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COMPACTION BEHAVIOR OF SAND-MODIFIED CHINA YUNNAN LATERITE

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In order to study the compaction behavior of sand-modified Yunnan laterite, mixed soils with different sand content are prepared. Standard, non-standard compaction and CBR tests are also carried out. The results show that liquid limit and plasticity index are reduced after being mixed with sand; maximum dry density increases and optimum moisture decrease with the increase of sand content under standard compaction; standard compaction can not make the mixed soil reach the most dense; when the blows number increases to 128 per layer, dry density and CBR reach the maximum. The results can be used as reference for laterite engineering.

Keywords: Yunnan laterite; liquid limit; dry density; compaction work; CBR

1. Introduction

Yunnan is among the areas in China with the widest presence of laterite, which is a red-based soil originating from iron-rich parent rocks in a hot, humid climate after three complete processes—weathering, microgranulation, and pedogenesis [1]. Yunnan laterite is a special clayey soil characterized by high clay content, high liquid limit, high natural porosity, low permeability coefficient, high dispersivity, low expansibility, and high contractibility [2]. So far, researches on Yunnan laterite have mostly been focused on the most basic physical-mechanical parameters [1-4], chemical composition [5], effects of rainfall erosion into laterite side slopes on the physiochemical properties of the soil [6-9], and dry-wet cycle effects [10,11]. Yunnan, as a less-developed area in China where a large number of railway and expressway projects are underway, is exposed to numerous engineering problems related to laterite. In fact, the area has suffered quite many laterite-related engineering disasters due to the lack of knowledge about the essentials of the local laterite within the engineering community, including road surface subsidence caused by strength degradation as a result of the presence of contraction cracks in the laterite subgrade, and post-rain landslide caused by dry shrinkage of the laterite side slopes as a result of groundwater mining.

Yunnan laterite is an undesirable subgrade filler which would make compaction difficult when directly used for filling [12] and could deteriorate the

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stability of the subgrade so filled by virtue of its high contractibility. However, there is a simple, inexpensive way of modifying Yunnan laterite: the liquid limit and plasticity index of the material can be reduced and, consequently, the soil contractibility can be inhibited simply by adding a given amount of coarse-grained soil. In the present study, the basic physical parameters of Yunnan laterite mixed with 10%, 20%, and 40% sand, respectively, are measured. The optimum moisture contents and maximum dry densities of the mixed soil samples with the three sand contents are determined through standard heavy compaction (Ⅱ-2) and nonstandard heavy compaction. The results show that adding sand can greatly reduce the liquid limit and plasticity index of the mixed soil and increasing the number of blows identified by the *Test methods of soil for highway engineering* [13] to a given limit can increase the maximum dry density of the mixed soil. The results also show that the CBR (California Bearing Ratio) value of the mixed soil is increased in the range of 10% - 40% sand content. The dry density and CBR of the mixed soil reach the maximum values under 128 blows per layer. Our findings will provide useful clues for subgrade engineering related to Yunnan laterite.

2. Experimental Scheme

Pure Yunnan laterite (standard compaction): Typical Yunnan laterite material was sourced from Kunming East Ring Expressway, cleared of grassroots and other unwanted matters, air-dried and crushed. The particle composition of the soil was analyzed and its basic physical parameters measured. Next, five samples were prepared, added with different masses of water by increasing the water mass at 2% moisture content interval, mixed up and cured for 24 h. The mixed soil samples so prepared were then subjected to standard compaction as recommended by *Test methods of soil for highway engineering* [13]. The post-compaction dry densities of the samples were calculated and their dry density to moisture content relations were plotted before the optimum moisture and maximum dry density of each of the samples were yielded.

Mixed soil for standard compaction: Mixed soil samples containing Yunnan laterite and Chinese ISO standard sand were prepared, their liquid and plastic limits were measured and their plasticity indexes calculated. Sand was added at the content of 10%, 20%, and 40%. Five samples were prepared for each group, totaling 15 samples. Sand content is defined as ratio between the mass of the standard sand added and the mass of the mixed soil. For each group, the five samples were added with different masses of water by increase increasing the water mass at 2% moisture content interval, mixed up and cured for 24h to ensure that the moisture content was homogeneous. The mixed soil samples so prepared were then subjected to standard compaction. The post-compaction dry densities of the samples were calculated and their dry density to moisture content relations were plotted before the optimum moisture and maximum dry density of each of the mixed soil samples were yielded.

