Study on Bearing Capacity Performance and Influence Factors of Phyllite Soil Blended with Red Clay

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Abstract. Phyllite soil has low bearing capacity and can not meet the mechanical properties of subgrade, so it is proposed to use special soil (red clay) to reinforce and improve phyllite soil. The shear strength indexes of unsaturated and saturated mixed soil were obtained by shear strength tests, and the ultimate bearing capacity calculation model was established based on shear strength indexes and plate load test. The calculation results show that the reduction of the ultimate bearing capacity can exceed 50% after saturation. According to the detection indexes of foundation coefficient ($K_{30}$) and the requirement of medium and long-term bearing capacity in the subgrade code, the minimum blending ratio of red clay in different filling layers of subgrade was obtained through comparison, which can provide a basis for improving special soil with special soil.

1. Introduction
Phyllite soil and red clay are widely distributed in Jiangxi Province. Phyllite soil is the product of completely weathered phyllite, with low hardness and easy to be powdered [1-3]. As subgrade filler, its strength is low and its bearing capacity can not meet the requirements, so it is often treated as abandoned earthwork.

Red clay is a typical special soil, and which has high strength when the moisture content is low. However, the strength of red clay is very sensitive to the moisture content, and strength will decrease rapidly with the increase of the moisture content [4] [5]. Therefore, the influence of the amount of red clay on the strength and bearing capacity must be studied when applying mixed soil filler composed of phyllite soil and red clay.

2. Basic Physical Properties of Mixed Soil
In order to fully grasp the effect of different amounts of red clay on the engineering properties of phyllite soil, the dry mass ratio of red clay to phyllite soil was defined as the blending ratio ($\lambda$) of 0:5, 1:5, 2:5, 3:5, 4:5 and 5:0, and the blending ratios are marked as 0%, 20%, 40%, 60%, 80%, 100%, where 100% represents pure red clay. The basic physical properties were shown in Table 1.

According to Table 1, the maximum dry density ($\rho_{d_{\text{max}}}$) and optimal moisture content ($w_{\text{op}}$) of the mixed soil are relatively close. For uniform comparison, the approximate average value of 1.70g/cm$^3$ is adopted as $\rho_{d_{\text{max}}}$ of mixed soils, and the value 18.0% is adopted as optimal water content of mixed soils.
Table 1. Physical properties of mixed soil

| $\lambda$ (%) | $w_L$ (%) | $w_p$ (%) | $\rho_{dmax}$ (g.cm$^{-3}$) | $w_{op}$ (%) |
|---------------|-----------|-----------|---------------------------|-------------|
| 0             | 43.3      | 28.9      | 1.64                      | 19.20       |
| 20            | 39.6      | 24.4      | 1.70                      | 18.30       |
| 40            | 37.1      | 23.1      | 1.69                      | 18.91       |
| 60            | 42.6      | 25.0      | 1.71                      | 18.35       |
| 80            | 44.3      | 24.8      | 1.71                      | 17.80       |
| 100           | 48.4      | 26.4      | 1.75                      | 17.80       |

Note: $w_L$ - Liquid limit; $w_p$ - Plastic limit;

3. Shear Strength Tests of Phyllite Soil Blended with Red Clay

In order to obtain the bearing performance of the compacted subgrade, the shear strength indexes of the mixed soil needs to be obtained. Because the red clay is water sensitive, too high moisture content may also cause rubber clay to be unfit for compaction. Therefore, the moisture content ($w_0$) of the test samples is 14% and 18%. Considering the requirements of different parts of the Class I railway in the Design Specifications for Railway Subgrades (TB10001-2016), the $K(\rho_d/\rho_{dmax} \times 100)$ design is 93%, 95% and 97%.

The fast-shear test of direct-shearing test was adopted in this study, and the shear rate of the test is 0.8mm/s. The unsaturated and saturated tests were carried out respectively. The test results of the shear strength indexes are shown in Table 2.

