Study on prevention and treatment of capillary water rise for construction waste expansive soil subgrade

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A B S T R A C T
This paper solves the technical difficulties of the capillary water rising height of the construction waste improved expansive soil subgrade (CWS), analyses the capillary water rising mechanism of the construction waste improved expansive soil subgrade cushion and evaluates the improvement effect of the improved cushion by comparing different working conditions with simulation software. The analysis results show that: (1) a reasonable ratio of the improved subgrade bed can effectively improve the porosity of the cushion layer, thus effectively inhibiting capillary water rising height. (2) The practical improvement of the thickness of the cushion layer can slow the matrix suction effect of expansive soil. (3) The construction waste had a more significant influence on the particle gradation for the capillary water rise, poor grading cushion layer has a significant influence on the capillary water rise. (4) The construction waste particles in the improved graded cushion of construction waste have strong water absorption, which improves the matrix suction effect of expansive soil. (5) Through experiments and simulation tests, this paper concludes that the optimal grade subgrade bedding of construction waste expansive soil is of specific theoretical value and practical significance for developing the construction waste material transformation subgrade. Keyword: Construction Waste, the capillary water rise mechanism, well-graded CWS.

1. Introduction

In recent years, with the acceleration of urban development, there have been more and more highway construction projects between cities, and expansive soil, as a widespread soil layer on the surface, is widely distributed in six continents, especially in central and eastern China (Sha et al., 2018; Koch, 2002). Expansive soil has strong water absorption and is easy to soften (Min et al., 2011). In subgrade construction in broad soil distribution areas, the engineering problem of “every cut will slip, and if there is an embankment, it will collapse” is often encountered (Cuss et al., 2014; Perronnet et al., 2008). The filling and physical and chemical modification methods are generally used for expansive soil subgrade cushions. Covering method, interlayer method, and general roadbed protection methods, such as soil sample replacement, chemical reagent injection, gravel and fly ash modification, etc., not only increase the economic cost of the project but also increase the environmental cost of road construction (Ziari et al., 2014; Man et al., 2019; Xie et al., 2018).

According to the research on the damage mechanism of expansive soil subgrade (Hu et al., 2019; Elmashad and Eldin, 2017; Anifowose, 1996), it is found that the damage of expansive soil subgrade is mainly caused by rainfall, especially when the rain penetrates the subgrade bottom and contacts the extended soil cushion, a thick fluffy layer will be produced. As a highly hydrophilic soil, bentonite can quickly form an ultra-high capillary water elevation line (Rafalski, 1994; Nurus et al., 2016; Lubelli et al., 2013). Moreover, when bentonite meets water, the swelling amount increases sharply, which leads to a more significant lateral soil swelling force, which leads to roadbed collapse, uplift, or cracks. However, the repeated expansion and contraction deformation caused by the precipitation of bentonite subgrade and the low strength when encountering water are engineering difficulties of subgrade treatment in this area.

The construction waste produced by urban development has good particle gradation, high skeleton strength, good water absorption and comprehensive material sources. Therefore, it is necessary to study the solid waste utilization performance of construction material particles when used as new materials in the subgrade. Among them, Schütz (Schütz et al., 2016) used construction waste recycled materials in railway subgrade filling and analysed that the stress curve of construction waste recycled materials is logarithmic with the increase of construction aggregate. According to this phenomenon, the physical and mechanical
2. Analysis and implementation

In this paper, the improved inflation theory was analysed. Expansive soil cushion increases the particles of construction waste, and the idea of capillary water rise of ordinary soil needs to be improved. Based on the hydraulic coupling theory of capillary water’s ascending mechanism (G. et al., 1992), an enhanced model of capillary water ascending permeability of the cushion layer is put forward, which provides a theoretical basis for the data analysis of later indoor experiments and the establishment of the simulation analysis model.