Mixed soil for nonstandard compaction: Mixed soil samples containing 10%, 20%, and 40% sand, respectively, were prepared using the optimum moisture content determined by the standard compaction tests of the mixed soil. 5 samples were prepared for each group, totaling 15 samples. These samples were then cured for 24 h. The number of blows on each layer was changed to 88, 108, 118, 128, and 138. The dry density related to each of these numbers of blows was calculated and the dry density to number of blows relation was plotted for each of the samples.

Mixed soil for CBR tests: According to the test results of the standard compaction group of the mixed soil, the mixed soil samples containing 10%, 20% and 40% sand content were prepared using the optimum moisture content. 18 samples were prepared for each group of sand content (54 samples in total), and these samples were then cured for 24 h. When making CBR samples, the number of blows per layer was 88, 98, 108, 118, 128 and 138 respectively. The CBR values of the samples were tested after immersion in water for 4 days.

The Chinese ISO standard sand had a SiO_2 content of greater than 96%, a loss on ignition of smaller than or equal to 0.4% and a mud content of smaller than or equal to 0.2%. The particle composition of the sand is given in Table 1.

Table 1

Particle composition of Chinese ISO sand

Sieve pore diameter (mm)	Accumulated retained percentage (%)
0.65	<3
0.40	40±5
0.25	>94

3. Results and Analysis

The laterite material sourced for the tests looked brown when dried and reddish brown when exposed to water. Its particles were comprised of 41.25% clay, 47.93% silt, and 10.82% sand. Its physical parameters are given in Table 2. According to the moisture content to dry density relation of the pure laterite shown in Fig. 1, yielded from standard compaction test (conducted using parameters given in Table 3), the maximum dry density (ρ_{dmax}) was 1.62 g/cm^3 and the corresponding moisture content (ω_{op}) was 17.8%.

Table 2

Basic physical parameters of Yunnan laterite

Natural wet density ρ(g/cm^3)	Specific density of solid particles G_s	Natural moisture content ω(%)	Liquid limit ω_L(%)	Plastic limit ω_P(%)	Plasticity index I_P
1.76	2.64	29.2	52.0	27.0	25

Table 3

Standard compact test parameters

Hammer mass (kg)	Hammer bottom diameter (cm)	Drop height (cm)	Sample height (cm)	Sample volume (cm^3)	Layers number	Number of blows per layer	Compaction work (kJ/m^3)
4.5	5	45	12	2177	3	98	2677

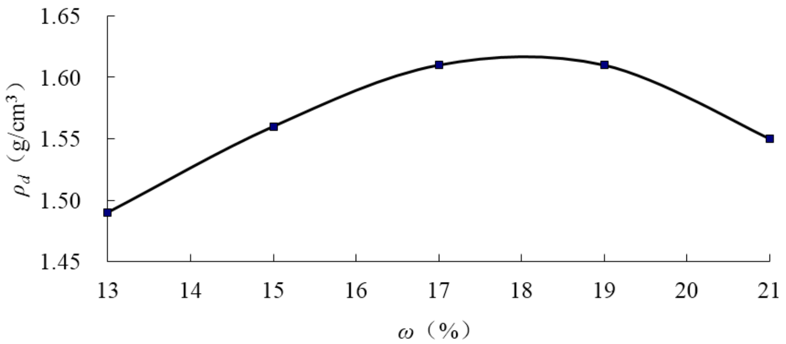

Fig. 1 Compaction curve of the pure laterite sample

When mixed with 10%, 20%, and 40% sand, the liquid limit of the mixed soil reduced remarkably to 41%, 37%, and 28%; the plasticity index also dropped to 20, 18, and 14, respectively. According to the compaction curves of the mixed soil under standard compaction shown in Fig. 2, the maximum dry density (ρ_{dmax}) was 1.69 g/cm^3, 1.74g/cm^3, and 1.79g/cm^3; the optimum moisture content (ω_{op}) was 14.0%, 13.1%, and 11.3%, respectively.