Table 2. Shear strength indexes of mixed soils

| $w_0$ (%) | 14 | 14 | 14 | 18 | 18 | 18 | 18 | 18 |
|-----------|----|----|----|----|----|----|----|----|
| K (%)     | 93 | 95 | 97 | 93 | 95 | 97 | 93 | 95 |
| c (kPa)   | 0  | 13.4 | 13.9 | 15.2 | 12.0 | 13.1 | 9.4 | 10.0 | 11.0 | 8.4 | 8.8 | 11.2 |
|           | 20 | 19.5 | 25.2 | 27.5 | 16.2 | 25.2 | 26.4 | 11.1 | 12.3 | 12.7 | 13.3 | 11.7 | 12.6 |
|           | 40 | 31.0 | 32.7 | 35.1 | 34.1 | 30.9 | 34.4 | 16.0 | 17.1 | 17.8 | 14.6 | 15.0 | 17.0 |
|           | 60 | 53.8 | 55.0 | 57.1 | 46.4 | 54.6 | 54.3 | 19.0 | 20.3 | 21.7 | 22.8 | 20.8 | 23.1 |
|           | 80 | 57.8 | 67.3 | 76.9 | 53.3 | 55.8 | 60.1 | 19.0 | 17.9 | 19.3 | 23.3 | 23.4 | 24.7 |
|           | 100 | 80.0 | 84.9 | 90.7 | 62.1 | 59.7 | 59.4 | 17.3 | 19.0 | 20.1 | 24.1 | 25.9 | 27.9 |
| $\phi$ (°) | 0 | 24.0 | 25.4 | 27.2 | 22.0 | 26.6 | 28.0 | 17.2 | 18.1 | 19.0 | 17.8 | 17.2 | 18.2 |
|           | 20 | 26.1 | 29.2 | 30.1 | 23.5 | 31.3 | 31.4 | 18.6 | 19.1 | 21.2 | 19.2 | 18.1 | 20.3 |
|           | 40 | 28.0 | 31.2 | 33.2 | 32.4 | 34.3 | 35.2 | 23.4 | 25.2 | 26.1 | 26.4 | 26.1 | 27.2 |
|           | 60 | 30.7 | 32.3 | 34.0 | 33.4 | 37.1 | 37.3 | 21.5 | 23.0 | 24.1 | 24.5 | 25.1 | 25.9 |
|           | 80 | 37.9 | 37.1 | 38.3 | 36.2 | 38.1 | 38.9 | 25.1 | 27.1 | 28.9 | 29.1 | 28.0 | 28.2 |
|           | 100 | 35.1 | 34.0 | 37.0 | 31.7 | 37.1 | 38.1 | 23.6 | 25.3 | 26.0 | 25.0 | 24.0 | 23.0 |

Note: 0,20,40,60,80,100 are red clay blending ratio($\lambda$) value, and unit is %.

According to the analysis in Table 2, the cohesion ($c$) and internal friction angle ($\phi$) of phyllite soil increase with the increase of blending ratios of red clay.

4. Ultimate Bearing Capacity Model Based on Plate Load Test

The foundation coefficient ($K_{30}$) shall be tested after each layer is completed. As shown in Figure 1, $K_{30}$ is a bearing plate with a diameter of 30cm, which is pressurized by stages(40kPa-stage), and then the load ($p_1$) corresponding to the settlement of 1.25mm is obtained according to the load settlement curve(see Figure 1(b)). The calculation method of $K_{30}$ is shown in formula (1).

$$K_{30}=p_1/1.25$$ (1)
Assuming that the load plate in Figure 1 handles the limit equilibrium state, the load acting on the load plate is the ultimate load capacity $p_u$. The calculation method of the ultimate bearing capacity recommended in the book “Soil Mechanics” for circular foundations is shown in formula (2).

$$p_{usu} = 0.6 \times \frac{1}{2} b N_q + \gamma_0 z N_q + (1 + N_q / N_c) \times c N_c$$  \hspace{1cm} (2)$$

$N_q$, $N_q$, and $N_c$ are the bearing capacity coefficients related to the internal friction angle ($\phi$). Where $\gamma_0$ is the bulk density of the filler, for calculation convenience, 19.5kN/m$^3$ is adopted; $z$ is the thickness of the soil layer above the load-bearing plate. Layer1 is 0.6m and layer2 is 2.5m in the Class I railway.

For Group I railways in Code for design of railway earth structure (TB 10001-2016)$^6$, the $K_{30}$ value of layer2 and layer1 should not less than 90 MPa/m and 110 MPa/m respectively. According to the concept of the bearing capacity of the foundation in the Code for design of building foundation (GB50007-2011)$^7$, the allowable bearing capacity can be considered as the load $p_2$ corresponding to the settlement of 0.01$d$ (see Figure 1 (b)), where $d$ is the diameter of the bearing plate. According to the above principles, the corresponding allowable bearing capacities ($p_2$) are 270kPa and 330kPa, respectively. The safety factor ($F_s=p_u/p_2$) of formula (2) is often taken as 2, so the corresponding $p_u$ of layer2 and layer1 required by $K_{30}$ are 540kPa and 660kPa.

Existing railway inspection specifications require a bearing capacity of 150kPa, so 300kPa can be adopted as long-term ultimate bearing capacity ($p_{usu}$).

