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Research Article

Experimental Study on Dynamic Resilient Modulus of Lime-Treated Expansive Soil

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Dynamic resilient modulus is the design index of highway subgrade design code in China, which is significantly affected by the traffic loads and environmental changes. In this study, dynamic triaxial tests were conducted to investigate the influence of moisture content, compaction degree, cyclic deviator stress, and confining pressure on lime-treated expansive soil. The suitability of UT-Austin model to lime-treated expansive soils was verified. The results indicate that the dynamic resilient modulus of lime-treated expansive soils increases nonlinearly with the increase of compaction degree, while decreases nonlinearly with the increase of dynamic stress level. The dynamic resilient modulus decreases linearly with the increase of moisture content and increases linearly with the increase of confining pressure. Moreover, the moisture content has a more significant effect on the dynamic resilient modulus of lime-treated expansive soil. Therefore, it is necessary to ensure the stability of soil humidity state and its excellent mechanical properties under long-term cyclic loading for the course of subgrade filling and service. Finally, the calculated results of the UT-Austin model for dynamic resilient modulus show a good agreement with the test results.

1. Introduction

Expansive soil is rich in expansive clay minerals, which contributes to the remarkable engineering characteristics of swelling and softening when exposed to water and shrinkage and cracking after losing water. The behaviors of expansive soil pose a severe threat to many overlying structures, including roads and lightly loaded structures [1–4]. So it often needs to be improved before it can be used as the filling material for subgrade. Over the past few decades, many scholars have proposed many methods to reduce or limit the destructive effect of the volumetric change of expansive soil. The chemical stabilization [5, 6], replace of surface expansive soil, increasing the compaction, moisture control [7], and traditional treatment including lime, cement, and fly ash [8–12] have been used to control the behavior. Lime treatment is by far the most commonly used way to suppress the change of volume and enhance the strength of expansive soil because of the low cost and abundant availability [9]. Such changes in the properties of lime-treated expansive soil can be attributed to the short-term and long-term reactions. The short-term reactions mainly include the cation exchange between ions on the surface of clay particles and calcium ions in lime, causing the changes of electrical charge density around the clay particles, and flocks (flocculation) are formed by particles attracting each other [13–17]. Besides, the reaction between silica and some alumina of the clay mineral lattice is also a significant factor [18, 19]. The long-term reaction known as the stabilization is occurring based on the added amount of lime that exceeds the optimum for lime modification or the initial lime consumption value [20].

The treated expansive soil subgrade is always subjected to long-term traffic load, which will result in the degradation of the service performance of the subgrade. Therefore, cyclic dynamic load becomes one of the important factors that determine the long-term performance of expansive soil subgrade. At present, the dynamic resilient modulus is adopted as the design index in the newly revised design specification of subgrade in China [21] which reflects the influence of long-term cyclic dynamic load on subgrade. The resilient modulus of subgrade was first proposed by Seed [22] which was originally used to study the relationship between the resilient characteristics of subgrade soil and the fatigue damage of asphalt pavement. Subsequently, the concept of the resilient modulus is quickly accepted by many countries and widely used as one of the main parameters to characterize the mechanical properties of subgrade soil [23]. In recent years, many scholars have studied the influence factors of dynamic resilient modulus of subgrade for different filling materials [24–28]. In brief, the dynamic resilient modulus of clays increases with the increase of confining pressure and compaction and decreases with the increase of dynamic stress and moisture content. Navarrete et al. [29] evaluated the effect of frequency and strain ratio on dynamic resilient modulus of clay soil in Mexico by using the resonant column test and laser ultrasonic test. Sas et al. [27] conducted triaxial tests to study the effect of loading characteristics and stress on the resilient modulus of subgrade cohesive soil. Furthermore, Elkady et al. [8] added 0%–6% lime dry weight to an expansive soil and studied the moisture hysteresis on the resilient modulus of lime-treated expansive clay. Similarly, Rahman and Tarefder [30] claimed that the moisture influences on the dynamic resilient modulus of lime-treated soils were less than those for untreated soils. Bhuvaneshwari et al. [31] performed the laboratory experiments that the lime-treated expansive soils exhibited higher dynamic resilient modulus values compared to the untreated soil.

In addition to the experimental studies, many scholars have studied the prediction model of dynamic resilient modulus [32, 33]. The models of the dynamic resilient modulus can be divided into three groups: models for stress, experimental methods, and models for the stress and matric suction [34–36]. Salour et al. [37] established the prediction model of dynamic resilient modulus of silty sandy soil by means of dynamic triaxial test which can control the matrix suction of soil. Khoury et al. [38] developed a prediction model for the resilient modulus of stabilized filling soils in relation to moisture content. Dong [39] obtained a quantitative model for resilient modulus of cement-improved high liquid-limit clay considering multiple factors by a large number of tests. By the repeated load triaxial tests, Zhang et al. [32] proposed a new model to estimate the resilient modulus of subgrade soils with matric suction, relative compaction, and the stress state. Bhuvaneshwari et al. [31] used the octahedral stress state model to predict the resilient modulus of lime-treated expansive soils.