2.1. Soil-water characteristic curve model

Two main factors causing capillary water to rise are gravity potential and matrix potential. The elevation of capillary water mainly causes gravity, and the matrix potential is especially the water ad sorption by the soil’s matrix soil (S. et al., 2015). When the water content changes, the matrix suction reflects the ads. As shown in Figure 1.

The matrix potential relationship curve is the soil-water characteristic curve, mainly by the infiltration test. The soil-water characteristic curve of the improved cushion under the static action is taken from the empirical formula of soil-water (S. et al., 2015).

\[ \phi = \theta / \{ \ln [ e + (\theta / \theta_s) ] \}^m \] (1)

In Eq. (1), \( \phi \) is volumetric water content, \( \theta \) is saturated volumetric water content, \( \theta_s \) is negative pore water pressure, \( a, n, m \): curve fitting parameters, obtained from the fractional curve.

2.2. Calculation equation of water movement in cushion

Darcy’s law infiltration experiments have excavated the fundamental laws of water movement from saturated soil because the upward flow is caused by the water cushion and negative pressure in the water flow, and the water flow \( H \) is a functional law of the soil. As shown in Eq. (2),

\[ q = k(h) \nabla H \] (2)

\( \nabla H \) is the potential water gradient, \( k(h) \) is hydraulic conductivity that has flowed through the sample per unit area.

Water conductivity generally takes the function of volume water content \( \theta \), that is, the position of \( k(0) \), to avoid the function effect (Sharma et al., 2021).

In cartesian coordinate system, the equation of soil moisture movement, As shown in Eq. (3):

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ k(\theta) \frac{\partial H}{\partial z} \right] \] (3)

2.3. Numerical calculation model of the liquid phase in expansive soil (seepage model)

The Navier-Stokes equation can provide a calculable micro-test method, pass the corresponding pore fluid flow laws, and generate related deformation effects. These forms are as shown in Equation 4 and Equation 5.

\[ \frac{\partial n}{\partial t} + \Delta / n \theta_f = 0 \] (4)

\[ \rho_f \left( \frac{\partial n_f}{\partial t} + \Delta (n_f \theta_f) \right) = \Delta (n_f \theta_f) - \sum_p \sigma_s p_{ng}(x-y)ds_y + n_f \rho_f f_k \] (5)

In Eq. (5), \( n = n(x) = \int_{s_y} g(r) \, ds_y \) is the local porosity near \( x \), \( g(r) = g(|x-y|) \) is \( A \) monotonically increasing weight function, \( r \) is local radius, \( \theta_f \) and \( \sigma_s \) are average fluid velocity and average stress tensor, respectively, \( \rho_f \) is fluid mass density, \( f_k \) is gravity acceleration vector, \( n (n = 1, 2, 3...) \) is the particle in the average volume, \( s_y \) is The surface area.

It is considered that Jackson’s momentum Eq. (2) can be written as follows.

\[ \rho_f \left( \frac{\partial n_f}{\partial t} + \Delta (n_f \theta_f) \right) = n \Delta \mathbf{f}_f - \mathbf{f}_f + n \rho_f f_k \] (6)

In Eq. (6), \( \mathbf{f}_f \) is the average unit volume fluid-particle interaction, \( \mathbf{f}_f \) is the average stress tensor of the fluid. This tensor includes a Reynolds
stress term, like turbulent flow, in addition to the average conventional stress $\tau_i$.

2.4. The interaction between the buffer particles and the fluid is improved

Turbulence force of the expansive soil particles in the action of fluid can be calculated by some semi-empirical formulas (A et al., 2014). In this paper, the Ergun porosity calculation formula of less than 0.8 ($n \leq 0.8$) is adopted. As show in Eq. (7),

$$f_i = (1 - n) \left( \frac{1}{n^2} \left( \frac{\mu f \left( 1 - n \right)}{n^2 \mu_f} + 1.75 \frac{n}{d_p} \right) \left( \frac{\eta_f - \eta_p}{\eta_p} \right) \right)$$  \hspace{0.5cm} (7)

