FLUCTUATION EFFECT OF EQUILIBRIUM MOISTURE CONTENT OF LOW SUBGRADE UNDER HIGH GROUNDWATER LEVEL IN HOT AND HUMID CLIMATIC REGIONS

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ABSTRACT

In order to reveal the fluctuation effect of equilibrium moisture content of low subgrade in hot and humid climatic regions, the effect of temperature on the fluctuation of the equilibrium moisture content of subgrade was analysed. Taking the typical climate and the subgrade soil in Fujian province as an example, three technological methods - theoretical analysis, numerical simulation and indoor simulation experiment - were adopted in the investigation of the fluctuation effect of equilibrium moisture content of subgrade. The results show that, computing results from the formula of the equilibrium moisture content of subgrade, the numerical simulation results are closer to each other in consideration of the temperature effect. The test results can not reflect the relationship between the equilibrium moisture content and the height of embankment. The maximum fluctuation range of the equilibrium moisture content of the cement concrete pavement is less than 2 percent in Fujian area, and this phenomenon presents the effect of the moist-hot climate on the equilibrium moisture content. Equilibrium moisture content presents a declining trend with the increment of the temperature and the compactness. So, if matric potential considering temperature indirectly reflects the influence of thermal potential, then the equilibrium moisture content of low subgrade under high groundwater level can be estimated approximately. The fluctuation range of equilibrium moisture content in different layers of subgrade can be reduced effectively with the increment of the roadbed compaction degree.

KEYWORDS

High groundwater level, low subgrade, equilibrium moisture content, fluctuation effect, hot and humid climatic regions

INTRODUCTION

In China, low subgrades exist widely in soft soil areas due to its small land occupation. It is well known that a moisture content of subgrade soil is close to the optimum moisture content during the filling construction of subgrade. The moisture content near the centre of the subgrade will present seasonal variation because of factors such as the fluctuation of groundwater level and traffic load and it can reach equilibrium moisture content within about 5 years. Therefore, the design parameters of subgrade under equilibrium moisture content conditions are much more suitable for the long-term performance of subgrade.

In light of this background, many scholars have made further research on the equilibrium moisture content of subgrade. Furthermore, a large amount of achievements have been obtained in this field, such as the equation for prediction of equilibrium moisture content in the subgrade based on field monitoring data [1-2], the equilibrium moisture content of subgrade obtained by test of mould of water curing [3-4], and the prediction method of equilibrium moisture content of unsaturated clay subgrade outside the affected zone of atmospheric precipitation/evaporation based on a single-valued function relationship between moisture content and matric suction of soils [5-6].

All of these results have important significance for perfecting the durability design method of subgrade, but there is limited information on the effect of temperature on the equilibrium moisture content of subgrade.

However, it is known that changes of air temperature in different seasons will lead to a change of suction, and the temperature characteristics of suction play an important role in the pavement-subgrade system. For example, annual variation of measured temperature of roadbed in Nanping City of China is about 25 ˚C. Even so, how they influence the fluctuation effect of equilibrium moisture content of roadbed is still unknown. To address these issues, this paper takes a typical hot and humid climatic region in Fujian province of China as an example, and the fluctuation effect of equilibrium moisture content of subgrade in this zone is analysed based on the combination of theoretical analysis, numerical simulation and indoor simulation experiment.

PREDICTION OF EQUILIBRIUM MOISTURE CONTENT OF SUBGRADE CONSIDERING THE TEMPERATURE EFFECT

Soil-Water Potential Principle of Subgrade Under High Groundwater Level Condition

According to the theory of soil water potential, soil water potential consists of five parts: matric potential, gravitational potential, solute potential, pressure potential and temperature potential. In general, pressure potential of unsaturated soil is equal to zero and solute potential of unsaturated soil may not be considered. Because it is very difficult for the temperature potential to be stated by a mathematical formula, the matric potential considering the temperature effect is used to indirectly reflect the effect of temperature on soil water potential in this paper. As shown in Fig. 1, the matric potential of subgrade will lead to a rise of the capillary water. Finally, when the moisture content of subgrade reaches equilibrium state, then the total soil-water potential under different depth of subgrade should be equal. If the base level is groundwater, the total soil-water potential of subgrade should be zero. So, the total soil-water potential of subgrade at point A can be described by:

$$\psi = \psi_{\mathrm{m}} + \psi_g = 0 \tag{1}$$

Where,

ψ ---the total soil-water potential, m;

ψ_m ---the matric potential, m;

ψ_g ---the gravity potential, m.