At present, there are few studies on the resilient modulus for treating expansive soil which is chosen as filling material for subgrade. Moreover, the test of the resilient modulus requires a suitable dynamic triaxial instrument, and the test process is complex, so this method has not been popularized in engineering design departments. In this paper, dynamic triaxial tests were conducted to study the effect of moisture content, compaction degree, cyclic deviator stress, and confining pressure on lime-treated expansive soil. Then a prediction model for the resilient modulus is statistically validated and verified. The results indicate that the model is suitable for the lime-treated expansive soil and can provide the references to the researchers concentrating on the lime-treated expansive soil.

2. Materials and Testing Methods

A series of laboratory tests were performed to study the influence of moisture content, compaction degree, cyclic deviator stress, and confining pressure on lime-treated expansive soil. Firstly, the expansive soil was treated by 5% lime. Secondly, the physical index and the relationship between CBR and compaction degree of lime-treated expansive soils were obtained. Thirdly, the dynamic resilient modulus tests were conducted to study the influence of mentioned factors on lime-treated expansive soils.

2.1. Materials. The soil used in this study is taken from Nanning, Guangxi province, which belongs to the weak expansive soil. In road construction, this kind of expansive soil is usually treated with lime and then used as filling materials because of the low cost. Based on the literature [8–10, 40], the expansive soil was treated by lime with the content of 5% by soil dry weight to reduce the property of swelling. And then, the free expansion ratio of lime-treated expansive soil was less than 40% and changes into the cohesive nonswelling soil [41]. Before the preparation of specimens, lime will react with the water in the soil and contribute to the loss of water. In order to control the moisture content of the specimens accurately, quantitative lime was mixed into the soil, and then the sample was placed in a closed container which is capable of controlling both humidity and temperature and cured for 3 days. The soil samples were cured in a controlled environment of constant temperature ($23 \pm 2^{\circ}$C) and high relative humidity environment (>95%). After that, the moisture content of the soil sample was measured again and adjusted to the target value by supplementing water. The physical index of expansive soil after treatment is shown in Table 1. All the specimens must be cured at constant temperature and humidity for 7 days after completion of the preparation before the subsequent tests.

2.2. California Bearing Ratio (CBR) Tests. The California bearing ratio (CBR) tests were carried out at the compaction degree of 90%, 92%, 94%, 96%, and 98% with optimum moisture content, respectively. The test results are shown in Figure 1. As can be seen from Figure 1, the CBR values of the lime-treated expansive soil increase with the increase of compaction degree. The abovementioned lime-treated expansive soil as subgrade filling can meet the requirements of the compaction degree and CBR at the same time according to the design specification of subgrade in China [21]. The relationship between compaction degree and CBR can be expressed as

Table 1: Basic physical properties of the treated expansive soil.

Specific gravity	Liquid limit (%)	Plastic limit (%)	Plastic index	Maximum dry density (g/cm^3)	Optimum moisture content (%)
2.68	32.7	23.0	9.7	1.77	15.4

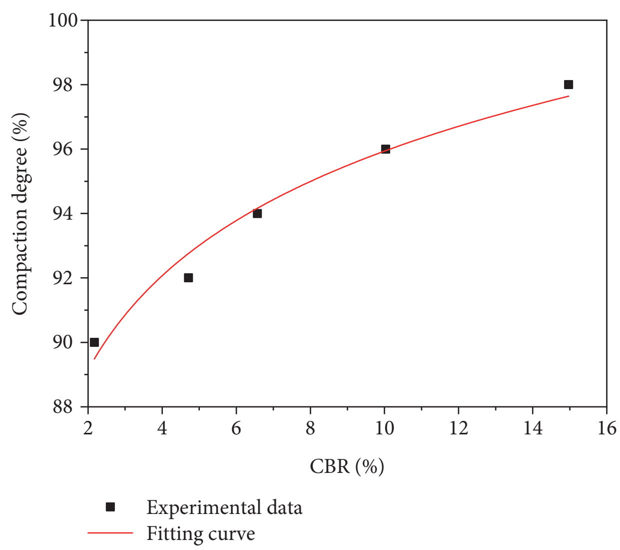

Figure 1: Relationship between CBR and compaction degree of the lime-treated expansive soil.

$$k_c = 4.34 \cdot \ln(\text{CBR}) + 85.37\left(R^2 = 0.9009\right), \quad (1)$$

where k_c is the compaction degree (%) and CBR is the California bearing ratio (%).

2.3. Dynamic Resilient Modulus Tests. The main factors affecting the resilient modulus of compacted soil include moisture content, compaction degree, cyclic deviator stress, and confining pressure. In this study, the dynamic resilient modulus tests of the lime-treated expansive soil were carried out considering the four factors mentioned above. The experimental scheme was designed as follows:

(1) The moisture content of subgrade filling is generally near the optimal moisture content, so the moisture contents of lime-treated expansive soil samples are set at 13.4%, 15.4%, and 17.4%, respectively.

(2) According to the standard compaction degree of highway subgrade, the compaction degrees considered in the test are 93%, 95%, and 97%, respectively.