Ergun equation covers a wide range of fluid conditions and is suitable for high Reynolds number pore flow with nonlinear energy dissipation. When the porosity is greater than 0.8, we can use Xun’s formula (Xun et al., 2017), As show in Eq. (8).

$$f_i = (1 - n) \left( \frac{3}{4} \frac{C_d n}{d_p} \left( \frac{2.66 \mu_f}{d_p} \right) \left( \frac{\eta_f - \eta_p}{\eta_p} \right) \right)$$  \hspace{0.5cm} (8)

In Eq. (7), $\mu_f$ fluid viscosity coefficient; $Re_p = n \rho_f d_p |\eta_f - \eta_p| / \mu_f$; Re Reynolds coefficient of granules with a flat velocity $\eta_p$ and an average radius $d_p$;

$$C_d = \left\{ \begin{array}{ll} \frac{24}{Re_p} \left( 1 + 0.15Re_p^{0.687} \right) & Re_p < 1000 \\ 0.44 & Re_p \geq 1000 \end{array} \right.$$  \hspace{0.5cm} (9)

Compared with the two-phase flow formula commonly used in the continuum models, the drag term of the above procedure represents the function of the skeleton porosity of the soil permeability and the properties of the solid phase and pore fluid (Siroux et al., 2018). Different from the current continuum model, the spatial and temporal variation of soil permeability varies with the properties of soil and fluid during the calculation.

3. Numerical modelling and calculation

This paper uses Particle Flow simulation software PFC (Particle Flow Code), a widely used discrete element calculation software (Zhou et al., 2017). Discrete element numerical simulation is built on the constitutive co-relation between discrete particles and extended to the macroscopic model constitutive relation. Therefore, the pore pressure change can influence the contact relation of particles in numerical analysis and calculation. Then the position and migration of pore water in soil are analysed.

3.1. Numerical model

The height of the subgrade is 4 m, the size of the groundwater level is 1 m, the permeability coefficient of subgrade filler is 4.72, the initial water content of CWS 1 is 23.8%, that of CWS 2 is 22.5%, that of CWS 3 is 23.5%, and that of the ordinary sand cushion (OSC) is 22.1%.

The proportion of the roadbed, the size of the model set 240 mm × 840 mm, particles 5000, base the experimental data is divided into three kinds of sample cushion construction waste gradation, respectively, the average particle radius of 0.5 mm–3 mm. According to the particle size range and related particle size mix of each type of construction waste cushion, although the particle size of construction waste is different, its porosity shows various realisations after uniform distribution. After adjustment, the porosity of CWS is 38.5%, 29.6% and 19.2%, respectively, and the porosity of CWS was 28.6. The model is shown in Figure 2.

3.2. Simulation parameters

The data simulation software sets the model’s particle size distribution and parameters according to the laboratory test parameters. As shown in Table 1. The lower surface water pressure is 50 Pa, and the upper surface water pressure is 0 Pa. With time, the expansive soil particles expand with the free expansion rate. 0.02–0.075mm, and the average particle radius of construction waste particles is 0.5mm–3mm. The proportions of the three types of aggregate are 80%, 60% and 40%, respectively, and the ratio of coarse aggregate in the contrast sand cushion is set at 40%, according to the actual project. Physical parameters such as porosity, liquid plastic limit and expansion rate are determined by experiments and used for numerical simulation parameters of particle flow.

![Figure 2. The Model (a) Simulation model (b) Contact diagram.](image-url)

### Table 1. Simulation parameters.

| Type   | CWS 1 | CWS 2 | CWS 3 | OSC |
|--------|-------|-------|-------|-----|
| Lime and aggregate ratio | 2:8   | 4:6   | 6:4   | 6:4 |
| Porosity | 38.5% | 29.6% | 19.2% | 28.6% |
| $W_p$   | 22.6% | 21.8% | 22.2% | 26.8% |
| $W_c$   | 52.5% | 45.3% | 39.5% | 42.8% |
| $W_c-W_p$ | 17.1  | 16.7  | 17.3  | 16.0 |
| Free swelling ratio | 36.0% | 45.2% | 57.2% | 48.5% |
| Cohesion (KPa) | 82.2  | 81.2  | 77.2  | 80.5 |
| Inner friction angle (°) | 23.89 | 22.13 | 21.02 | 21.02 |
| Natural moisture content | 23.8% | 22.5% | 23.5% | 22.1% |
3.3. Numerical model verification

