the compression modulus of the mixed soil.

From the improving mechanism of cohesive soil with cement perspective, the hardening reaction process develops gradually with time, implying that the compression modulus will increase with the increase of curing period. The change pattern of compressive modulus of improved soil by cement with curing period is shown in Fig. 3 for various blending ratios.

It can be seen from Fig. 3 that the compression modulus of mixed soil with cement increases with curing time. The compression modulus of mixed soil increases fastest when the curing period increases from 0 day to 1 day, which is mainly due to the hardening reaction caused by cement hydrolysis and hydration, which are fast chemical processes in this stage. The compression modulus also increases rapidly when the curing period increases from 1 day to 7 days. At this stage, in addition to hydrolysis and hydration reaction, ion exchange also occurs, which makes the compression modulus of the mixed soil further increase. The compression modulus increases only slightly when the curing time increases from 7 days to 28 days, during which is mainly due to the activation of SiO_2 and Al_2O_3 in cohesive soil and the reaction with hydration product $Ca(OH)_2$ in alkaline environment.

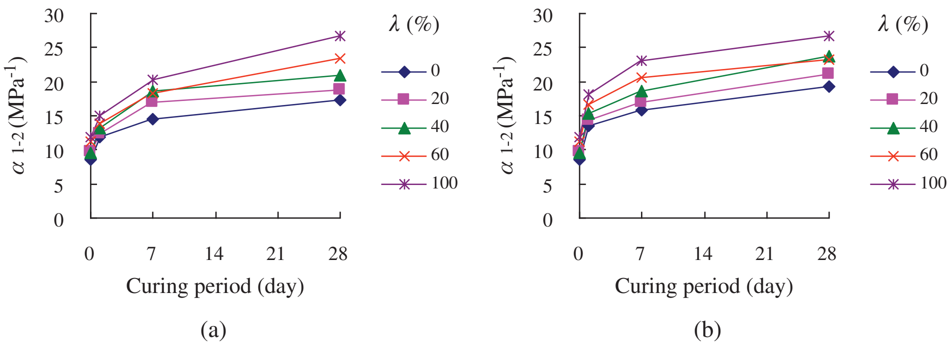


Figure 3: Variation of compressive modulus with curing period (a) Cement content is 3% (b) Cement content is 5%

The slope of each line is the growth rate of compression modulus in each curing period. It can be noted from Fig. 3, the fastest growth rate is when the curing period increases from 0 day to 1 day, which is mainly due to the hardening reaction caused by cement hydrolysis and hydration, which are fast chemical processes in this stage.

3.4 Influence of Double Improvement of Red Clay and Cement on Subgrade Settlement

The most important governing factor of high-speed railway stability is post-construction settlement. The calculation of post-construction settlement(s) of embankment is shown in Eq. (2) [32].

$$s = \frac{\Delta p}{E_s} H = \sum \frac{\Delta p_i}{E_s i} H_i \quad (2)$$

where Δp is the load increment (caused by rails, trains, etc.) at the top of the subgrade; H is the thickness of the compressive layer within the influence zone; Δp_i, E_{si}, H_i are the load increment, compression modulus and layer thickness of the ith layer calculated by the layered-sum method.

According to *the Design Code of High-Speed Railway* (TB 106241-2014) [33] the equivalent uniformly distributed load (UDL) at the subgrade surface is 54 kPa, and the settlement of the 10 m high embankment filled with pure CWP is calculated to be 28.39 mm by the layered-sum method. The settlements of other combinations of the same fill embankments after improvement by cement and red clay are summarized in Table 2.

Table 2: Subgrade settlements of 10 m high embankment treated by cement and red clay

Cement content (%)	0	0	0	3	3	3	5	5	5
Blending ratio (%)	0	40	60	0	40	60	0	40	60
E_s (MPa)	8.53	9.63	11.28	17.31	20.86	23.34	19.27	23.31	23.74
Settlement (mm)	28.39	25.15	21.47	13.99	11.61	10.38	12.57	10.39	10.20

According to Table 2, the post-construction settlement of CWP subgrade is 28.39 mm, which exceeds the settlement limit requirement of 15 mm at subgrade level. The settlement of subgrade is 21.47 mm, which is more than 15 mm even if the red clay blending ratio is 60%. That is to say, the settlement of CWP improved by red clay alone cannot meet the requirements of settlement limit of 15 mm for high-speed railway.

When the cement content reaches 3%, the post-settlement is lower than the limit requirement of 15 mm, that is, cement should be added to blended soil of CWP and red clay. By comparing the increase of compression modulus with cement content of 3% and 5%, benefit of increase of cement from 3% to 5% is not significant. Therefore, it is considered that the optimal cement content is 3% from this study.