(3) The traffic loads on highway roadbed are characterized by low amplitude and high cycle times. Therefore, the cyclic deviator stress selected in this dynamic resilient modulus test is 10 kPa, 20 kPa, 30 kPa, and 40 kPa, respectively. The confining pressures of the test are 15 kPa, 30 kPa, 45 kPa, and 60 kPa, respectively, and the loading frequency is 1 Hz. Based on the loading sequence of AASHTO T307-99 [42] and considering actual state of stress on the subgrade in Nanning, the experimental program of the resilient modulus was developed, as shown in Table 2.

First, the specimens were preloaded 1000 cycles and then were loaded with 100 cycles for every sequence. The average resilient strains of the last 5 cycles were used to calculate the dynamic resilient modulus according to the following equation:

$$M_R = \frac{\sigma_d}{\varepsilon_R}, \quad (2)$$

where M_R is the dynamic resilient modulus (MPa), σ_d is the cyclic deviator stress (kPa), and ε_R is the average resilient strain for the last 5 cycles of each loading sequence.

3. Results and Discussion

This section presents the results and discussion on trends obtained for the dynamic resilient modulus tests performed on a number of lime-treated expansive soils. And then, the experimental results were used to verify the suitability of the UT-Austin model to lime-treated expansive soils.

3.1. Effect of Moisture Content on Dynamic Resilient Modulus. The effect of moisture content on the dynamic resilient modulus of lime-treated expansive soil under different confining pressures with 97% compaction degree is shown in Figure 2. It can be seen that there is a linear relationship between the dynamic resilient modulus and moisture content under a certain confining pressure. The dynamic resilient modulus decreases significantly with the increase of moisture content. For example, the moisture content increases by 2%, and the dynamic resilient modulus decreases by about 25%. This shows that the moisture content in the subgrade soil has a significant effect on the dynamic resilient modulus. With the increase of moisture content, the water film becomes thicker on the surface of the soil particles, resulting in a corresponding decrease in cohesion and soil strength. Moreover, when the subgrade soil is subjected to dynamic loads, the gas in the pores is compressed and the pore water pressure in the soil increases. The increase of pore water pressure leads to the decrease of effective stress of soil, which results in the stiffness degradation of subgrade. In this case, the resilient displacement increases under dynamic loads, which causes the reduction of dynamic resilient modulus of subgrade. Therefore, it is necessary to ensure the stability of its humidity in the process of subgrade filling and service.

3.2. Effect of Compaction Degree on Dynamic Resilient Modulus. Figure 3 shows the variation of the dynamic resilient modulus with the increase of compaction degree under different confining pressures when the moisture content of lime-treated expansive soil is 13.4%. As presented in Figure 3, the dynamic resilient modulus increases nonlinearly with the increase of compaction degree. The

Table 2: Loading sequence of the dynamic rebound modulus test.

Loading sequence number	Confining pressure, σ_3 (kPa)	Contact stress (kPa)	Cyclic deviator stress, σ_d (kPa)	Maximum axial stress (kPa)	Cycle times
0-preloading	30	6	20	26	1000
1	60	12	10	22	100
2	45	9	10	19	100
3	30	6	10	16	100
4	15	3	10	13	100
5	60	12	20	32	100
6	45	9	20	29	100
7	30	6	20	26	100
8	15	3	20	23	100
9	60	12	30	42	100
10	45	9	30	39	100
11	30	6	30	36	100
12	15	3	30	33	100
13	60	12	40	52	100
14	45	9	40	49	100
15	30	6	40	46	100
16	15	3	40	43	100

