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Experimental Study on Chemical Treatment Performance of Quicklime Based on Multi-layer Elastic Model

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Ca^{2+} can be dissociated with quicklime added into over-wet soil, and then has the exchange reaction with the selected Na^+ and H^+ in the soil, reducing the thickness of the water film on the surface of the original soil particles and further lowering the water content and plasticity of the over-wet soil. In this paper, typical thickness and modulus values of the reinforced layer of quicklime-processing over-wet soil were selected. And then with the bi-wheel uniaxial BZZ-100 as an example and the multi-layer elastic model as the basis, then influencing path of the reinforced layer of quicklime-processing over-wet soil on the dynamical deviatoric stress in soil base was analyzed. It was found that the thickness and modulus of the reinforced layer of quicklime-processing over-wet soil both pose negative effect on the dynamical deviatoric stress in the soil base. And the effect of the former is weak, while that of the latter is significant.

1. Introduction

Over-wet soil refers to very moist clay soils or silty soils with high moisture content, featuring poor stability, low bearing capacity, and deformation tendency (Zhou, 2017). In the course of construction, the “spring phenomenon” often occurs if improper disposal is performed on over-wet soil. That is to say, when the subgrade soil is rolled, the over-wet soil subsides under the pressure with its surroundings bouncing to form a soft plastic volume, in which condition the subgrade soil will easily fail to meet the specified compaction requirements and becomes loose (Chen, 2017). If it is not found in time, after the completion of the project, the over-wet soil section will easily cause instability, deformation, and even subsidence under various ground loads, which will seriously reduce the quality of the project. At this stage, the over-wet soil can be treated with the sun-cure drying, replacement, and admixture methods (Kun, 2017). The sun-cure drying method requires clear weather and constant relatively high temperature. Despite of simple construction, it is time-consuming and spot-specific for drying. As for the replacement method, though simple and effective, it involves huge work and high costs. Therefore, most projects choose the admixture treatment method (Xu and Wang, 2017). Despite of certain cost, the admixture treatment can quickly and effectively reduce the water content of the over-wet soil so that the over-wet soil zone can meet the rolling requirements. The admixtures mainly include quicklime, hydrated lime, cement, lime ash and NCS curing agents. Considering the cost and construction demands, quicklime becomes the main way to process over-wet soil. Domestic and foreign scholars have also done a lot of researches on reinforced layer of quicklime-processing over-wet soil. A series of research results have been obtained in terms of lime incorporation ratio, specific construction process design, and strengthening layer mechanical properties. In 2014, Qian et al., conducted an experimental study of the effect of water content, compaction degree, and stress state on the resilience modulus of quicklime-processing over-wet soil, and obtained a resilience modulus prediction model of the quicklime-processing over-wet soil. Wang Tianliang et al., studied the mechanism of the influence of the freeze thawing on the mechanical properties of quicklime-processing over-wet soil through indoor static and dynamic triaxial tests (Qian, 2016).
It is easy to encounter over-wet soil in road works, which will not only severely reduce the stability of the subgrade and bring serious safety hazards, but will also shorten the engineering life cycle. As one of the main over-wet soil treatment methods, the quicklime processing can not only effectively reduce the water content of over-wet soil, but also improve the over-wet soil plasticity, so that the soil layer reaches the compaction condition. At present, there have been studies mainly on the treatment process, lime incorporation ratio, and

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treatment methods and effects, while few studies focus on the mechanical properties of the reinforced layer of quicklime-processing over-wet soil. It is helpful to further optimize the design parameters of the quicklime-processing over-wet soil by investigating the effect of the reinforcement layer on the mechanical response of the pavement. In view of this, through the mechanical analysis, this paper explored the influence law of the modulus and thickness of the reinforced layer of over-wet soil on the dynamical deviatoric stress in soil base, in order to provide theoretical support for the application of quicklime-processing over-wet soil in road engineering.