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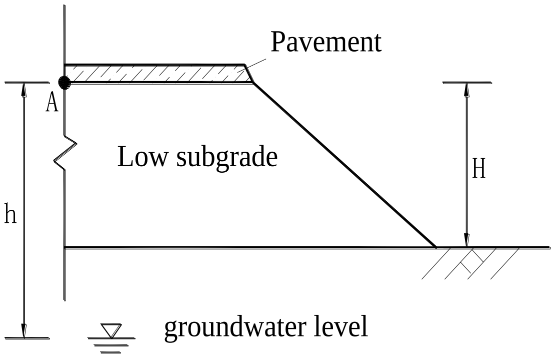

Fig. 1. - Typical Cross Section

The Matric Potential Considering the Temperature Effect

Three different types of granite residual soil in Fujian province of China were chosen for test research on soil-water characteristic curve. Physical properties of granite residual soil are shown in Tab. 1.

Tab. 1. - Physical Properties of Granite Residual Soil

Soil Sample	Particle Composition（%）				Maximum Dry Density	Optimum Moisture Content	Specific Gravity	Liquid Limit	Plastic Limit	Plastic Limit Index
	>2 mm	2~ 0.075 mm	0.002~ 0.075 mm	<0.002 mm	g·cm^{-3}	%	-	%	%	-
Ⅰ	22.22	24.36	37.13	16.29	1.76	14.7	2.64	40.48	18.36	22.12
Ⅱ	13.54	50.78	25.32	10.36	1.83	13.5	2.60	46.82	22.78	24.04
Ⅲ	8.00	31.56	39.42	21.02	1.71	17.7	2.55	60.12	33.47	26.65

The filter paper test was used to determine soil-water characteristic curve [5]. The test data of seven soil samples will determine the relationship between the moisture content and the matric suction. Each type soil of test consists of four different temperature conditions (5 ˚C, 20 ˚C , 30 ˚C , and 45 ˚C). According to the test data, the Van Genuchten Model was used to fit the relationship between the moisture content and the matric suction of soils. It can be described by [7]:

$$\theta=\frac{\theta_s-\theta_r}{\left[\left(a\psi_m\right)^n+1\right]^m}+\theta_r \tag{2}$$

Where，

θ ---the moisture content, %;

θ_s ---the saturated water content, %;

θ_r ---the residual water content, %;

a---the fitting parameter of soil-water characteristic curve, 1/cm;

m, n---the fitting parameters of soil-water characteristic curve, m=1-1/n.

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The Fitting parameters of Van Genuchten Model of three soil samples are shown in Tab. 2.

Tab. 2. - Fitting Parameters of Van Genuchten Model of Three Soil Samples

Soil Sample	Temperature(℃)	a(1/cm)	n	θ_r (%)	θ_s (%)	Residual Sum of Squares
Soil sample Ⅰ	5	0.4343	1.1843	2.51	24.91	1.0456E-4
	20	0.4980	1.2214	2.43	26.83	7.3821E-4
	30	0.1385	1.2531	2.3	24.98	8.8935E-4
	45	0.1317	1.1473	3.10	25.86	4.5761E-4
Soil sample Ⅱ	5	0.5935	1.1617	2.19	25.83	1.6514E-4
	20	0.1720	1.2279	3.97	25.19	6.4134E-4
	30	0.4655	1.1731	3.9	25.31	2.9543E-4
	45	0.2021	1.2519	2.46	24.25	6.4099E-4
Soil sample Ⅲ	5	0.0299	1.1903	4.97	27.18	8.45098E-5
	20	0.0011	1.5485	3.62	25.03	4.8977E-4
	30	0.0084	1.2663	2.5	25.63	3.1787E-5
	45	0.0030	1.3270	6.52	25.68	2.309E-4