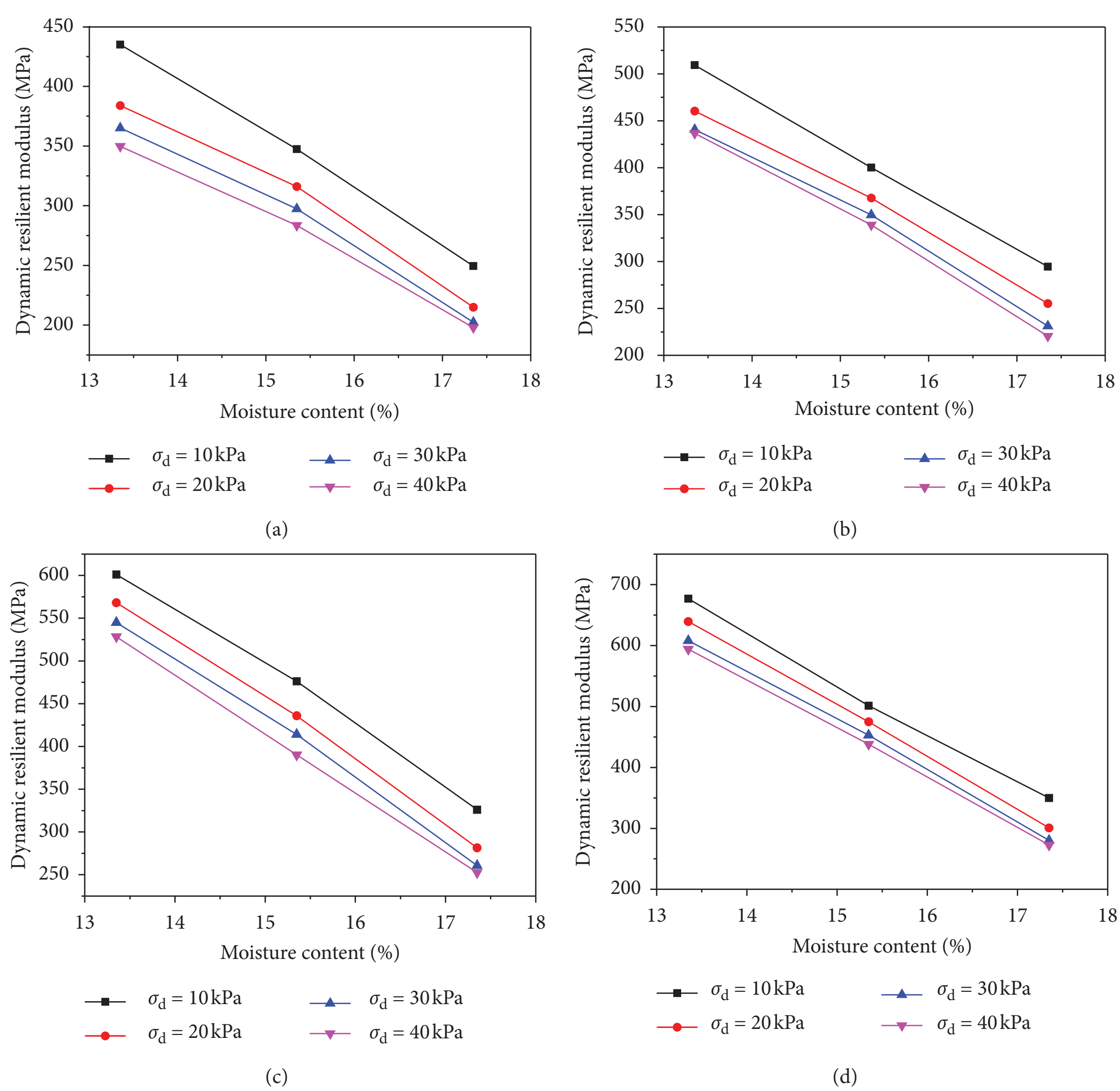

Figure 2: Variation of the dynamic resilient modulus with moisture content. (a) $\sigma_3 = 15$ kPa, (b) $\sigma_3 = 30$ kPa, (c) $\sigma_3 = 45$ kPa, and (d) $\sigma_3 = 60$ kPa.