Compared with the theoretical value, the simulation result of capillary water rise of sand cushion in the model can be calculated according to formula (9) in the process of capillary water rise, and the simulation value of capillary water rise is close to the theoretical value, and the overall change trend is consistent. However, according to the data of pore water rise height of cushion in Figure 3 compared with the simulation value, the theoretical value is small in the initial calculation but significant in the last calculation. The maximum rising height can reach 36mm. According to the data analysis of water content at different depths in Figure 3b, only the depth is 40cm in the initial numerical simulation, and the water content difference between theoretical calculation and numerical simulation is the largest, reaching 6%. The water content of each layer calculated theoretically is higher than the corresponding simulation value. Still, the difference value is less than 6%, which is in line with the calculation error range of numerical simulation. Based on this numerical model, we can further an improved cushion of construction waste with different gradations. As shown in Figure 3.

4. Results

According to the simulation process, the capillary water rising process of groundwater level is simulated, and the water content of each type of sample at different times is changed by software, such as the rising height of capillary water, the final rising analysis of capillary water and different sizes. The specific simulation results and analysis are as follows.

4.1. Influence of capillary water on rising height

Firstly, the rising height trend of capillary water with different matrix cushions is simulated, and the simulation data of graded sand cushions and bare soil are compared. The rising speed of the pore can be divided into three parts: steep increasing section, steady increasing section, and stable section. The pore water height of the rising vertical area increases sharply. In contrast, the constant increasing section increase rises gentle slope, while the sound section remains unchanged at a certain height. Through the comparative analysis of the data in Figure 4, the particle size of construction waste significantly influences the increase of capillary water, and the sand cushion can limit the effective expansion of capillary water. The improved stratum rises obviously at the initial stage. The \( h_{\text{type 3}} \) with poorly graded particles has a height of 50 mm, nearly 50% lower than \( h_{\text{type 1}} \) princesses to 27 mm, and \( h_{\text{type 2}} \) rises to 29 mm. The gap of 32.1 mm is not apparent, and in terms of increasing height, \( h_{\text{OSC}} \) > \( h_{\text{type 2}} \) > \( h_{\text{type 1}} \).

CWS can significantly inhibit the rise of capillary water. The best gradation is Type 1. Compared with plain soil, the value of \( h_{\text{type 1}} \) decreases by nearly 70 mm, the gradation is uniform, and the capillary water increases higher. The expansive soil particles absorb water but do not expand, so in the process of the extensive soil expansion, the construction waste particles play a skeleton role, effectively improving the reduction of porosity \( e \) and rising height of capillary water.

Comparison of the ratio of capillary water rising from the cushion layer. The rising rate of the middle \( V_{\text{plain soil}} \) is from the initial 40.8 mm/d to the final 9 mm/d, and the increasing average speed of the \( V_{\text{bare soil}} \) is 9.8 mm/d.

In other types of CWS, except for the \( V_{\text{type 1}} \), the \( V_{\text{type 2}} \) has a relatively high initial rising rate of 30 mm/d, and additional pads can be stabilized at about 20 mm/d. Compared with the stable period, the longest time for the OSC to reach a regular period is 11 days, and the shortest time for Type 1 of CWS is 7 days.

The growth rate of capillary water is different, and this comparison reflects the suction effect of the cushion material matrix. \( V_{\text{plain soil}} > V_{\text{type 3}} > V_{\text{type 2}} > V_{\text{type 1}} \). CWS is lower than plain soil by 32%, 58% and 60%, respectively. Adding construction waste particles can effectively reduce the water absorption of the expansive soil. Because the construction waste particles would not soften, the mechanical properties of the cushion are effectively guaranteed, and the waterproof performance of the cushion is improved.