4 Analysis of Influencing Factors on Shear Strength of Improved Soil

The shear strength parameters are important indexes to analyze the stability of embankment slope and the bearing capacity of subgrade surface. Each group of samples can obtain four shear strengths under a group of 4 normal pressures, and then the data can be linearly fitted by Mohr-Coulomb model, as shown in Eq. (3). According to Eq. (3), the shear strength indexes of various combination improvement schemes can be calculated [32].

$$\tau = \sigma \tan \varphi + c \tag{3}$$

4.1 Influence of Blending Ratio of Red Clay on Shear Strength Indexes

The blending ratio of red clay has significant influence on the shear strength index of CWP or cement modified CWP. The variation of cohesion and internal friction angle is shown in Fig. 4.

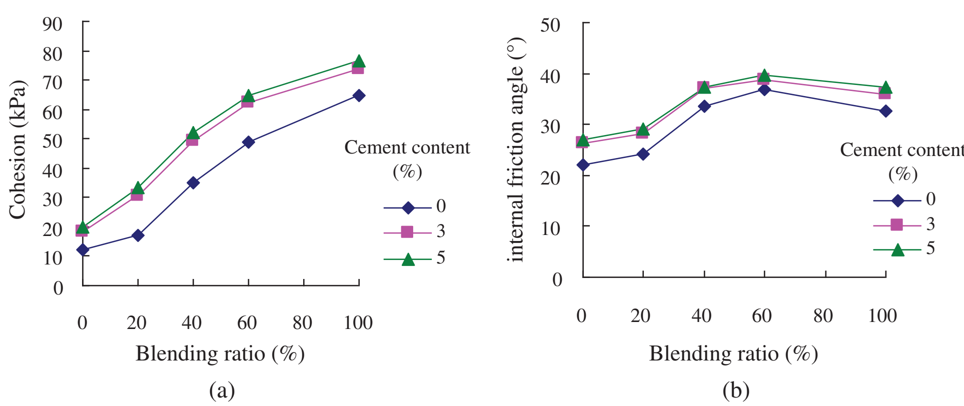


Figure 4: Variation of shear strength indexes with red clay blending ratio (a) Cohesion (b) Internal friction angle

It can be seen from Fig. 4a that the cohesion of CWP or cement improved CWP increases greatly after blending with red clay. Taking pure CWP as an example, the cohesion index increases by 39.8%, 184.5%, 294.7% and 426.2% when the blending ratios are 20%, 40%, 60% and 100%, respectively. For the cement improved CWP with 3% and 5% cement content, the change law of cohesion growth is similar to that of CWP after blending red clay.

Internal friction angle of CWP or cement modified CWP increases rapidly and then decreases when blending ratio exceeds 60%. Taking pure CWP as an example, the internal friction angle increases 95.2%, 172.9%, 197.7% and 163.9% when the blending ratios are 20%, 40%, 60% and 100%, respectively.

From the perspective of cohesion growth, the greater the blending ratio of red clay, the greater the cohesion of the modified soil. However, when the blending ratio of red clay reaches 40%, the contribution to the growth of internal friction angle has been very small or even decreased, so the optimal blending ratio of red clay should be set around 40%.

4.2 The Influence of Cement Content on Shear Strength

After the cement is added with a pure CWP or a blended soil of CWP and red clay, a series of hydration, hydrolysis and hardening reactions will occur, thereby enhancing the shear strength of soils. The influence of cement content on the cohesion and internal friction angle is shown in Fig. 5.

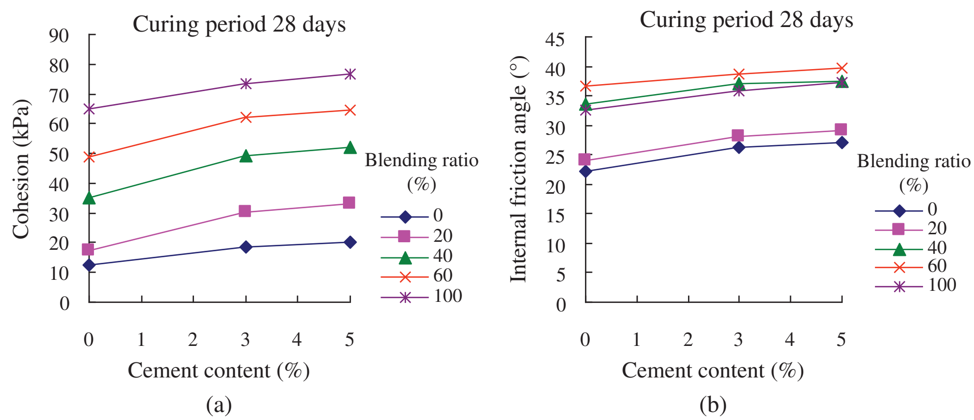


Figure 5: Variation of shear strength indexes of improved soil with cement content (Curing period 28 days) (a) Cohesion (b) Internal friction angle

It can be seen from Fig. 5 that the cohesion and internal friction angle of soil will increase with cement content. Taking red clay blending ratio of 40% as an example, the cohesion has increased by 40.5% and 48.6% when the cement content is 3% and 5%, respectively, and the internal friction angle has increased by 5.4% and 6.6%, respectively.