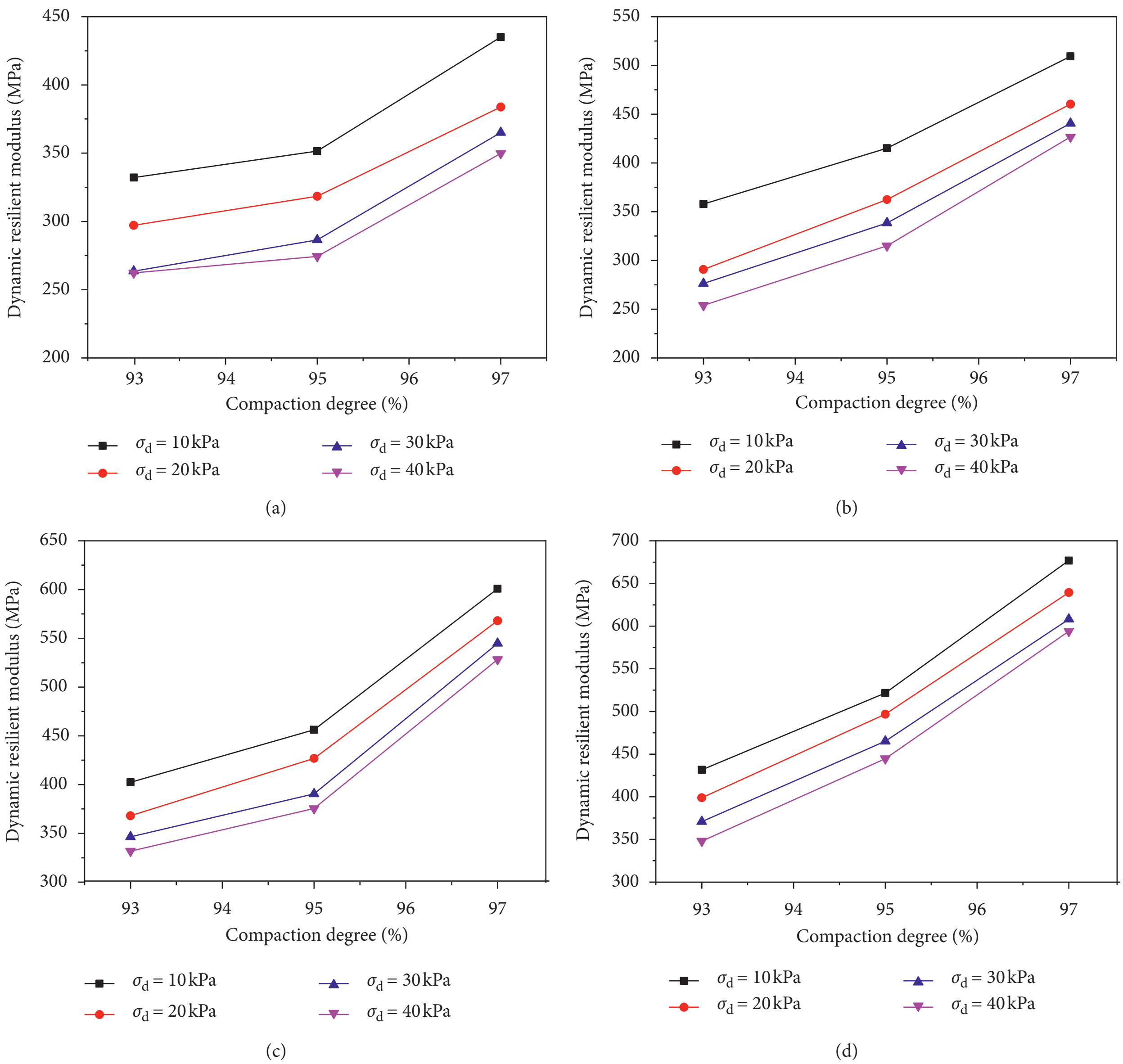

FIGURE 3: Variation of the dynamic resilient modulus with compaction degree. (a) $\sigma_3 = 15$ kPa, (b) $\sigma_3 = 30$ kPa, (c) $\sigma_3 = 45$ kPa, and (d) $\sigma_3 = 60$ kPa.

dynamic resilient modulus increases by about 10% when the compaction degree increases from 93% to 95%. While the compaction degree increases from 95% to 97%, the dynamic resilient modulus increases by about 22%. It indicates that the influence of compaction degree on the dynamic rebound modulus is more significant when the compaction is higher. Consequently, it is an effective way to enhance the whole mechanical properties of subgrade by appropriately improving the compaction degree of expansive soil. However, the improvement of compaction degree means the increase of construction cost. Therefore, safety and economy should be considered comprehensively in the design and construction of the subgrade.

3.3. Effect of Cyclic Deviator Stress on Dynamic Resilient Modulus. Figure 4 shows the variation of the dynamic resilient modulus of lime-treated expansive soils with cyclic deviator stress when the moisture content is 15.4%. According to the figure, the dynamic resilient modulus decreases nonlinearly with the increase of cyclic deviator stress under a certain confining pressure. The stiffness of lime-treated expansive soil is high at small strain, which corresponds to small cyclic deviator stress. However, it decays with the increase in strain level. The previous studies have also demonstrated it [32, 43]. When the cyclic stress level is low, the dynamic resilient modulus of lime-treated expansive soil decreases significantly with the increase of cyclic deviator stress. Then, the dynamic resilient modulus decreases slowly and tends to be stable after the cyclic deviator stress reaches a certain value. The reduction of the dynamic resilient modulus with the cyclic deviator stress is due to the shear softening [32]. This is consistent with the results for clayey soil by Seed [22].

