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*Research Article*

# Research on Design Indicators for Graded Crushed Stone Mixture Based on Vibration Molding Method

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The asphalt pavement easily shows the diseases like cracking, rutting, and structural water damage during the early service life in Fujian province for the complex effects of very high temperature, easily rainy climatic condition, and high-frequency heavy loading. However, the corresponding studies and strategies are still rare. Herein, in order to study the relationship of compaction methods on the stress-strain characteristics and shear strength of graded crushed stone mixtures, 11 kinds of typical graded crushed stone mixtures, which were taken from the five different expressways under construction in Fujian Province, were molded by both the modified vibration compaction and modified Proctor compaction. The results indicate that the modified vibration molding method matches much better with the compaction of practical projects and can be used to evaluate the performance of graded crushed stone mixtures. Further, the performance indexes got by the modified vibration compaction and the modified Proctor compaction have strong correlations. Therefore, based on the modified vibration compaction, the guidelines for standardized mix design of graded crushed stone mixture in Fujian province are proposed: the resilient modulus of 300 MPa and the deformation rate of $10^{-8}$ in the dynamic triaxial test are used as the performance indicators of the bearing capacity and the antideformation ability; the shear strength of 400 kPa in the static triaxial test is used as the performance indicators of the shear failure resistance. Besides, most limestone mixtures perform well and have the advantages of good resistance to permanent deformation and shear resistance.

## 1. Introduction

The different climatic environments and load conditions have a great influence on the early damage and durability of asphalt pavement [1, 2]. Choosing the appropriate pavement structure depending on the traffic, climate, and load conditions in different regions is the focus of research in the field of road engineering. Since the climate of Fujian province is characterized as mountainous, rainy, and long duration of high temperature, the early damage phenomena, including cracking, rutting, and structural water damage, widely appeared on the asphalt pavement with traditional semirigid base. According to the current situation, different pavement structures have been tried in Fujian Province, including the improved semirigid base, the thickened asphalt surface layer, the pavement structure with the inverted thin asphalt layer, and the fully flexible asphalt pavement. However, the poor durability of asphalt pavement under high temperature and rainy environment still cannot be effectively solved. Therefore, in order to adapt to the climatic environment and load conditions of Fujian province and to enhance the service life, the asphalt pavement with composite bases is proposed and applied, which overlay a graded crushed stone layer with a thickness of 15–18 cm between the asphalt surface layer and the semirigid base layer [3]. It shows that the water permeability coefficient of the graded crushed stone layer is $5 \times 10^{-3}$–$1 \times 10^{-4}$ m/s, so the asphalt pavement with the graded crushed stone layer has good drainage performance. In addition, the graded crushed stone layer plays a significant role in restraining the reflection cracking of asphalt surface course caused by shrinkage cracks in semirigid base [4]. Thus, the durability of the combined base asphalt pavement would be effectively improved due to the strong drainage ability and the decrease of reflection cracks in semirigid materials. According to relevant literature, for the raw materials and energy consumption during construction, it is about 840 MJ/t, 460 MJ/t, and 180 MJ/t for the asphalt concrete, the semirigid materials, and the graded crushed stone, respectively. So, the appropriate usage of the graded crushed stone base could effectively reduce energy consumption and emission.

For the asphalt pavement with composite bases, the mechanical characters of the graded crushed stone mixtures are critical to pavement performance. The pavement rutting and further structural failure may be caused by the low strength, low rigidity, and large plastic deformation in the traditional graded crushed stone layer [5–7], so the application of the composite bases asphalt pavement in the high-grade expressways is limited. How to accurately predict and improve the antipermanent deformation and antirutting abilities of graded crushed stone has attracted the road researchers' interest [8–12]. In earlier studies, the shear characteristics of graded crushed stone must be better characterized, because rutting in this type of pavement is primarily caused by the permanent deformations of base materials [13, 14]. The degree of compaction has been regarded as significantly important for the long-term behavior of graded crushed stone [15–18]. It is proved that compaction of the graded crushed stone layer is important to enhance the deformation resistance of asphalt pavement [16–18]. So, the reasonable gradation is essential to improve the strength and stability of graded crushed stone. Based on the material optimization design method, it is an effective way to improve the road performance by proposing new indexes and standardization for mix design of the graded crushed stone. This will lay the foundation for taking advantage of graded crushed stone and expanding the application in high-grade expressways.

At present, researchers have conducted a lot of research on the effects of different molding methods on the performance of the graded crushed stone [19–22], the indexes' development for the graded crushed stone [23], and different material designs [24, 25]. Meanwhile, the performance characterization and the evolution under various conditions (such as the layer thickness, the degree of compaction, and so on) are analyzed [5, 26, 27] to improve the performance of the graded crushed stone mixture. Although a lot of effort has been made to investigate the performance improvement and evaluation indicators of the graded crushed stone mixtures, the effects of high temperature and rainy factors and the systematically analyzation of the relationship between various performance parameters still have limitations and accuracy problems. At present, the mix design specifications of the graded crushed stone are mainly based on the modified Proctor compaction method. However, practical engineering shows that the modified Proctor compaction standard is seriously lower than the degree of the on-site compaction. Therefore, the solid volume ratio, CBR, dynamic triaxial, and static triaxial tests are used in this study to explore the effects and the relationship of two laboratory compaction methods on the stress-strain characteristics and shear strength of graded crushed stone mixtures. This work will not only better simulate the physical and mechanical performance of the mixture on the practical project, but also improve the quality of the graded crushed stone mixture.