As can be seen from Figs. 4 and 5, the shear strength of CWP can be improved by adding red clay or cement. Compared with pure CWP, the cohesion and internal friction angle increase by 184.5% and 33.68% respectively when the blending ratio of red clay is 40%; and the cohesion and internal friction angle increase by 49.3% and 18.5% when cement content is 3%. That is, the cohesive growth by blending with 40% red clay is 1.90 times that of 3% cement, and the internal friction angle growth is 1.28 times. It is readily found that the improvement effect of red clay on the shear strength of CWP is better than that of 3% (or 5%) cement content.

4.3 The Effect of Curing Time on Shear Strength

Since the cement hydration reaction and hardening reaction occur gradually, the curing period also influences the shear strength. The shear strength indexes of the improved soil variation with curing time (cement content 3%) are shown in Fig. 6.

It can be seen from Fig. 6 that the cohesion and internal friction angle of the improved soil with a cement content of 3% increase with the curing time. The cohesion increases by 0.55 kPa and the internal friction angle increased by 1.13° after 1 day of curing compared with CWP, accounting for 9.05% and 27.62% of the total increase at 28 days. The results show that the shear strength of the improved soil increases slightly when curing period is 1 day, which is mainly due to the cement content is small and slow interaction with cohesive soil.

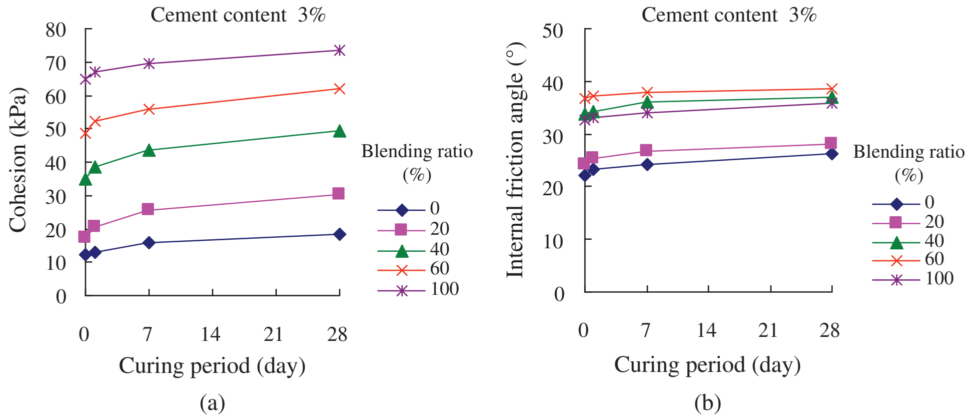


Figure 6: Variation of shear strength indexes of improved soil by 3% cement content with curing period (a) Cohesion (b) Internal friction angle

The shear strength of subgrade will be greatly improved after compaction when CWP is improved by red clay. However, 1 day or more is required to achieve the required strength when improved by cement. According to the construction of high-speed railway in China, each layer of compacted subgrade surface will be used as temporary access road for fill carrying vehicles. When the shear strength of the compacted subgrade surface is insufficient, the transportation of fill materials will be affected. Therefore, the waiting time required for cement improved CWP to reach the design shear strength will result in delays in the construction program, leading to increases in construction cost.

4.4 Influence of Soaking on Shear Strength Indexes

Nanchang is prone to sustained rainfall events in spring, so the subgrade is often in the state of soaking, which can be simulated by the shear strength test of samples after 24 h of soaking. The shear strength of CWP and improved soil decreases in different degrees after soaking. The change rate of shear strength index is defined as the ratio of the decreased value of shear strength index to the non-soaking one and converted into a percentage. The comparison of shear strength indexes between soaking and non-soaking is shown in Table 3.

Table 3: Influence of soaking on shear strength indexes

Cement content (%)		0			3			5		
	Blending ratio (%)	Non soaking	Soaking	Change rate (%)	Non soaking	Soaking	Change rate (%)	Non soaking	Soaking	Change rate (%)
Cohesion (kPa)	0	12.34	8.92	27.7	18.42	14.43	21.7	20.15	15.81	21.5
	20	17.25	13.63	21	30.39	23.03	24.2	33.26	25.32	23.9
	40	35.11	19.96	43.2	49.34	26.86	45.6	52.18	28.97	44.5
	60	48.71	26.73	45.1	62.15	37.98	38.9	64.64	40.28	37.7
	100	64.93	30.05	53.7	73.56	38.53	47.6	76.72	39.78	48.1
Internal friction angle (°)	0	22.15	17.68	20.2	26.24	21.03	19.9	27.05	21.76	19.6
	20	24.09	19.94	17.2	28.13	24.28	13.7	29.04	25.08	13.6
	40	33.68	23.57	30.0	37.02	27.41	26.0	37.42	28.13	24.8
	60	36.74	24.25	34	38.65	28.41	26.5	39.62	29.65	25.2
	100	32.56	24.16	25.8	35.87	27.19	24.2	37.23	27.74	25.5

The analysis in Table 3 shows that regardless of whether the samples were soaked in water or not during testing, the cohesion strength increases with the increase of the red clay blending ratio. The internal friction angle increases with the red clay blending ratio when the red clay blending ratio is less than 60%, while the internal friction angle decreases when blending ratio greater than 60%. Both cohesion and internal friction angle increase with the increase of cement content. The above shows that cement and red clay can not only increase the strength before soaking, but also increase the strength after soaking.