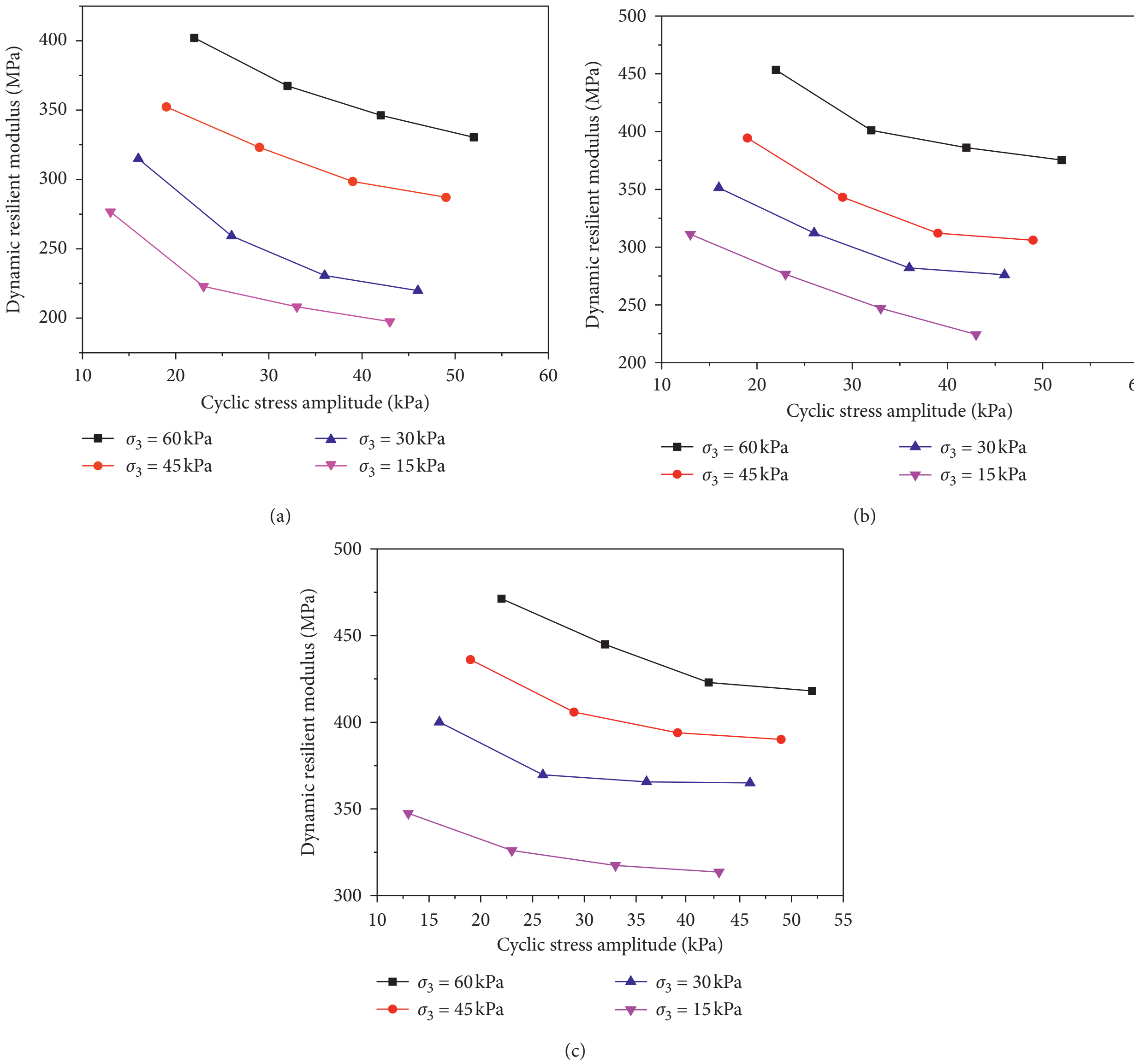

Figure 4: Variation of the dynamic resilient modulus with cyclic stress amplitude. (a) $k_c = 93\%$, (b) $k_c = 95\%$, and (c) $k_c = 97\%$.

3.4. Effect of Confining Pressure on Dynamic Resilient Modulus. Figure 5 shows the variation of dynamic resilient modulus with confining pressure under different compaction conditions when the moisture content of lime-treated expansive soil is 15.4%. As can be seen from Figure 5, there is a good linear relationship between the dynamic resilient modulus and confining pressure. The dynamic resilient modulus increases by about 10% when the confining pressure increases by 10 kPa. Chen et al. [44] tested the dynamic resilient modulus of clayey soil under a large confining pressure range and found that the dynamic resilient modulus increases linearly and slowly at lower confining pressure, while increases significantly under high confining pressure. For highway engineering, the depth of subgrade working area is generally in the shallow layer, and the soil is often under low confining pressure state which is below 60 kPa. Therefore, the relationship between the dynamic resilient modulus and confining pressure of lime-treated soil can be described by linear function.

In addition, according to the design specification of subgrade in China, the design requirements of dynamic resilient modulus at the top of subgrade for heavy traffic highway should not be less than 120 MPa. According to the test results of lime-treated expansive soil in this paper, it can be found that the moisture content has the most significant effect on the dynamic resilient modulus. Therefore, it is necessary to control the moisture content of lime-treated expansive soil near the optimum moisture content when constructing subgrade. Meanwhile, the dynamic resilient modulus under different compaction degree, cyclic deviator stress, and confining pressure all exceed 120 MPa, which can meet the design requirements of subgrade.