It can be seen from Tab. 2 that the model has high fitting accuracy, since the residual sum of squares of fitting is less than 0.001. Many studies show that the influence of temperature on soil-water characteristic curve of unsaturated soil should not be neglected. It is found that there is a power function relationship between temperature and parameters of Van Genuchten model based on the thermodynamics principle[8]. Using the method above, the relationship between temperature and parameters of Van Genuchten model was built based on the data in Tab. 2. It can be described by:

Soil sample Ⅰ:

$$\begin{cases} a = 8E\text{-}05T^3 - 0.0058T^2 + 0.1088T + 0.0252 & R^2 = 1 \\ n = -1E\text{-}05T^3 + 0.0006T^2 - 0.0075T + 1.2075 & R^2 = 1 \\ \theta_r = 7E\text{-}05T^3 - 0.0044T^2 + 0.0652T + 2.284 & R^2 = 1 \\ \theta_s = 0.0006T^3 - 0.0431T^2 + 0.9142T + 21.348 & R^2 = 1 \end{cases} \quad (3)$$

Soil sample Ⅱ:

$$\begin{cases} a = -0.0001T^3 + 0.008T^2 - 0.1743T + 1.2769 & R^2 = 1 \\ n = 2E\text{-}05T^3 - 0.0015T^2 + 0.0318T + 1.0382 & R^2 = 1 \\ \theta_r = 4E\text{-}05T^3 - 0.007T^2 + 0.2755T + 0.984 & R^2 = 1 \\ \theta_s = -0.0001T^3 + 0.0097T^2 - 0.2141T + 26.674 & R^2 = 1 \end{cases} \quad (4)$$

Soil sample Ⅲ:

$$\begin{cases} a = -4E\text{-}06T^3 + 0.0003T^2 - 0.0077T + 0.0613 & R^2 = 1 \\ n = 8E\text{-}05T^3 - 0.0067T^2 + 0.1477T + 0.6094 & R^2 = 1 \\ \theta_r = 0.0004T^3 - 0.023T^2 + 0.2737T + 4.126 & R^2 = 1 \\ \theta_s = -0.0003T^3 + 0.0224T^2 - 0.5677T + 29.49 & R^2 = 1 \end{cases} \quad (5)$$

The equilibrium moisture content of subgrade considering the temperature effect can be approximately predicted by Equation (2).

NUMERICAL SIMULATION OF EQUILIBRIUM MOISTURE CONTENT OF SUBGRADE

Hydrothermal Modelling

Hydrothermal modelling can be described by [9] [10]:

$$\begin{cases} \dfrac{\partial \theta}{\partial t} = \dfrac{\partial}{\partial z}\left(\mathrm{D}(\theta,T)\dfrac{\partial \theta}{\partial z} \right) + \dfrac{\partial}{\partial z}\left(\mathrm{D}_T \dfrac{\partial T}{\partial z} \right) - \dfrac{\partial k(\theta,T)}{\partial z} \\ \rho c_v(\theta)\dfrac{\partial T}{\partial t} = \lambda_h(\theta)\left(\dfrac{\partial^2 T}{\partial z^2} \right) \end{cases} \tag{7}$$

Where，

T---the temperature, ℃;

$D(\theta,T)$ --- the moisture diffusion coefficient considering temperature effect, cm^2/min;

D_T --- the moisture diffusion coefficient considering temperature gradient effect, cm^2/（min.℃）;

$k(\theta,T)$ ---the hydraulic conductivity considering the temperature effect, cm/min;

$c_v(\theta)$ ---the specific heat capacity considering temperature effect, J/(kg.℃);

$\lambda_h(\theta)$ ---the thermal conductivity considering moisture effect, W/(m.℃) .