2. The mechanism of Quicklime-processing over-wet soil

2.1 Identification of over-wet soil

Before the practical construction, the soil quality shall be checked by calculating the average consistency of the soil, so as to identify whether the soil is over-wet soil according to the wetness and consistency of the soil and relevant engineering specifications. The formula for calculating the average consistency of the soil is $w_c = \frac{w_L - \overline{w}}{w_L - w_p}$

In the formula, w_L refers to the liquid limit of the soil, with w_P as the plastic limit of the soil, $\overline{w}$ as the average water content of the soil, and w_c as the average consistency of the soil. When $w_c \geq 1$, the soil is semi-solid and could be used normally. For clay soil, if $w_c \leq 0.8$, the soil is identified as the over-wet soil. As for silty soil, the soil is identified as the over-wet soil when $w_c \leq 0.75$.

2.2 The specific improvement of Quicklime on over-wet soil

First of all, quicklime can effectively reduce the water content of over-wet soil (Xiao, 2016). On the one hand, when quicklime is incorporated into over-wet soils, the mixing of dry and wet materials can reduce the water content of over-wet soil. On the other hand, quicklime can react chemically with water to produce calcium hydroxide. The specific chemical reaction formula is GaO+H_2O=$Ga(OH)_2$. In this process, about 32 grams of water are consumed per 100 grams of calcium oxide, with much heat released at the same time, which further promotes the evaporation of the original moisture in the over-wet soil.

Secondly, the quicklime added can expand the optimal water content range of over-wet soil compaction. There is a clear requirement for the dry density of soil in road construction, and the maximum dry density of different soils corresponds to an optimal moisture content. The range of soil dry density required by construction corresponds to a minimum critical moisture content and a maximum critical moisture content. When the soil moisture content in the construction area is in this range, the construction requirement is met. The incorporation of quicklime into over-wet soils will increase the optimum moisture content, which in turn will increase the optimum moisture content of the corresponding dry density (Han, 2016).

Finally, the addition of quicklime can effectively reduce the plasticity of over-wet soil. When quicklime is incorporated into the over-wet soil, Ca^{2+} will be dissociated. With a large number of Na^{+} and H^{+} in the soil, the three ions will undergo the exchange reaction to reduce the thickness of the water film on the surface of the original soil particles (Yan et al., 2011). And through the cementation between lime and soil, the soil particles will see agglomeration or flocculation, thereby reducing the plasticity of over-wet soil. In this way, the compaction can be easily achieved with the soil stability further improved.

3. Analysis of the influence

3.1 Model selection and methods

The bi-wheel uniaxial BZZ-100 was used to analyze the stress of the quicklime-processing over-wet soil pavement. The contact surface between the tire and the road surface of the vehicle is represented by a circular uniformly distributed load, and the diameter of the equivalent circle is $d=\sqrt{\frac{4 \cdot p}{\pi \cdot p}}$. In the formula, the wheel load is P(kN) with P= Axial Load/4, and the tire ground pressure is p (kPa).

The instantaneous nature of the driving wheels makes the visco-plastic deformation of the pavement structure extremely small. Therefore, a high-strength and high-thickness highway can be considered as a linear elastic system, and a multi-layer elastic model can be used for calculation and analysis. The multi-layer elastic model is represented by cylindrical coordinates, as shown in Figure 1. E_i refers to the rebound modulus of each layer, with v_i as the Poisson's ratio of each layer, q as the circular uniformly distributed load, a as the radius, and H as the distance between the top surface and the uppermost boundary of the bottom layer.