If the change rate of shear strength index is defined as the ratio of the shear strength index change value before and after soaking to the index before soaking, the shear strength indexes of the improved soils of various schemes are greatly reduced after soaking. Taking the red clay blending ratio of 40% as an example, the change rates of cohesion are 43.2%, 45.6% and 44.5% when the cement content is 0%, 3% and 5%, respectively, and the change rates of internal friction angle are 30.0%, 26.0% and 24.8%, respectively. The above analysis shows that the shear strength of the improved soil is greatly reduced after soaking, and the change rate of internal friction angle can be reduced by adding cement, but the change rate of cohesion is less affected.

5 Numerical Simulation Analysis of Foundation Coefficient

According to *The Code for Design of High-Speed Railway (TB 106241-2014)* [33], compaction coefficient K and foundation coefficient K_{30} are two key parameters for the quality control of subgrade compaction. The K_{30} test is to place a circular load plate with a diameter of 300 mm on each layer of compacted subgrade, and then apply the graded load of 0.04 MPa step by step on load plate until the settlement exceeds 1.25 mm. The settlement under each grade load is measured to obtain the pressure-settlement (p-s) curve, as shown in Fig. 7a. If the load intensity corresponding to the settlement of 1.25 mm is p_1 (unit: MPa) on the p-s curve, K_{30} can be calculated by Eq. (4) [30], and the unit is MPa/m.

$$K_{30} = \frac{p_1}{1.25 \times 10^{-3}} \tag{4}$$

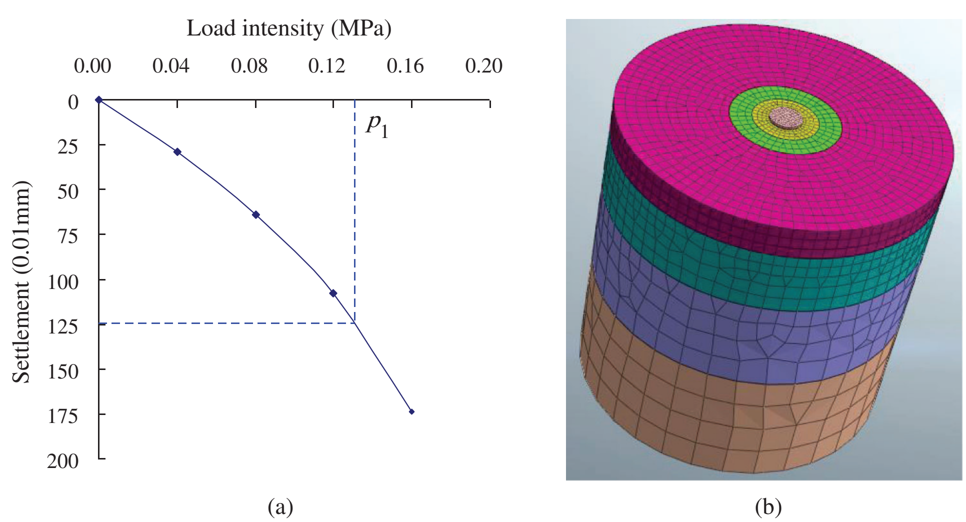


Figure 7: Numerical simulation principle and numerical analysis model for K30 (a) p-s curve and K_{30} calculation principle (b) Finite element model of K_{30} calculation

According to *the Code for Design of High-Speed Railway (TB10001-2014)* [33], different subgrade layers have different requirements for foundation coefficient and fill material. The topmost layer of subgrade between depths of 0 and 0.4 m must be filled with graded crushed stone, and it is not suitable to use fine-grained soil or improved soil. K_{30} of the bottom layers at depths of 0.4 m and 3 m of subgrade shall not be less than 130 MPa/m, and the layer of subgrade below 3 m shall not be less than 110 MPa/m.

Because there are many improved combination schemes, it will cost a lot of manpower and material resources to determine K_{30} by field test section, so this paper has proposed to use numerical simulation method to determine K_{30} based on the laboratory results. The numerical analysis model is established by Midas finite element software by assuming the soils obeying the Mohr-Coulomb yielding criteria. According to the general law, the influence range of the load plate is generally three times of the plate diameter. To eliminate the influence of the boundary, the finite element model selects a larger range, and the diameter and depth of the geometric model are set to be 3 m and 3 m, respectively. The mesh is composed of mixed polygons, and the finite element model is shown in Fig. 7b. In the middle of the model is a circular rigid plate with a diameter of 300 mm and a thickness of 25 mm. The mesh under the rigid plate is encrypted. Fixed nodes are used at the bottom of the model to constrain all the degrees of freedom of the bottom, and the lateral cylindrical surface constrains the rotation and displacement in the horizontal direction. The load is gradually increased by 0.04 MPa on the central rigid plate until the settlement value exceeds 1.25 mm.