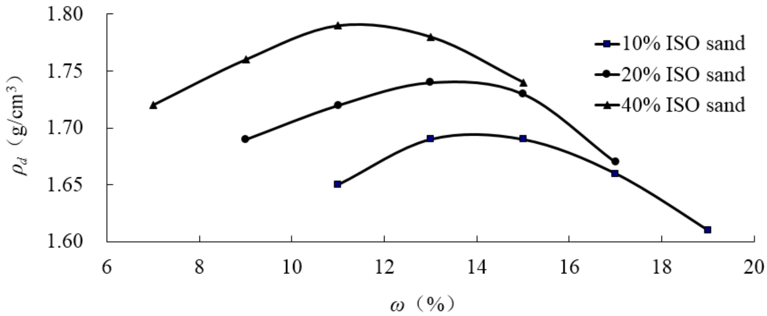

Fig. 2 Compaction curve of the ISO sand-modified soil samples

From Fig. 2, as the sand content increases, so does the maximum dry density of the mixed soil. When mixed with 10%, 20%, and 40% sand, the maximum dry density of the mixed soil is 4.3%, 7.4%, and 10.5% higher than the pure laterite. As the pure laterite used for our experiment contained sand itself, with a sand content of 10.82%, in order to visualize how the maximum dry density of the mixed soil varied with total sand content, the correlation between these two parameters and the fitted functional expression of this correlation were plotted into Fig. 3. The optimum moisture content of the mixed soil reduces with increasing total sand content. The correlation between these two parameters and the fitted functional expression of this correlation were plotted into Fig. 4. In Figs. 3 or Figs. 4, R was the coefficient of determination.

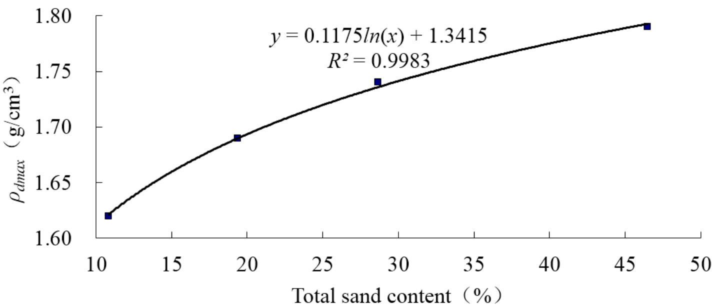

Fig. 3 Total sand content versus maximum dry density

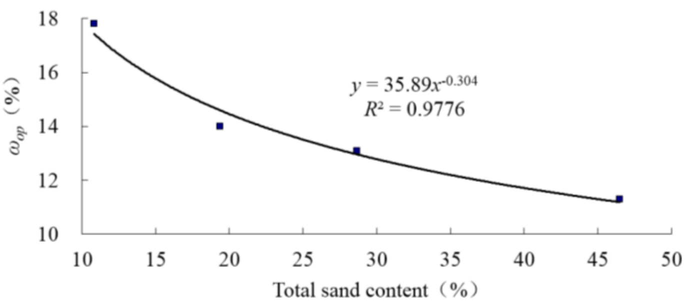

Fig. 4 Total sand content versus optimum moisture content

Mixed soil samples containing 10%, 20%, and 40% sand were prepared using the optimum moisture content determined by the standard compaction tests. Nonstandard compaction tests were conducted by changing the number of blows. The number of blows on each layer was determined to be 88, 108, 118, 128, and 138, corresponding to a compaction work of 2404, 2950, 3224, 3497, and 3770 kJ/m^3, respectively. Other compaction parameters were the same as standard compaction. The dry density related to each different number of blows was calculated and the dry density to number of blows relations were plotted into Fig. 5.

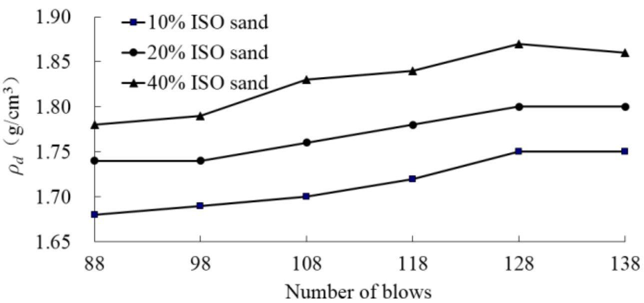

Fig. 5 Dry density versus number of blows for the mixed soil samples

Obviously, for the mixed soil with sand, the "maximum dry density" yielded by standard compaction is not its true maximum dry density. Instead, increasing the number of blows to a given limit can further increase its dry density. In our experiment, increasing the number of blows to 128 brought the mixed soil to its maximum dry density; however, when the number of blows was further increased to 138, the dry density remained the same or dropped a little. When 10%, 20%, and 40% sand was added, under 128 blows, the resulted dry density was 3.55%, 3.45%, and 4.47% higher than that determined by the standard compaction tests, respectively.