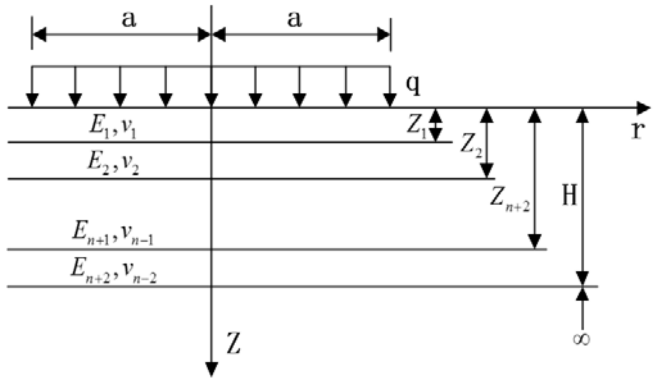

Figure 1: The multi-layer elastic model

In view of the fact that the pavement design is mostly based on the analysis of the mechanical properties of the soil base through the rebound modulus, this study mainly used the rebound modulus of the top surface of the soil base to analyze the influence of the reinforced layer of quicklime-processing over-wet soil on the dynamical deviatoric stress in the soil base. Specifically, based on the multi-layer elastic theory, the value of the thickness, modulus, and vehicle load of the reinforced layer of quicklime-processing over-wet soil were used to calculate the deflection value of the top surface pf the soil base in the pavement structure system. And then the deflection value equivalent principle was used to calculate the rebound modulus of the top surface of the soil base. The specific calculation process was as follows:
Stage 1: Search for design-oriented data, determine the pavement structure, obtain the thickness and modulus values of the reinforced layer of quicklime-processing over-wet soil, set the rebound thickness or modulus of the reinforced layer of quicklime-processing over-wet soil, and then add the vehicle load to calculate the reference deflection value I_O of the top surface of the reinforcement layer.
Stage 2: Under the same or similar vehicle load conditions, the above-mentioned pavement structure layer covered the homogeneous elastic semi-infinitive soil base. The rebound modulus was constantly adjusted to repeatedly calculate the deflection value of the top surface of the soil base until the difference of I_O values obtained at the first stage met the set tolerance requirement. The finally adjusted value was the rebound modulus value of the top surface of the soil base.

3.2 The experimental Process

Before analyzing the effect of the reinforced layer of quicklime-processing over-wet soil on the dynamical deviatoric stress in soil base, the effect of the reinforced layer of quicklime-processing over-wet soil on the strength of the soil base and the top compressive stress of the soil base must be determined, which was conducted based on the BISAR 3.0 program from two perspectives of the thickness and modulus of the reinforced layer of quicklime-processing over-wet soil.
Firstly, the effect of thickness and modulus of the reinforced layer of quicklime-processing over-wet soil on the strength of soil base was analyzed based on the multi-layer elastic model. According to the results of tests with different moisture contents, the modified soil base rebound modulus value ranged from 10MPa to 30MPa, and the thickness of the reinforced layer of quicklime-processing (Antiohos et al., 2006; Ruiz et al., 2008) over-wet soil ranged from 20cm to 60cm,with the modulus value between 100MPa and 500MPa. In the above ranges, the efficacy of the reinforced layer of quicklime-processing over-wet soil can be effectively exerted as shown in Table 1.

Table 1: Applicable ranges for efficacy of the reinforced layer of quicklime-processing over-wet soil

Soil base rebound modulus (MPa)	Thickness of the reinforced layer of quicklime-processing over-wet soil (cm)					Modulus of the reinforced layer of quicklime-processing over-wet soil (MPa)				
	20	30	40	50	60	100	200	300	400	500
10	10.9	11.6	12.4	13. 5	14. 2	11.4	12.5	13.7	14.9	16.3
15	16.5	17.5	18.9	19.5	20.9	17.9	18.7	19.8	21.4	22.8
20	21.8	23.7	24.6	25.8	27.6	22.8	23.6	25.4	27.5	29.9
25	27.2	28.9	30.4	31.9	33.1	28.4	29.8	31.2	34.1	36.4
30	32.8	34.7	36.7	39.1	40.3	32.7	35.9	37.6	40.5	43.7

From the above table, it can be seen that when the rebound modulus of the soil base is the same, the greater the thickness of the reinforcement layer, the smaller the increase in the strength of quicklime-processing over-wet soil subgrade; the larger the modulus of the reinforcement layer, the greater the increase in the strength of the quicklime-processing over-wet soil subgrade.

Secondly, the rebound modulus of the over-wet soil base and the modulus of the reinforced layer of quicklime-processing over-wet soil were selected as 15 MPa and 200 MPa respectively, and the influence of the thickness and modulus of the reinforced layer of quicklime-processing over-wet soil on the top compressive stress of the soul base were analyzed. The calculation points were set as shown in Figure 2. *x* axis is the driving direction of the traffic vehicle, with y axis as the direction of the road cross-section and *z* axis as the depth direction of the roadbed and the road surface.