When Midas finite element software is used to simulate, a Poisson's ratio is 0.3, the other material parameters are compression modulus, cohesion, density, and internal friction angle, and all the parameters are based on the test data. The same material parameters are used for each layer of subgrade. Through the numerical analysis, the variation law of the load intensity at the central point of the load plate with the settlement can be obtained, as shown in Fig. 7a, and then the foundation coefficient value K_{30} under each blending proportion can be obtained.

5.1 Variation of Foundation Coefficient with Blending Ratio

The test data of 0 days for CWP blended with red clay and 28 days of mixed soil with cement were used to numerical analysis and then variation of K_{30} with red clay can be obtained, as shown in Fig. 8.

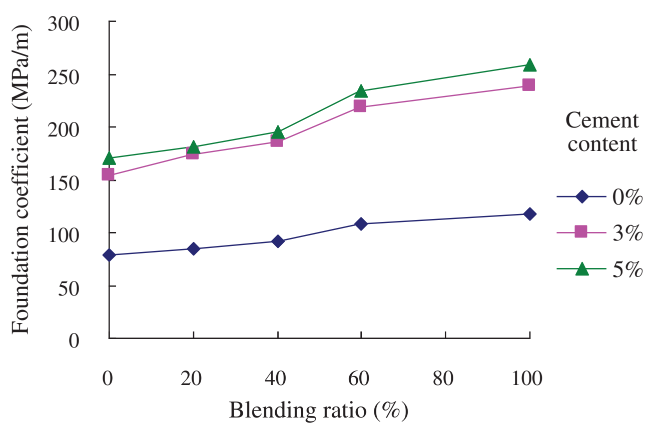


Figure 8: Variation of foundation coefficient with red clay mixing ratio

According to the analysis in Fig. 8, the foundation coefficient increases with the increase of red clay blending ratio. The K_{30} of pure CWP is the smallest, only 78.6 MPa/m, which is lower than the requirement of 90 MPa/m for ordinary grade I railway. Therefore, CWP cannot be used as subgrade fill directly without any treatment. When the blending ratios of red clay are 40% and 60%, the K_{30} values of the blended soils are 91.5 MPa/m and 107.8 MPa/m, increased by 16.5% and 37.2%, respectively, which can meet the subgrade requirements of K_{30} for ordinary grade I railway, but it is still lower than K_{30} of

110 MPa/m of subgrade layer for high-speed railway. That is, CWP improved with red clay only cannot meet the requirements of K_{30} for high-speed railway.

K_{30} also increases with the increase of blending ratio of cement ratio as shown in Fig. 8. The higher the cement content the higher the foundation coefficient, K_{30}, will be. Furthermore, it can be noted that the foundation coefficient will achieve a value of 110 MPa/m when the cement ratio is 3% or greater.

5.2 *Variation of Foundation Coefficient with Cement Content*

Based on the experimental data of 28 days curing period, K_{30} of compacted soil with different cement content can be obtained by same numerical analysis method. The variation of K_{30} with cement content is shown in Fig. 9.

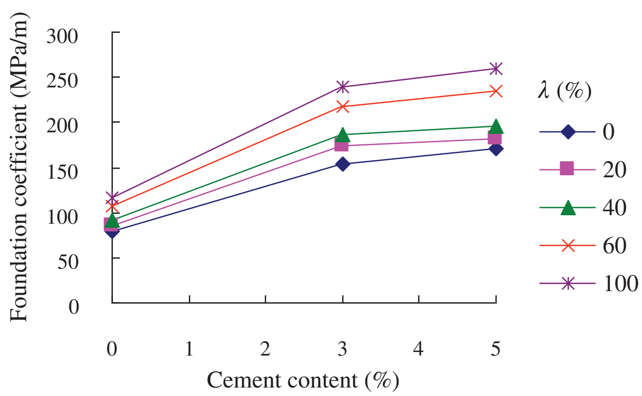


Figure 9: Variation of foundation coefficient with cement content

As shown in Fig. 9, the foundation coefficient increases with the increase of cement content, and the growth rate is fast first and then slower. After adding 3% and 5% cement to CWP, the calculated value of K_{30} is 154.4 MPa/m and 170.3 MPa/m respectively, which increased by 96.5% and 116.7% compared with CWP.

When the cement content is 3%, the K_{30} of all mixed soil is greater than the requirement of 130 MPa/m, hence they can be used as fill all layers of subgrade for high-speed railway except the surface layer of subgrade where crushed stone is required. The increase rate of K_{30} when the cement content ranges from 3% to 5% is far less than that of 0%~3%. Considering the actual economic and engineering needs, the optimal cement content is proposed to be 3%.