The finite difference model is adopted to solve the hydrothermal modelling based on alternating direction implicit method. Implicit differential scheme of Equation (7) can be described by [9]:

$$\begin{cases} \dfrac{\theta_i^{k+1} - \theta_i^k}{\Delta t} = D_{i+1/2}\left(\theta,T\right)\dfrac{\theta_{i+1}^{k+1} - \theta_i^{k+1}}{\Delta z^2} + D_{i-1/2}\left(\theta,T\right)\dfrac{\theta_{i-1}^{k+1} - \theta_i^{k+1}}{\Delta z^2} - \dfrac{k_{i+1/2}^k\left(\theta,T\right) - k_{i-1/2}^k\left(\theta,T\right)}{\Delta z} \\ \dfrac{T_n^{i+1} - T_n^i}{\Delta t} = \dfrac{T_{n+1}^i + T_{n-1}^i - 2T_n^i}{\Delta z^2}\dfrac{\lambda_k(\theta)}{\rho c_v(\theta)} \end{cases} \tag{8}$$

The height of the numerical model is 5 m. According to its basic ideology, the analysis is conducted using MATLAB.

Material Parameters

The material parameters in the numerical model are shown in Tab. 3 and Tab. 4. Tab. 3 shows the thermal parameters of cement concrete pavement which is simplified as a single layer, and Tab. 4 shows the hydrothermal parameters of subgrade considering the temperature effect.

Tab. 3. - Thermal Parameters of Cement Concrete Pavement [11]

Thermal Conductivity (W/m·℃)	Density (g·cm^{-3})	Heat Capacity (J/kg·℃)	Solar Radiation Absorption Rate	Pavement Emissivity	Stefan-Boltzmann Constant (J/s·m^2·K^4)
1.5	2.4	900	0.75	0.85	5.67E-8

Tab. 4. - Hydrothermal Parameters of Subgrade [11]

Soil Sample	Water Diffusivity (cm^2/min)	Diffusion Coefficient of Hygrothermal (cm^2/min.℃)	Hydraulic Conductivity (cm/min)	Specific Heat Capacity (J/kg.℃)	Thermal Conductivity (W/m.℃)
Ⅰ	$0.14\chi\left(\frac{\theta}{0.36}\right)^{5.4}$	4.6E-5	$4.2\text{E-}4\alpha\left(\frac{\theta}{0.36}\right)^{2.9}$	$1.31K+4.18\theta+0.001$	$\frac{\lambda_a G_s \lambda_{ha}+(\lambda_w\lambda_{hw}-\lambda_a\lambda_{ha})G_s\theta+(\lambda_m\lambda_{hm}-\lambda_a\lambda_{ha})\rho_d K}{\lambda_a G_s+(\lambda_w-\lambda_a)G_s\theta+(\lambda_m-\lambda_a)\rho_d K}$
Ⅱ	$0.26\chi\left(\frac{\theta}{0.31}\right)^{5.5}$	5.4E-5	$8.7\text{E-}5\alpha\left(\frac{\theta}{0.31}\right)^{3.2}$	$1.39K+4.18\theta+0.001$	
Ⅲ	$0.02\chi\left(\frac{\theta}{0.35}\right)^{4.7}$	6.2E-5	$3\text{E-}5\alpha\left(\frac{\theta}{0.35}\right)^{3.1}$	$1.32K+4.18\theta+0.001$	

In Tab. 4, every symbol is expressed as follows:

χ ---the coefficient of diffusion considering temperature effect;

α ---the coefficient of hydraulic conductivity considering temperature effect;

k ---the compactness of subgrade, 95%;

λ_m ---the weighted coefficient of soil particle, soil sample Ⅰ, λ_m = 0.33, soil sample Ⅱ, λ_m =0.27, soil sample Ⅲ, λ_m = 0.28;

λ_w ---the weighted coefficient of water, λ_w =1;

λ_a ---the weighted coefficient of air, $\lambda_a=\frac{0.6321\theta+0.2334}{1.8132\theta-1.8962\theta^2-0.075}$;

λ_{ha} ---the thermal conductivity of air, W/(m .℃);

λ_{hw} ---the thermal conductivity of water, W/(m .℃);

λ_{hm} ---the thermal conductivity of soil, W/(m .℃).