5. Analysis of Factors Affecting Ultimate Bearing Capacity

5.1. Effect of Red Clay Blending Ratio on Bearing Capacity

Substituting the unsaturated shear strength indexes and saturated shear strength indexes in Table 2 into formula (2), where $b$ takes the bearing plate diameter $d=30cm$, the ultimate bearing capacity ($p_u$) can be obtained. The variation of $p_u$ with $\lambda$ under different combinations is shown in Figure 2.
It can be seen from Figure 2, consider as a whole, $p_u$ and $p_{usat}$ increase with the increase of $\lambda$ when $\lambda < 80\%$, and decreases with the increase of $\lambda$ when $\lambda \geq 80\%$. That is, the red clay blending ratio did not contribute to the $p_u$ increase when $\lambda \geq 80\%$.

5.2. Unsaturated and Saturated Affect on Ultimate Bearing Capacity
Comparing Figure 2 (a) and (b), it can be obtained that the ultimate bearing capacity of the mixed soil decreases greatly after saturation. In contrast to Figure 2 (a), the bearing capacity of sample with 18% water content is higher than the ultimate bearing capacity of 14% moisture content when mixed soil saturated, so a higher saturated bearing capacity can be obtained under the optimal water content of 18%.

Taking $\lambda = 40\%$ as an example, the attenuation range of the ultimate bearing capacity after saturation is shown in Table 4.

| $w_0$ (%) | $K$ (%) | $P_u$(kPa) | $P_{usat}$(kPa) | Attenuation (%) |
|----------|---------|------------|-----------------|----------------|
| 14       | 93      | 455.3      | 227.6           | 50.0           |
| 14       | 95      | 580.9      | 264.1           | 54.5           |
| 14       | 97      | 707.8      | 288.4           | 59.2           |
| 18       | 93      | 655.7      | 253.8           | 61.4           |
| 18       | 95      | 685.1      | 253.8           | 63.0           |
| 18       | 97      | 800.7      | 298.2           | 62.8           |

It can be obtained from Table 4 that the attenuation of the ultimate bearing capacity after soil saturation increases by more than 50%, with an average decrease of 58.5%. After the soil is saturated, it can represent long-term bearing capacity state of subgrade.

5.3. Optimization of Blending Ratio Based on $P_u$ of Subgrade
According to above analysis, $p_u$ (temporary requirement) required for layer2 and layer1 are 540kPa and 660kPa, respectively, and long-term requirement of $p_{usat}$ is 300kPa. Linear interpolation is performed according to the adjacent data in Figure 2, and the minimum red clay blending ratio that meet the requirements of $K_{30}$ can be obtained as shown in Table 4.

| $w_0$ (%) | $K$ (%) | Unsaturated $\lambda$ (%) | Saturated $\lambda$ (%) |
|-----------|---------|---------------------------|------------------------|
| 14        | 93      | 49.4                      | 43.9                   |
| 14        | 95      | 43.7                      | 35.3                   |
| 14        | 97      | 36.1                      | 26.3                   |
| 18        | 93      | 40.3                      | 35.0                   |
| 18        | 95      | 37.7                      | 26.8                   |
| 18        | 97      | 31.0                      | 23.3                   |

6. Discussion on the Minimal Blending Ratio of Red Clay
In order to ensure the normal operation of subgrade, both temporary bearing capacity and long-term bearing capacity should be met. Therefore, a larger $\lambda$ should be adopted and the minimum of $\lambda$ in different combinations is shown in Table 5.
Table 5: Minimal $\lambda$ of mixed soils

| $w_0$ (%) | $K$ (%) | Layer1 | $\lambda$ (%) | Layer2 |
|-----------|---------|--------|--------------|--------|
| 14        | 93      |        | 43.9         |        |
| 14        | 95      | 76.6   | 35.3         |        |
| 14        | 97      | 59.3   | 26.3         |        |
| 18        | 93      | 54.7   | 35.0         |        |
| 18        | 95      | 54.5   | 26.8         |        |
| 18        | 97      | 40.7   | 23.3         |        |

7. Conclusions

Through laboratory direct shear tests and ultimate bearing capacity calculations of phyllite soil blended with red clay, the following conclusions can be drawn:

1. The ultimate bearing capacity of mixed soil increases with the increase of $\lambda$, so the red clay incorporation can effectively improve the bearing performance of the phyllite soil subgrade, and then the minimal blending ratios were obtained based on bearing capacity requirement of subgrade.

2. After the mixed soils are saturated, the bearing capacity attenuation is very significant. The decrease ratio is more than 50%, and the average amplitude is 58.5% when the blending ratio is 40%.

3. The red clay blending ratio ($\lambda$) of bottom layer of subgrade should be controlled by saturated bearing capacity, and $\lambda$ of layer below subgrade should be controlled by $K_{30}$ requirement. In order to ensure that the subgrade load bearing performance attenuation is small after saturation, it is recommended to compact at $w_0=18\%$.

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9. References

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