6 Analysis of Influencing Factors of Ultimate Bearing Capacity of Subgrade Surface

According to the *Code for Design of High-Speed Railway (TB 106241-2014)* [33], the filling material of railway subgrade is compacted layer by layer of 30 cm thickness. After the compaction of each layer of subgrade, it will be used as the temporary transportation route for the fill trucks, so the subgrade surface must be able to meet the bearing capacity requirements of the loaded truck. According to reference [32], the ultimate bearing capacity of subgrade surface can be calculated according to Eq. (5).

$$P_{\mathrm{u}} = 0.6 \times \frac{1}{2}\gamma b N_\gamma + \gamma_0 d N_q + c N_c = 0.3 \times \gamma b N_\gamma + c N_c \quad (5)$$

In the Eq. (5), b is the diameter of the equivalent circle of the contact surface between the tire and the ground, taking as 0.213 m according to the *Code for Design of Urban Road Engineering (CJJ 37-2012)* [34]; and γ is the bulk density of the compacted soil. Because the truck tire acts directly on the subgrade surface, the buried depth $d = 0$. N_c, N_q, and N_γ are the bearing capacity coefficients related to the internal friction angle (φ), and the calculation methods are shown in Eqs. (6)–(8), respectively.

$$N_q = \exp(\pi \tan \varphi)\tan^2(\frac{\pi}{4} + \frac{\varphi}{2}) \tag{6}$$

$$N_c = (N_q - 1)\cot \varphi \tag{7}$$

$$N_\gamma = (N_q - 1)\tan(\frac{\pi}{4} + \frac{\varphi}{2}) \tag{8}$$

6.1 Variation of Ultimate Bearing Capacity with Red Clay Blending Ratio

The variation of ultimate bearing capacity of CWP and CWP & cement blended with red clay is shown in Fig. 10.

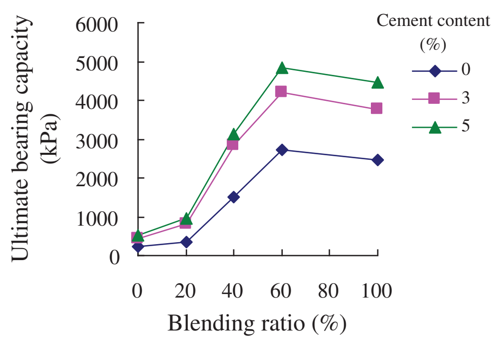


Figure 10: Variation of ultimate bearing capacity with blending ratio

It can be seen from Fig. 10 that when the red clay blending ratio exceeds 20%, the ultimate bearing capacity of improved soil increases rapidly with increase of blending ratio from 20% to 60% and decreases slowly with increase of blending ratio from 60% to 100. Taking CWP as an example, the calculated ultimate bearing capacity is 1498.9 kPa and 2737.3 kPa when the blending ratio of red clay is 40% and 60%, respectively, which is increased by 5.74 and 11.30 times. The results show that blending red clay into CWP can significantly improve the ultimate bearing capacity. When the blending ratio exceeds 60%, the ultimate bearing capacity does not increase, but decreases gradually. Therefore, to ensure the improvement effectiveness of the ultimate bearing capacity, the blending ratio of red clay should not be greater than 60%.

6.2 Variation of Ultimate Bearing Capacity with Cement Content

Since there is no cement in CWP and red clay modified CWP, the ultimate bearing capacity is calculated based on the shear strength data of 0-day curing. When cement is added to the blended soil, the curing time will affect the strength of the cement improved soil. At this time, the ultimate bearing capacity is calculated using the 28-day shear strength indexes. The variation of ultimate bearing capacity of double improved soil with cement content and red clay is shown in Fig. 11.

The ultimate bearing capacity of cement modified CWP soil is 438.1 kPa and 507.7 kPa when the cement content is 3% and 5%, respectively, which increases by 96.9% and 128.2% compared with pure CWP. The ultimate bearing capacity of cement treated blended CWP with red clay is 2848.7 kPa and 3128.5 kPa when cement content is 3% and 5% at blending ratio of 40%, which is increased by 11.84 times and 13.06 times compared with pure CWP and is increased by 90.1% and 108.7% compared with red clay improved CWP at blending ratio of 40%.

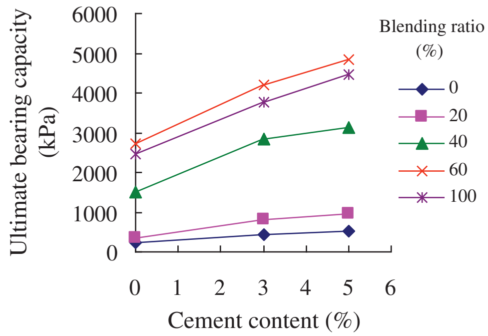


Figure 11: Variation of ultimate bearing capacity with cement content

The comparison of improving CWP with cement and red clay shows that the increase in the ultimate bearing capacity of cement is much less than the contribution of red clay blending ratio of 40% (or 60%). In addition, using cement treated CWP requires 28 days of curing period to reach this ultimate bearing capacity, but there is no need of curing time when red clay is used to improve CWP, that is, it can reach the corresponding bearing capacity after the completion of compaction. From the above, it can be inferred that using red clay to improve CWP bearing capacity is more effective than cements.