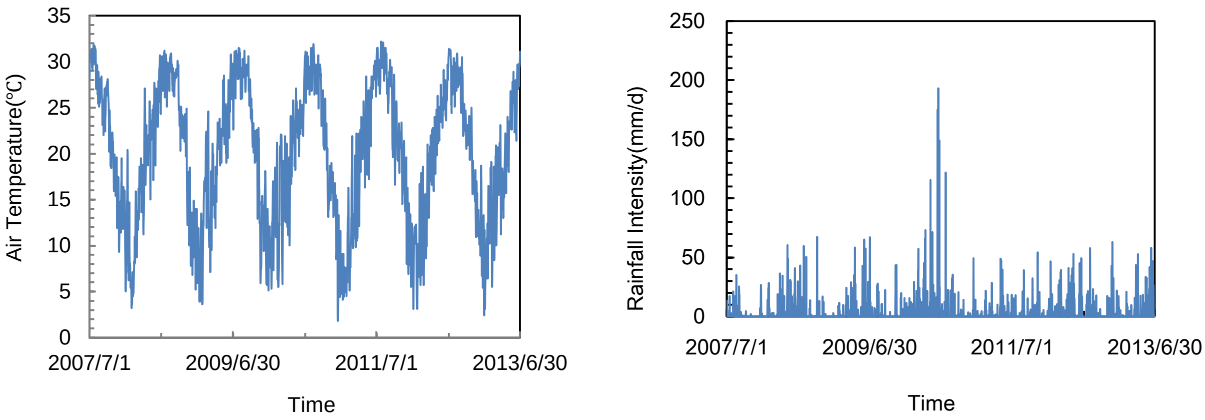
The Initial and Boundary Condition

The boundary condition of the upper surface of subgrade is heat flux and an impervious boundary without considering the impact of evaporation.

The initial moisture content of subgrade is the optimum moisture content and the initial temperature is the average atmospheric temperature (20˚C). The depth of groundwater level is 2.5m.

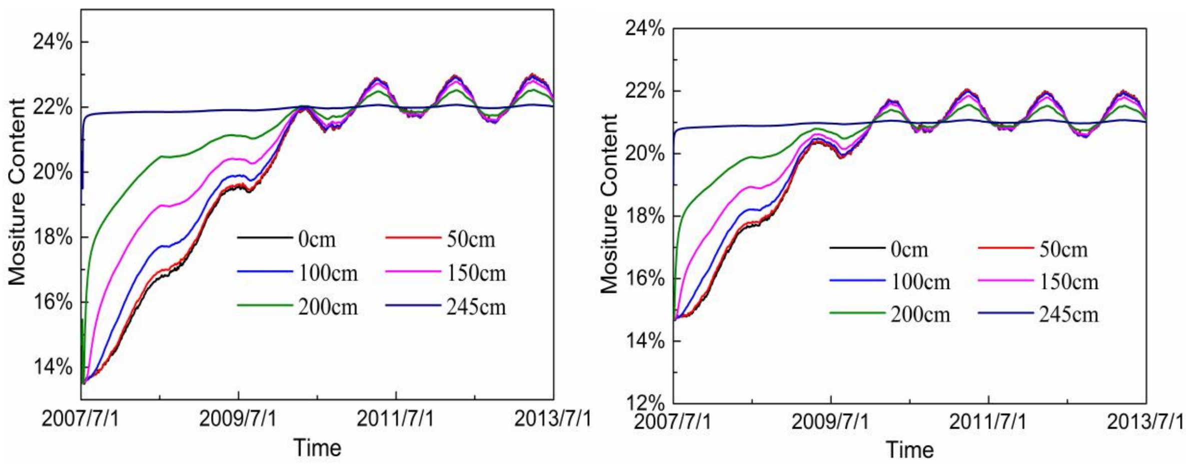
Numerical Simulation Results Analysis

In order to calculate seasonal variation of the moisture content of subgrade, climate data in Nanping City of China were selected as the typical meteorological boundary. The air temperature from July 1, 2007 to June 30, 2013 is shown in Fig. 4. The calculation results for different depths are shown in Fig. 5.