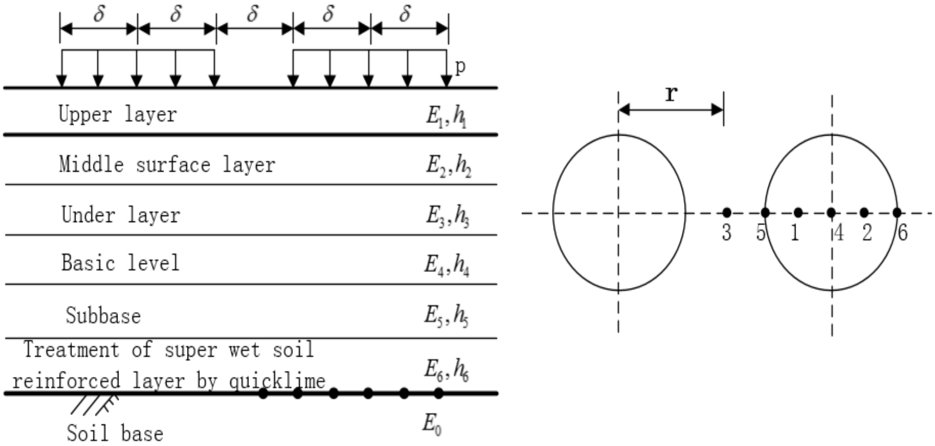

Figure 2: Calculating points

According to Figure 2 and the contact position between the wheel and the subgrade surface, the coordinates for feature points calculation were selected as shown in Table 2. Among them, Point 1 was the inner edge point where the wheel touched the subgrade surface; Point 2 was the center point of the contact area between the wheel and the subgrade surface; Point 3 was the outer edge point where the wheel and the subgrade surface contacted; Point 4 was the middle point of the gap between the wheel and the subgrade surface; Point 5 was the midpoint of Point 1 and Point 2; Point 6 was the midpoint of Point 3 and Point 2.

Table 2: Coordinates of calculating points (unit: m)

No.	1	2	3	4	5	6
Coord	x y	x y	x y	x y	x y	x y
Inate	0.0 0.053	0.0 0.16	0.0 0.267	0.0 0.0	0.0 0.106	0.0 0.213

From the calculation results, it can be seen that as for the improvement of the performance of the over-wet soil subgrade, when the thickness of the reinforced layer was 20cm-60cm, the maximum change rate of the compressive stress on the top surface of the soil base was 29%. When the modulus of the reinforcement layer was 100MPa-500MPa, the maximum change rate of the compressive stress on the top surface of the soil base was 23.7%. And the optimum value of the rebound modulus of the over-wet soil base and the modulus of the reinforced layer of quicklime-processing over-wet soil were 15 MPa.

Finally, due to the dynamical deviatoric stress generated by the traffic load in the soil base that can lead to the plastic deformation of the roadbed by accumulation to a certain extent, the traffic load was further added on the basis of the above optimal value for the analysis of the effect rule of the thickness and modulus of the reinforced layer of quicklime-processing over-wet soil on the dynamic deviatoric stress in the soil base.

Take the point 1.2m distant from the subgrade surface under Point 4 in Figure 2 as the research object, and calculate the dynamical deviatoric stress generated by the traffic load in the soil base through $\sigma_d = \sigma_z - \frac{(\sigma_x+\sigma_y)}{2}$. σ_d refers to the dynamical deviatoric stress of the traffic load in the soil base, with σ_z as the vertical stress and σ_x and σ_y as the stresses in the *x* and *y* directions respectively.

3.3 Experimental results

As for the thickness of the reinforced layer of quicklime-processing over-wet soil, the modulus of the reinforced layer of quicklime-processing over-wet soil was 200 MPa based on the optimum value of 15 MPa for the rebound modulus of over-wet soil base. The introduction of traffic load led to that the greater the thickness of the reinforcement layer, the smaller the dynamical deviatoric stress in soil base, as shown in Figure 3. During the thickness of the reinforced layer of quicklime-processing over-wet soil increasing from 20cm to 60cm, the dynamical deviatoric stress in soilbase decreased by 0.03. This means that the change in the thickness of the reinforcement layer has little influence on the dynamical deviatoric stress in soil base.