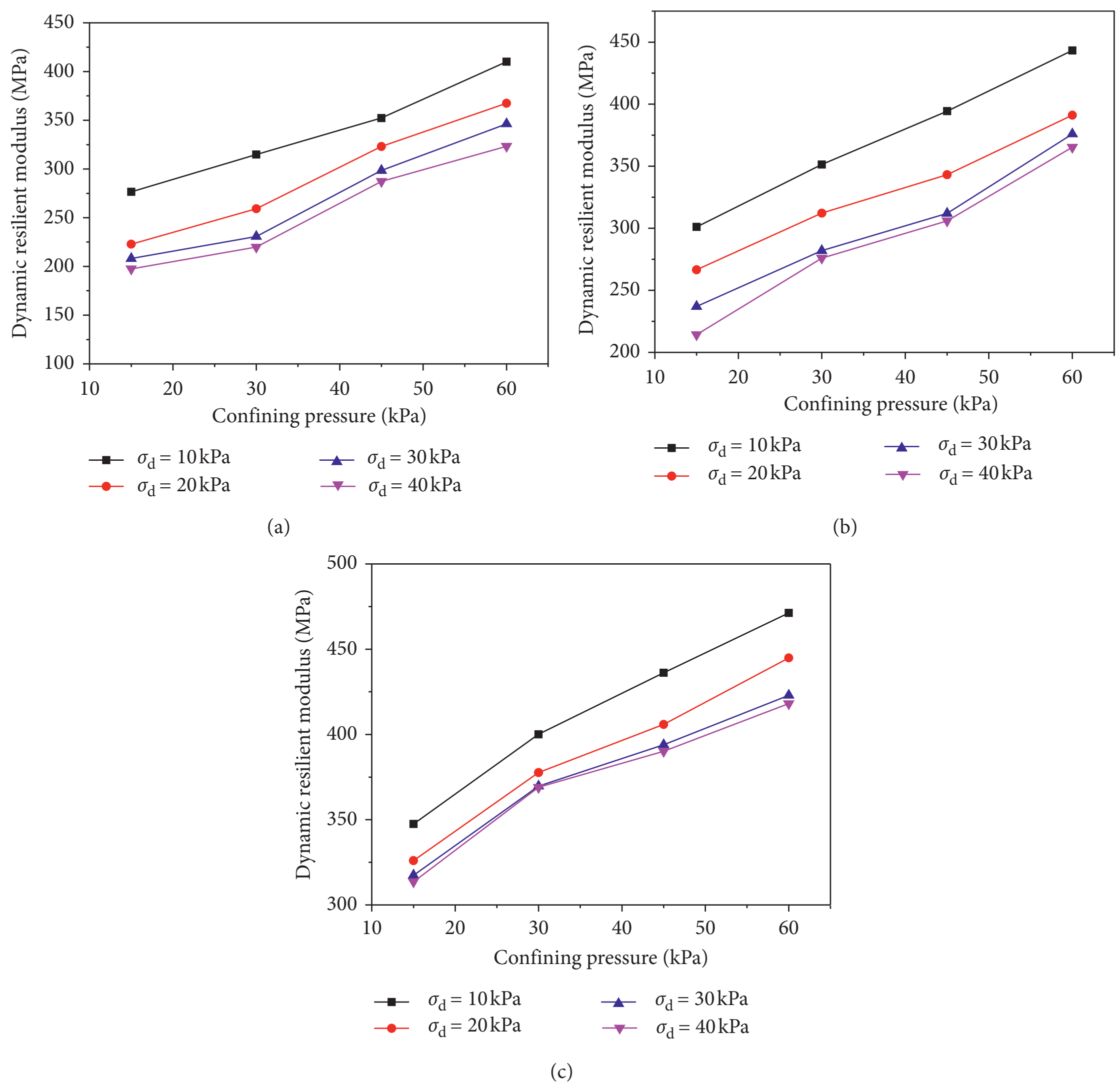

Figure 5: Variation of dynamic resilient modulus with confining pressure. (a) $k_c = 93\%$, (b) $k_c = 95\%$, and (c) $k_c = 97\%$.

3.5. Prediction Model for Dynamic Resilient Modulus of Lime-Treated Expansive Soil. From the above test results, it can be noticed that the moisture content, compaction degree, cyclic deviator stress, and confining pressure all have important effects on the dynamic resilient modulus of lime-treated expansive soil. Among the four factors mentioned above, moisture content and compaction degree belong to physical index, while cyclic deviator stress and confining pressure belong to mechanical index. Furthermore, the UT-Austin model can describe the relationship between material resilient behavior and stress state from the viewpoint of mechanics [45]. So, the experimental results of the dynamic resilient modulus for lime-treated expansive soil were used to validate and verify the suitability of the UT-Austin model:

$$M_R = k_1 {\sigma_d}^{k_2} {\sigma_3}^{k_3}, \tag{3}$$

where k_1, k_2, and k_3 are the test parameters.

The corresponding test parameters were obtained from the multiple regression analyses performed on the test data under various moisture content and compaction degree. The model regression coefficients of the UT-Austin model using 9 sets of experimental data are summarised in Table 3. It can be seen that the correlation coefficient (R^2) values are all more than 0.90, which indicated the UT-Austin model had an excellent fit with the lime-treated expansive soil.

In order to more clearly demonstrate the accuracy of the model, Figures 6–8 are presented. This model was adopted to calculate the resilient modulus of lime-treated expansive soil with the moisture content of 15.4% and the compaction degree of 97% under different confining pressures, as shown in Figure 6. Figure 7 shows the comparison of the measured and predicted dynamic resilient modulus for all soil samples. The model indicates an excellent goodness fit with $R^2 = 0.98$. As can be observed from Figure 8, the residuals showed a good normal distribution. In summary, the calculated results were consistent with the experimental data, which validated the rationality and reliability of the UT-Austin model for the dynamic resilient modulus of the lime-treated expansive soil.

Table 3: Regression coefficients of different soils.

Soil samples	k_1	k_2	k_3	R^2
13.4–93	152.453	−0.182	0.372	0.96
13.4–95	193.417	−0.158	0.327	0.96
13.4–97	240.801	−0.115	0.317	0.98
15.4–93	144.390	−0.184	0.356	0.94
15.4–95	184.510	−0.159	0.294	0.96
15.4–97	235.701	−0.098	0.224	0.99
17.4–93	133.812	−0.176	0.284	0.98
17.4–95	148.007	−0.189	0.303	0.98
17.4–97	200.864	−0.192	0.242	0.99

The soil sample 13.4–93 represents the presence of 13.4% of moisture content and 93% of compaction degree.