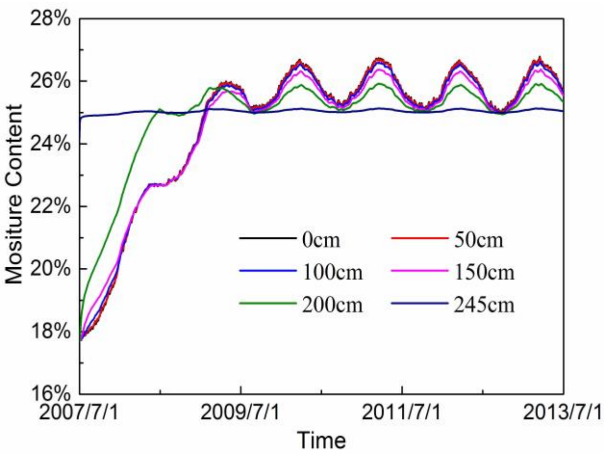


(a） Air Temperature *(b）Rainfall Intensity*

Fig. 4. - Seasonal Variation of Meteorological Data in Nanping Area



(a） Soil Sample Ⅰ *(b）Soil Sample Ⅱ*



(c) Soil Sample Ⅲ

Fig. 5. Seasonal Variation of Moisture Content of Low Subgrade in Nanping Area

In Fig. 5, it can be seen that moisture content at different depths of three types of subgrade present an initial increasing and then fluctuation trend. The maximum fluctuation range of the equilibrium moisture content of the cement concrete pavement is less than 2 percent.

THE TEST FOR EQUILIBRIUM MOISTURE CONTENT OF SOIL AT DIFFERENT TEMPERATURE CONDITIONS

Test Procedures

A mould of water curing was used to simulate the impact of field environment condition on the equilibrium moisture of subgrade [3-4]. The test device is shown in Fig. 6.

The test procedures are as follows:

(1) Wet curing mould making

A mould with a diameter of 7cm and height of 19 cm is made using PVC material. There are holes around the wall of the mould. In order to prevent water loss, wood blocks are used in the two ends of mould.

(2) Sample preparation

First, soil samples with the optimum moisture content are compacted by six layers in order to ensure adequate soil compaction. The height of each layer of soil is about 3 or 4cm. Soil samples are compacted by compaction instrument. Second, the samples are encapsulated by a non-woven material with a thickness of 0.01mm. Third, the samples are placed in the mould. In order to prevent lateral expansion, a nut is used to secure the mould. Sample preparation is shown in Fig. (7).

(3) Accelerated saturation stage of the soil sample

When compaction is completed, the soil sample is weighed. In order to accelerate saturation of the soil, the samples are put into a bucket under different temperature conditions for three hours.

(4) Wet curing stage of the soil sample

In order to ensure that the soil samples will absorb water uniformly because of imbalance of potential energy, the mould sealed by plastic bags is placed in a constant temperature and humidity system with a relative humidity of 100% and different temperatures of 5 ˚C, 20 ˚C, 30 ˚C, 45 ˚C, respectively. The soil samples should be inverted every 12h to ensure the uniformity. The relative humidity and moisture of soil samples should be recorded every 24 hours until the weight of soil samples do not change in two days. The test period is about 7d to 14d.

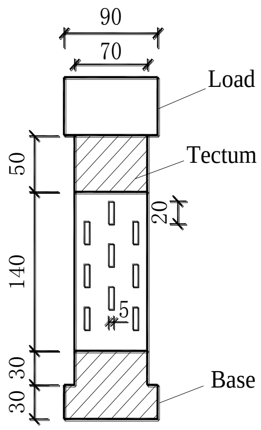


Fig. 6. - Mould of Water Curing (unit: mm)

Fig. 7. - Sample Preparation

Results Analysis of Indoor Test

Tests for equilibrium moisture content of three types soil of table 1 were conducted under the different conditions of three compaction degrees (88%, 95%, 100%) and four temperatures (5 ˚C, 20˚C, 30˚C, 45˚C). In order to reduce the errors, parallel tests of each test mode were conducted. The relationship curve of moisture content of soil sample Ⅰ and time is shown in Fig 8. Tab. 3 shows the equilibrium moisture content of the three types of soil.