CBR is widely used in highway engineering to evaluate the bearing capacity of subgrade filler. In this study, the CBR values of the mixed soil with 10%, 20% and 40% sand content at different blows were tested according to the test method [13]. The CBR test parameters were shown as Table 4 and the test results were shown as Table 5.

Table 4

CBR test parameters

Diameter of penetration bar (cm)	Length of penetration bar (cm)	Inner diameter of cylinder (cm)	Cylinder height (cm)	Layers number	Number of blows per layer	Penetration rate (mm/min)
5	10	15.2	17	3	88; 98; 108; 118; 128; 138	1

Table 5

CBR values of pure laterite and mixed soil under different blows per layer(%)

	88 blows	98 blows	108 blows	118 blows	128 blows	138 blows
pure laterite	8.4	8.6	8.6	8.6	8.5	8.5
10% sand	13.0	13.1	13.3	13.3	13.4	13.4
20% sand	11.8	12.0	12.2	12.2	12.2	12.1
40% sand	10.3	10.7	10.7	10.5	10.5	10.2

Although the CBR value decreased with the increase of sand content, it was higher than that of pure laterite under standard compaction condition (8.6%). With the same content of sand, when the number of blows per layer did not exceed 128, the CBR value increased with the number of blows, which showed that increasing the number of blows within a certain range was conducive to improving the strength and stability of the sand-modified Yunnan laterite subgrade.In order to facilitate visual comparison, some physical property parameters, optimum moisture content, maximum dry density and CBR value of pure Yunnan laterite and mixed soil with sand are listed in Table 6.

Table 6

Parameters comparison of pure laterite and mixed soil with sand

	ω_L (%)	ω_P (%)	I_P	ω_{op} (%)	ρ_{dma} (standard compaction) (g/cm^3)	ρ_{dmax} (nonstandard compaction) (g/cm^3)	CBR (%)
Pure laterite	52.0	27.0	25	17.8	1.62	1.63	8.6
10% sand	41.0	21.0	20	14.0	1.69	1.75	13.4
20% sand	37.0	19.0	18	13.1	1.74	1.80	12.2
40% sand	28.0	14.0	14	11.3	1.79	1.87	10.5

The CBR value of pure laterite is tested under the standard compaction condition; the CBR value of mixed soil is tested under the non-standard compaction condition (128 blows).

4. Discussion

The experimental results give an intuitive description of the relationships between dry density and moisture content for pure Yunnan laterite under standard compaction, the relationship between dry density and moisture content for Yunnan laterite mixed with different contents of sand under standard compaction, and the relationship between dry density and number of blows for the mixed soil under nonstandard compaction.

Sand particles contain almost no hydrophilic substances, featuring large pores and limited capillary activity among them, low water adsorbability and poor water-retaining capacity. As a result, adding sand can effectively reduce the liquid limit and improve the contractibility of Yunnan laterite. Our experiment shows that adding sand can reduce the optimum moisture content of the laterite and a higher sand content will mean a lower optimum moisture content, which concurs with what has been reported in [12]. After mixed with sand, under standard compaction, the maximum dry density of Yunnan laterite is higher than that of its pure counterpart; the higher the sand content, the higher the dry density. The explanation should be: on the one hand, sand itself has a dry density slightly higher than that of laterite; on the other hand, in the mixed soil, larger pores among the sand particles are filled up by thinner laterite particles during mixing and compaction.