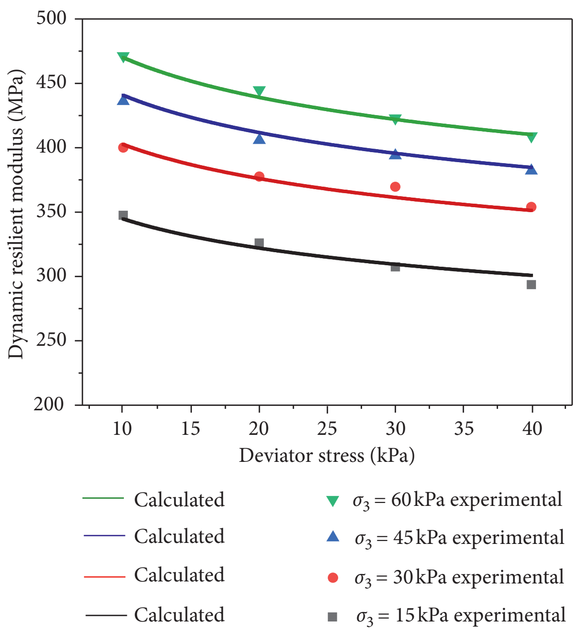

Figure 6: Comparison between the experimental data and calculated results for the samples with a moisture content of 15.4% and compaction degree of 97%.

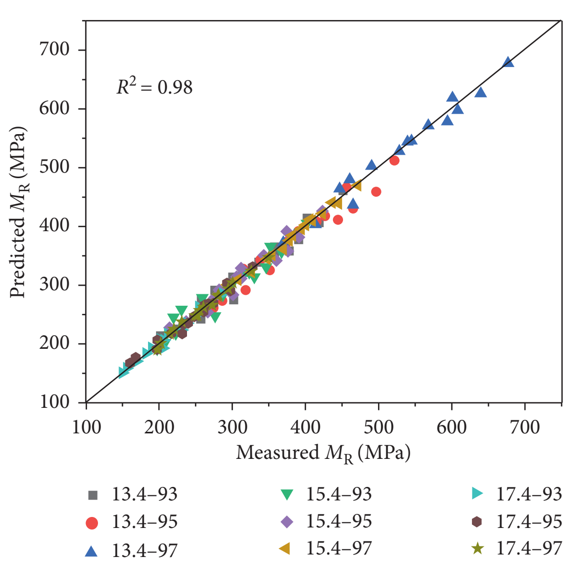

Figure 7: Comparison of the predicted and measured dynamic resilient modulus values.

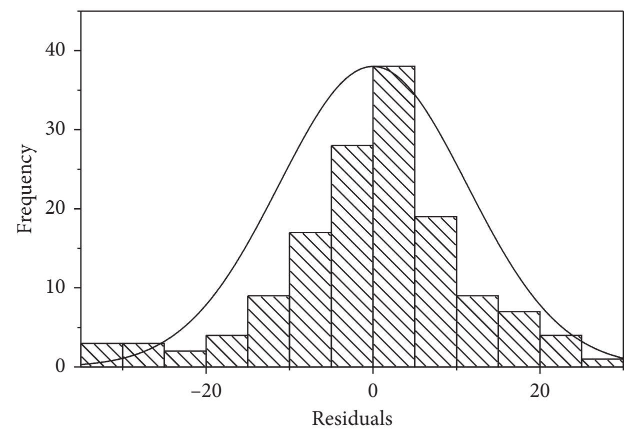

Figure 8: Distribution of residuals.

4. Conclusions

By studying the dynamic characteristics of lime-treated expansive soil, the following conclusions can be drawn:

(1) The influence of moisture content on the dynamic resilient modulus of lime-treated expansive soil is most significant. With the increase of moisture content, the dynamic resilient modulus decreases significantly. An increase of 2% in the moisture content will contribute to a decrease of about 25% in the dynamic resilient modulus.

(2) The dynamic resilient modulus of lime-treated expansive soil increases nonlinearly with the increase of compaction degree. Moreover, when the compaction degree is relatively high, it will exert more significant influence on the dynamic resilient modulus.

(3) The dynamic resilient modulus of lime-treated expansive soil decreases with the increase of cyclic stress amplitude. When the cyclic stress level is low, the dynamic resilient modulus decreases significantly with the increase of dynamic stress amplitude; once the dynamic stress amplitude increases to a certain extent, the dynamic resilient modulus decreases slowly and gradually becomes stable. The stable value of dynamic resilient modulus can be used as a reference for subgrade design.

(4) There is a good linear relationship between the dynamic resilient modulus and confining pressure. The increase of confining pressure by 10 kPa will results in the increase by about 10% in the dynamic resilient modulus.

(5) As analyzed above, it can be concluded that the UT-Austin model is valid for the dynamic resilient modulus of the lime-treated expansive soil. The results can provide valuable references for the future studies of expansive soil.

In this study, dynamic triaxial tests were conducted to investigate the influence of the mentioned factors. However, the durability including wetting-drying cycles and freezethaw cycles is very significant to the lime-treated expansive soil, and the matric suction is the main factor affecting the behavior of expansive soils. The effect of these factors will be further studied in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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