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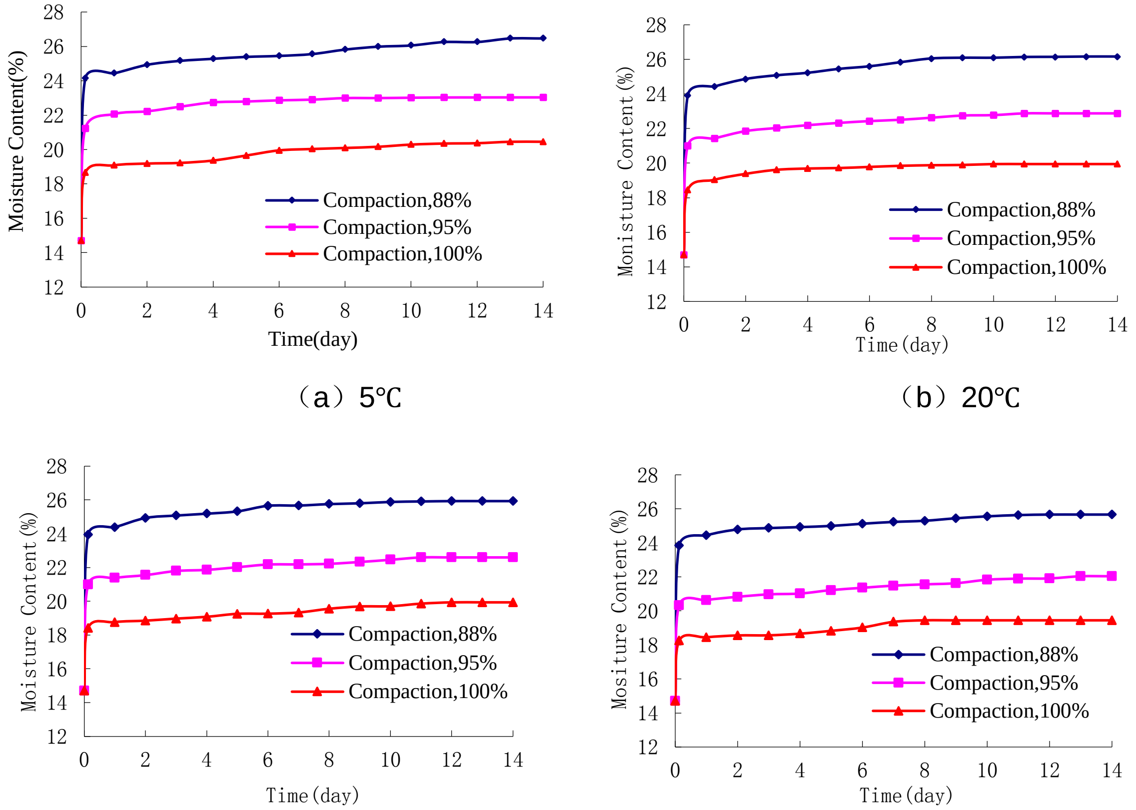

（a）5℃ （b）20℃

(c) 30℃ (d) 45℃

Fig. 8. - Time-dependent Curve of Moisture Content of Soil Sample Ⅰ

Tab. 5 - Test Results of Equilibrium Moisture Content

Temperature(℃)	Compaction(%)	Soil sample Ⅰ		Soil sample Ⅱ		Soil sample Ⅲ	
		Optimum Moisture Content (%)	Equilibrium Moisture Content (%)	Optimum Moisture Content (%)	Equilibrium Moisture Content (%)	Optimum Moisture Content (%)	Equilibrium Moisture Content (%)
5	88	14.7	26.47	13.5	24.76	17.7	28.44
	95	14.7	23.03	13.5	21.63	17.7	26.21
	100	14.7	20.45	13.5	19.96	17.7	21.74
20	88	14.7	26.16	13.5	24.47	17.7	26.95
	95	14.7	22.88	13.5	21.40	17.7	25.85
	100	14.7	19.95	13.5	19.15	17.7	20.23
30	88	14.7	25.93	13.5	24.27	17.7	27.85
	95	14.7	22.60	13.5	21.17	17.7	25.54
	100	14.7	19.93	13.5	18.99	17.7	21.64
45	88	14.7	25.66	13.5	24.20	17.7	26.13
	95	14.7	22.03	13.5	20.95	17.7	25.01
	100	14.7	19.45	13.5	18.56	17.7	20.53

In Fig. 5 and Tab. 5, it can be seen that the equilibrium moisture content of samples decreases with the increase of temperature. For example, the equilibrium moisture content of three soil samples decreases slightly when the temperature increased from 5 ˚C to 45 ˚C. Compaction has a great influence on the equilibrium moisture content. The equilibrium moisture content of samples decreases with the increase of the compaction. For example, the equilibrium moisture content of three soils decreases from 5% to 7% when the compaction of three soils increases from 88% to 100%.