Yunnan laterite is a kind of typical special soil, which has the characteristics of high clay content, high liquid limit, low expansibility and high contractibility, which determines that it can not be directly used as subgrade filling material. Dry density is an important constraint for subgrade installation. For the same soil, increased dry density will mean increased soil compactness, which in turn signifies improved subgrade strength and stability. For pure laterite, as our previous studies have demonstrated, the maximum dry density is merely 1.62 g/cm^3, and increasing the compaction work hardly helps increase the maximum dry density. As noted by [14], compaction only works to change pores having larger diameters in the soil and does not make much difference to the smaller ones. Similarly, for lateritic clay subgrade, compaction helps increase the soil compactness only to a limited extent. Our present experiment indicates that, for the laterite mixed with sand, the "maximum dry density" determined by standard compaction tests is not its true maximum dry density. Instead, increasing the number of blows to a given limit can further increase its dry density: in our experiment, adding the number of blows to 128 (corresponding to a compaction work of 3497 kJ/m^3) brought the mixed soil to its maximum dry density; however, when the number of blows was further increased to 138, the dry density of the mixed soil remained the same or dropped a little. This indicates that the standard compaction work is not enough to bring the mixed soil to its greatest compactness, which concurs with what has been reported in [15]. The explanation should be that larger pores among the sand particles are gradually filled up by finer laterite particles over constant, repeated compaction. For sand-modified Yunnan laterite subgrades, measures should be taken to increase the compaction work so as to increase the dry density of the subgrade soil and consequently improve the strength and stability of the subgrade.

CBR is an important index to evaluate the bearing capacity of subgrade filler in highway engineering, and it is the main basis to select subgrade filler. According to Osula [16-18], the CBR value of high liquid limit soil is very sensitive to remolded water content. It is reported by reference [19] and [20] that when the moisture content of soil is high, too much compaction work will lead to the decrease of CBR value of soil, and the phenomenon of "spring" appears after the soil is rolled in subgrade engineering. The CBR tests shows that when the sand content of the mixed soil is 10%, 20% and 40%, the CBR values of the samples are the maximum under 128 blows per layer and the optimum moisture content determined by the standard compaction tests. These CBR values are also higher than those based on 98 blows per layer. The variation of CBR values with the number of blows is consistent with the dry density. The variation of CBR value with compaction times is consistent with the dry density. For the mixed soil with a certain sand content, if the number of blows per layer further increase, more than 128, the CBR value will show a downward trend, which is adverse to the long-term stability of the subgrade, especially when the soil is in dry-wet cycles. With the increase of sand content, the CBR value decreases. The possible mechanism is that when there are more sand particles, the cohesion between soil particles is weakened, and water is easier to penetrate into the sample, which reduces the ability of the sample to resist penetration.

In this paper, the compaction behavior of sand-modified Yunnan laterite in laboratory is studied. How to apply the conclusions in Yunnan laterite subgrade engineering remains to be further explored in combination with the actual project, so as to put forward the sand content and compaction process control method. In order to reveal the engineering properties of the modified Yunnan laterite, it is necessary to strengthen the research on the strength and characteristics under dry-wet cycle of the modified laterite.

5. Conclusions and Recommendations

(1) After mixed with sand, the liquid limit and plasticity index of Yunnan laterite reduce remarkably: when 10%, 20%, and 40% sand is added, the liquid limit of the mixed soil drops to 41%, 37%, and 28%; its plasticity index dropped to 20, 18%, and 14, respectively. This suggests that adding sand can effectively improve the contractibility of Yunnan laterite.

(2) Under standard compaction, the maximum dry density of the mixed soil increases with increasing sand content and there is a logarithmic functional relationship between these two parameters; the optimum moisture content of the mixed soil reduces with increasing sand content and there is a power functional relationship between them.

(3) Unlike pure Yunnan laterite, for the mixed soil with sand, increasing the number of blows to a given limit can further increase its dry density. Increasing the number of blows to 128 (corresponding to a compaction work of 3497 kJ/m^3) brings the mixed soil to its maximum dry density. This suggests that for the sand-modified laterite, the standard compaction work is not enough to bring it to its greatest compactness. When the number of blows is 128, the CBR value of the mixed soil with sand is higher than that of the pure laterite under the standard compaction condition, but the CBR value decreases with the increase of the content of sand.

(4) When 10% sand is added, Yunnan laterite already conforms to the criteria set out in the current *Specifications for design of highway subgrades* (JTG D30-2015), namely, having a maximum liquid limit of 50% and a maximum plasticity index of 26. The CBR value of mixed soil with 10% sand is also higher than that of higher sand content. In practical applications, the sand content to be added should be determined according to the cost of installing Yunnan laterite subgrades and the availability of sand material. In the present study, we have concentrated on the compaction behavior of sand-modified Yunnan laterite. Further studies on the strength and dry-wet cycle effects of sand-modified Yunnan laterite will be carried out in future, in order to further reveal the engineering properties of the modified laterite, at the same time, to explore the compaction process control method in the actual laterite subgrade engineering.

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