4.2. Influence of pore water pressure in different horizons

The bottom of the cushion layer is set as layer 0, and the changes in the void pressure of every 10 units are as follows: \( h_{10}, h_{20}, h_{30}, h_{40} \). These points, in turn, analyse the changes in void water content, which can reflect the changes in the void skeleton on the side of the cushion layer. As shown in Figure 5.

The data analysis and simulation show that when the longitudinal hole diameter of each cushion changes compared with the pressure, the sand moisture content of \( h_{40} \) changes significantly in speed.

In the other three layers, the rate reached 62.5 Pa/d, and the different three layers are more consistent. The CWS 1 type changed slowly in \( h_{20} \), the CWS 2 type appeared at \( h_{30} \), and the CWS 3 type appeared at \( h_{40} \). Through the analysis of these data, the thickness of the cushion layer can effectively reduce the protective effect of capillary water breaking through the cushion layer. During the change of the cushion layer's pore water pressure, the cushion layer's thickness should not be less than 0.4m.

Comparing \( \omega_{\text{type 2}} \) and \( \omega_{\text{type 3}} \), \( \omega_{\text{type 3}} \) is significantly increased. When \( \omega_{\text{type 3}} \) is compared to \( \omega_{\text{type 1}} \), it has a significantly increased water content of about 20%. The gradation of the cushion greatly influences the waterproof performance of the pillow. This is because the permeability

![Figure 3](image_url). Comparison of simulated and theoretical values (a) numerical and theoretical value trend graph (b) Trend graph of numerical and theoretical values in different horizons.
Figure 4. Capillary water rising height trend of different cushions.

Figure 5. Variation of pore water pressure in different horizons (a) the OSC (b) the CWS’s type 1 (c) the CWS’s type 2 (d) the CWS’s type 3.
and diffusion coefficient of the cushion change with the gradation, affecting the cushion's matrix suction of expansive soil. The calculated results are compared with the experimental data of CWS, and the simulation is carried out with software. The data increase is consistent with the rate of change in the experiment. Because the CWS's Type 1 pore is large and permeability is strong, the capillary water at the bottom of the cushion layer rises rapidly, and its height is negligible. CWS's Type 3 infiltration channel is small, so the seepage velocity is slow. However, due to the suction of the matrix, the capillary water rises higher, and the humidity of each layer changes significantly. This is detrimental to the protection of the cushion.

5. Conclusion

This paper establishes a three-dimensional numerical simulation to study the stress and deformation characteristics of the construction waste protective layer applied to high fill expansive soil subgrade support. The influence of construction waste cushion on the rise of capillary water is analysed. The main conclusions are as follows:

1. Through theoretical analysis, it can be known that the critical factors affecting the rise of capillary water of expansive soil subgrade are the thickness of subgrade cushion, the material ratio of subgrade cushion and the matric suction of cushion materials.

2. Through the comparative analysis of theoretical and numerical simulation data, the theoretical formula established in this paper can accurately analyse the rising trend of pore water in bentonite foundation, and the numerical calculation model can conveniently check the parameters of different working conditions in the engineering site.

3. This paper innovatively uses construction waste to improve expansive soil subgrade. Through experiment, theoretical calculation, and numerical simulation analysis, it is found that construction waste particles can effectively improve subgrade porosity and reduce the space for capillary water to rise through good mechanical properties, artificially controllable particle size distribution and good hydrophilicity.

4. When the bentonite roadbed is improved by construction waste, the particle size distribution is the dominant factor. Through experiments and simulation analysis, it can be seen that when the average particle radius of construction waste is 0.5mm – 3mm, the proportion of construction waste admixture with the best dosage of type 1 is 80%.

Declarations

Author contribution statement

Yanzhao Yuan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, agents, materials, analysis tools or data; Wrote the paper.

Ruixia He: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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