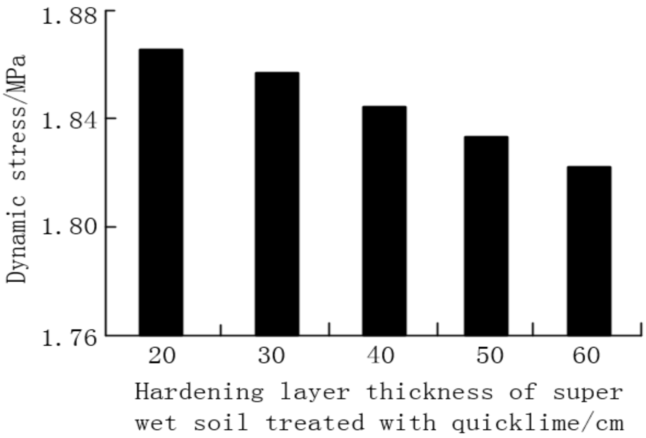

Figure 3: The influence of the thickness of the reinforced layer of quicklime-processing over-wet soil on the dynamical deviatoric stress in soil base

Similarly, as for the modulus of the reinforced layer of quicklime-processing over-wet soil modulus, based on the optimal rebound modulus of over-wet soil base, the thickness of the reinforced layer of quicklime-processing over-wet soil was selected as 40 cm. The introduction of traffic load concluded that the higher the modulus of the reinforced layer, the smaller the dynamical deviatoric stress in soil base, as shown in Figure 4. As the modulus of the reinforced layer of quicklime-processing over-wet soil increased from 100 MPa to 500 MPa, the dynamical deviatoric stress in soil base decreases by 0.27, indicating the change in the modulus of the reinforcing layer has significant influence on the dynamical deviatoric stress in soil base.

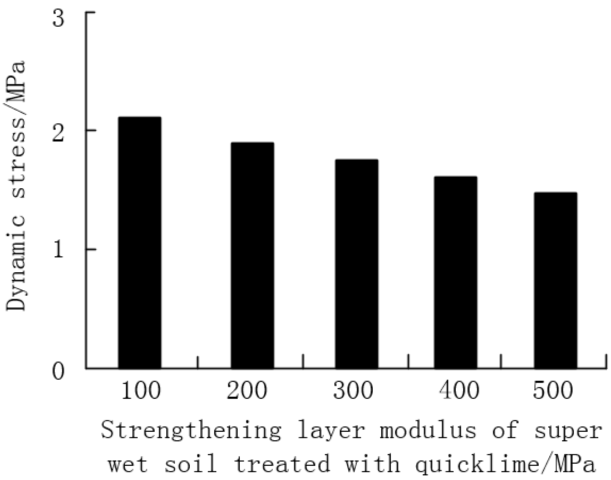

Figure 4: The influence of the modulus of the reinforced layer of quicklime-processing over-wet soil on the dynamical deviatoric stress in soil base

4. Conclusion

In summary, the incorporation of quicklime into over-wet soil will dissociate Ca^{2+}, and through the exchange reaction with the selected Na^{+} and H^{+} in the soil, the water film thickness on the surface of the original soil particles can be reduced. In addition, the cementation between lime and soil can reduce the water content and plasticity of the over-wet soil and enhance the stability of the reinforced layer. As a component of the subgrade pavement structure, the reinforced layer of quicklime-processing over-wet soil mainly influences the internal dynamical deviatoric stress in the soil base by its thickness and modulus. When the thickness and modulus of the reinforced layer of quicklime-processing over-wet soil increase, the dynamical deviatoric stress in the soil base decreases, with little effect by the thickness change and significant effect by the modulus change. Due to simple processing method and enhancement in the quicklime-processed over-wet soil, the quicklime-processed over-wet soil brings good economic benefits in practical road projects. Therefore, in the future, the quicklime treatment of over-wet soil should be fully utilized to provide technical support for road engineering optimization in seasonally frozen areas.

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