6.3 Discussion on Mix Proportion Optimization Based on Ultimate Bearing Capacity

According to the Chinese truck load standard, the design value of the ground pressure of the filling truck is 700 kPa. Generally, the ultimate bearing capacity calculated is generally 3 times of the critical plastic-edge load [35], so the safety factor obtained by Eq. (5) requires a safety factor of 3. Considering that each layer of compacted subgrade is only used for temporary traffic, the safety factor can be taken as 2, and then the requirement of ultimate bearing capacity is 1400 kPa. The ultimate bearing capacity analysis shows that even if 5% cement is added into CWP, it cannot meet the requirements of bearing capacity, so it is not feasible to improve CWP using cement alone. Through this study, it has found that the ultimate bearing capacity of CWP blended with 40% red clay reaches 2848.7 kPa, which can fully meet the requirements of truck loading. Considering the economic principle, the optimal blending ratio of red clay is 40%.

7 Discussion on the Optimal Mix Proportion Combination and Improvement Mechanism

7.1 Comprehensive Analysis Based on Post-Construction Settlement and Temporary Bearing Capacity

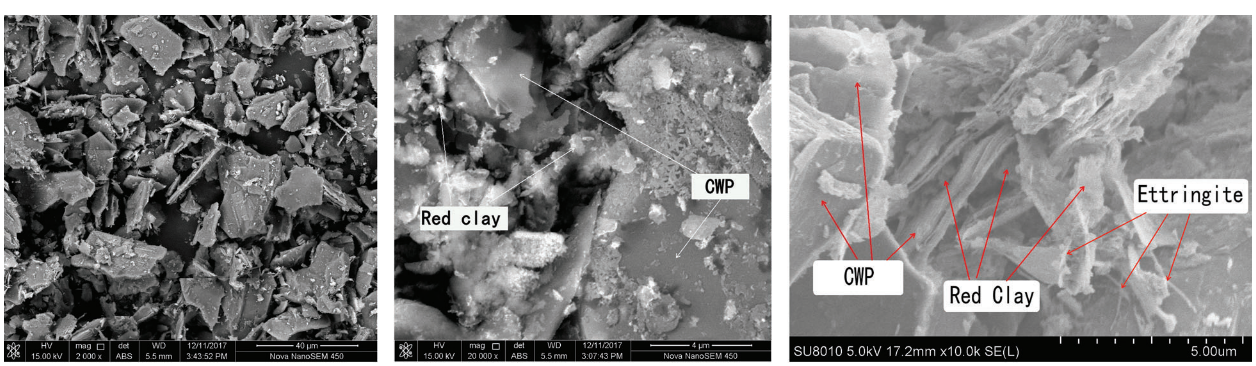
The calculated post-construction settlements and ultimate bearing capacities of various improved soils by red clay and cement content for a 10 m high embankment are shown in Table 4. It can be seen from Table 4 that CWP with appropriate amount of cement treatment only can meet the requirements of post-construction settlement for high-speed railway subgrade but cannot meet the requirements of temporary bearing capacity for truck load; CWP after blending with an appropriate amount of red clay can meet the requirements of temporary bearing capacity after compaction but cannot meet the requirements of post-construction settlement. When the following combination scheme is adopted: adding 40% red clay and 3% cement into CWP, the compaction coefficient is 93%, and the compaction moisture content is 18%, the post-construction settlement of 10 m high embankment is 10.36 mm, and the ultimate bearing capacity is 2848.7 kPa, which can not only meet the requirements of post-construction settlement, but also meet the requirements of the ultimate bearing capacity as a temporary construction access road. Therefore, it can be inferred that that this combination is the optimal mixing ratio of cement and red clay improvement.

Table 4: Evaluation on whether settlement and bearing capacity meet the requirements

Mixed soils		Post-settlement (mm)		Bearing capacity (kPa)		Evaluation
Red clay blending ratio (%)	Cement content (%)	Calculated value	Requirement for high-speed railway	Calculated value	Requirement for truck loads	Meet the requirements or not (Yes/No)
0	0	28.39	15	222.48	1400	No
20	0	25.20	15	351.09	1400	No
40	0	25.15	15	1498.88	1400	No
60	0	21.47	15	2737.32	1400	No
100	0	20.39	15	2466.74	1400	No
0	3	13.99	15	438.10	1400	No
20	3	12.86	15	819.12	1400	No
40	3	10.36	15	2848.70	1400	Yes
60	3	11.61	15	4197.50	1400	Yes
100	3	9.04	15	3758.82	1400	Yes
0	5	12.57	15	507.66	1400	No
20	5	11.48	15	960.35	1400	No
40	5	10.39	15	3128.48	1400	Yes
60	5	10.20	15	4826.55	1400	Yes
100	5	9.07	15	4465.87	1400	Yes

7.2 Analysis of Microstructure and Improvement Mechanism

The characteristics of the particles were measured by the SU8010 type field emission scanning electron microscope produced by Japan Hitachi Company. The sample is prepared by cutting the ring knife sample after curing. The cut observation sample is a thin sample with a diameter of 4 mm and a thickness of 1 mm. After drying, it is analyzed by scanning electron microscope. Fig. 12 shows the SEM images of CWP and improved soil.