It indicates that the increase of compaction of the subgrade can reduce the increase of equilibrium moisture content and improve the water stability of the subgrade.

A COMPARISON ON DIFFERENT PREDICTIONS OF EQUILIBRIUM MOISTURE CONTENT

In order to contrast different predictions of equilibrium moisture content, the calculation results of formula which considering the temperature effect, numerical simulation and indoor test are shown in Tab. 6.

Tab. 6. - Prediction of Equilibrium Moisture Content of Different Soils

Soil Sample	Temperature (℃)	Formula Method (%)			Indoor Test (%)	Numerical Simulation (%)
		h=1m	h=2.5m	h=4m		h=2.5m
Soil sample Ⅰ	5	23.83	23.46	21.47	23.03	21.10~22.81
	20	24.31	23.40	22.06	22.88	
	30	24.61	23.93	23.26	22.60	
	45	25.59	25.15	24.74	22.03	
Soil sample Ⅱ	5	24.44	22.91	21.87	22.63	20.85~22.09
	20	24.77	24.03	23.35	22.40	
	30	24.26	22.96	22.04	22.17	
	45	23.70	22.75	21.89	21.95	
Soil sample Ⅲ	5	27.13	27.02	26.91	26.21	25.01~26.60
	20	25.03	25.03	25.03	25.85	
	30	25.62	25.59	25.56	25.54	
	45	25.68	25.67	25.67	25.01	

From Tab. 6, the following conclusions can be drawn:

1. The equilibrium moisture content decreases with the increase of height of subgrade. This indicates that if the temperature potential is constant, the matric potential will decrease with the increase of gravitational potential and the soil tends to be more dry;
2. Although the equilibrium moisture content determined from the tests is close to formula method and numerical simulation, the test results cannot reflect the relationship between the equilibrium moisture content and the height of embankment. Therefore, the test method needs further improvement;
3. The annual variation of temperature of roadbed in Fujian province range from 8 ˚C to 28˚C [11]. Although the numerical analysis method cannot obtain the moisture

content of subgrade at a specified temperature, the peak of equilibrium moisture content calculated by the numerical analysis method is close to the formula method considering the temperature effect where the temperature is 5 ˚C and 30 ˚C, and their quantitative difference is less than 1.5%. This indicates that if matric potential considering the temperature indirectly reflects the influence of thermal potential, the equilibrium moisture content of low subgrade under high groundwater level can be estimated approximately;

4. The results of the three methods show that the maximum fluctuation range of the equilibrium moisture content of the cement concrete pavement is less than 2 percent in Fujian area, and this phenomenon presents the effect of the moist-hot climate on the equilibrium moisture content.

CONCLUSIONS

This paper presents a study on fluctuation effect of equilibrium moisture content of low subgrade under high groundwater level in hot and humid climatic regions. Based on this study, the following conclusions can be made:

1）Computing results from the formula of the equilibrium moisture content of subgrade, the numerical simulation results are closer to each other in consideration of the temperature effect. This indicates that if matric potential considering temperature indirectly reflects the influence of thermal potential, the equilibrium moisture content of low subgrade under high groundwater level can be estimated approximately.

2）Although the equilibrium moisture content from the test is close to the results of the formula method and numerical simulation, the test results can not reflect the relationship between the equilibrium moisture content and the height of embankment. Therefore, the test method needs further improvement.

3）The maximum fluctuation range of the equilibrium moisture content of the cement concrete pavement is less than 2 percent in Fujian area, and this phenomenon presents the effect of the moist-hot climate on the equilibrium moisture content.

4）Equilibrium moisture content presents a declining trend with the increment of the temperature and the compactness. Furthermore, the fluctuation range of equilibrium moisture content in different layers of subgrade can be reduced effectively with the increment of the roadbed compaction degree.

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