(a) (b) (c)

Figure 12: SEM images of CWP and improved soil (a) CWP only (b) Red clay (40%) improved soil (c) Red clay (40%) and cement (3%) improved soil

Fig. 12a is the SEM image (2000x) of CWP microscopic particles. The compacted and crushed CWP particles maintain the original phyllite structure, which is in the form of flakes or long columns. The particle size ranges from 10–40 μm, which is a powder particle size range, so CWP has the characteristics of low cohesion (only 12.34 kPa). CWP belongs to extremely soft rock (which can be crushed by hand). In the shear box test, if the shear stress is too high, it will directly cut phyllite particles or directly grind CWP particles, therefore, the internal friction angle of CWP is not high, only 22.15°. Due to the special particle shape of CWP, it is easy to form angle-angle contact or angle-surface contact between the particles after compaction, which means it is easy to form a void structure with larger porosity. In the consolidation test, the CWP particles are softened by soaking in water. This result in collapse of the void structure, resulting in large compression deformation, and corresponding low compression modulus.

Fig. 12b is SEM of red clay (blending ratio is 40%, 20000x) of CWP. It can be seen from the figure that red clay particles are far smaller than CWP particles. During compaction, the pores between CWP particles can be filled by red clay particles. The gradation of CWP is changed due to clay cementation and partial iron cementation being formed at the contact point of CWP, so the shear strength of the blended soil has been greatly improved. Red clay is a water sensitive material, therefore, the compression deformation of the soil is still large when the compacted soil sample is immersed in water during consolidation test. This is also the reason why the shear strength of CWP is greatly improved by red clay, but the increase in compression modulus is relatively small.

Fig. 12c is the SEM image (10000x) of double modified soil using red clay and cement, in which the content of red clay is 40% and the content of cement is 3%. From the analysis of the microstructure diagram, it is found that the red clay has played a better role in changing the gradation. The small red clay particles fill the large pores among the CWP particles, making the pores smaller. Due to the hydrolysis and hardening reaction of cement, hardening substances such as ettringite are formed to form a network connection in the improved soil. Due to the cementation effect of cement hardened products in small pores and good water stability, the dual improvement can greatly improve the shear strength and the compression modulus in consolidation test.

From the microstructure analysis, it can be concluded that the red clay and cement improved soil makes full use of the filling function of red clay and cement to enhance the water stability, and the macroscopic performance is that the shear strength and compression modulus are greatly improved. According to the theoretical calculation, the dual improved compacted CWP can not only meet the requirements of post-construction settlement of high-speed railway, but also the requirements of the bearing capacity of temporary access for construction truck loads.

8 Conclusions

Through the systematic study of the CWP, red clay and cement improved soils and micro analysis by SEM, the following conclusions can be drawn:

1. The compression modulus of CWP can be improved by adding cement or red clay. The compression modulus increases generally with the blending ratio of red clay and the cement content. The compression modulus is increased by 116.7% when cement content is 3%, while the compression modulus is increased by 13.61% when the blending ratio of red clay is 40%. The comparison study shows that the effect of cement on improving the compression modulus of CWP is better than that of red clay, and the optimal cement content is 3%.
2. The addition of cement or red clay can improve the shear strength indexes of CWP. The cohesion and internal friction angle increase by 49.3% and 18.5% when the cement content is 3%; the cohesion and internal friction angle increase by 184.5% and 172.9% when the red clay content is 40%. Through comparison, it can be concluded that adding red clay has a better effect on improving shear strength

than cement. Furthermore, red clay improvement does not need a curing period while cement needs a curing period of 1 day or longer.

3. The post-construction settlement and foundation coefficient K_{30} after subgrade construction can meet the requirements of high-speed railway when the cement content is 3%, but it cannot satisfy the ultimate bearing capacity requirements of truck loads. The ultimate bearing capacity of the compacted subgrade surface can meet the requirements of truck loads and does not need any waiting time when the ratio of red clay is 40% or 60%, but K_{30} and post-construction settlement cannot meet the requirements for high-speed railway. To take full advantages of the dual improvements by cement and red clay, an optimum improvement scheme, with a blending ratio of red clay to 40% and a cement content of 3%, is proposed.
4. Red clay can greatly improve the shear strength and ultimate bearing capacity by changing the gradation of CWP and iron cementation. The analysis of SEM shows that through hardening and hydrolysis reaction, network connections of cementitious materials among clay particles is formed to improve the compression modulus and foundation coefficient and reduce the post-construction settlement. An appropriate portion of red clay and cement content added to CWP soil can improve the immediate and long-term shear strength and reduce the post-construction settlement for subgrade underneath the high-speed railway.
5. This ground improvement method will reduce the cost for disposal of unsuitable CWP and enhance constructability of earth works, therefore bringing the environmental benefits for civil engineering works.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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