## 2. Graded Crushed Stone Mixtures

11 kinds of the typical graded crushed stone mixtures in Fujian province are selected in this study, and the gradations are shown in Table 1. The mixtures are taken from the five different expressways under construction in Fujian Province, and the gradations are determined according to the engineering mix design. The raw materials, such as limestone, sandstone, tuff, and granite, are widely used on Fujian expressways. The technical indexes of the 11 kinds of the typical graded crushed stone mixtures, such as the particle breakage and the Los Angeles abrasion, accord with the requirements for graded macadam mixture in the guidelines of Fujian Province [28].

## 3. Test Methods

*3.1. Comparison and Selection of Molding Methods.* At present, the compaction method is used for determining the optimal moisture content and maximum dry density of graded crushed stone mixture in China. The modified Proctor compaction method is currently used to simulate the static rolling effect of 12–15*t*. The vibration compaction method used in this study is modified by using the synchronous motor pneumatic loading, which is different from the traditional single-motor weight loading. The work parameters of the three used compaction instruments are shown in Table 2. The compaction degree of the laboratory vibration compaction molding instrument is more representative and has a better correlation with the working of on-site roller. Therefore, the vibration compaction molding method is increasingly used in expressway engineering.

The modified vibration and traditional vibration molding test equipment are shown in Figure 1. The single-motor counterweight loading is commonly used in the vibration compaction testing equipment. In order to reach the requirements for the graded crushed stone mixture, the parameters of the single-motor counterweight loading vary through adding or subtracting the number of the counterweights. So, the standardization of the device of the centrifugal force is low. Besides, the effects of vibration compaction depend on the different parameters and quality of the devices. The synchronous motor pressure loading vibration is adopted in the modified vibration molding test equipment, rather than the traditional single-motor counterweight loading. At the same time, it is conducive to the standardization of vibration compaction parameters. The equipment structure has the advantages of simple operation, low noise, and good stability.

The maximum dry density test results of graded crushed stone mixtures with different molding methods are shown in Table 3. For different mixtures with various raw materials,

Table 1: The gradations of the mixtures of graded crushed stone used in the test.

| No. | 31.5 | 26.5 | 19 | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 | Raw material |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1# | 100 | 99.9 | 83.6 | 74.0 | 63.9 | 53.5 | 35.1 | 24.1 | 18.5 | 13.6 | 8.7 | 6.3 | 3.8 | Limestone |
| 2# | 100 | 99.0 | 85.5 | 71.7 | 61.2 | 55.2 | 39.2 | 28.9 | 23.2 | 18.5 | 13.1 | 9.4 | 4.6 | Limestone |
| 3# | 100 | 99.8 | 85.7 | 75.0 | 67.0 | 60.2 | 40.6 | 29.9 | 22.3 | 16.8 | 11.0 | 7.8 | 4.9 | Limestone |
| 4# | 100 | 96.9 | 85.7 | 74.2 | 65.4 | 60.6 | 40.9 | 25.5 | 17.4 | 11.7 | 6.9 | 4.4 | 2.6 | Sandstone |
| 5# | 100 | 98.6 | 79.8 | 70.5 | 63.4 | 56.0 | 41.9 | 26.3 | 18.0 | 12.1 | 7.5 | 5.4 | 3.7 | Sandstone |
| 6# | 100 | 100 | 84.2 | 74.6 | 66.3 | 56.0 | 39.8 | 22.9 | 15.7 | 10.8 | 7.4 | 5.7 | 4.0 | Tuff |
| 7# | 100 | 99.9 | 89.4 | 81.4 | 74.4 | 64.3 | 42.8 | 27.1 | 20.0 | 14.5 | 10.0 | 7.7 | 5.0 | Limestone |
| 8# | 100 | 97.4 | 84.2 | 73.9 | 66.6 | 58.0 | 40.5 | 31.7 | 22.5 | 14.2 | 8.9 | 6.9 | 4.7 | Limestone |
| 9# | 100 | 96.8 | 80.6 | 69.7 | 62.1 | 53.2 | 34.9 | 27.0 | 19.2 | 12.2 | 7.7 | 6.0 | 4.1 | Limestone |
| 10# | 100 | 96.1 | 80 | 68.9 | 59.8 | 47.5 | 34.8 | 24.3 | 18.4 | 13.0 | 9.1 | 6.2 | 4.3 | Sandstone |
| 11# | 100 | 98.6 | 86.1 | 76.9 | 70.6 | 53.8 | 36.7 | 26.5 | 20.7 | 14.7 | 10.2 | 7.8 | 5.0 | Granite |

Table 2: Parameters of three compaction instruments.

| | | | | | | |
|---|---|---|---|---|---|---|
| Modified Proctor compaction | Hammer mass | Hammer diameter | Height | Compact layer | Compact times | Compaction work |
| | 4.5 kg | 5.0 cm | 45 cm | 3 | 98 | 2.677 J |
| Traditional vibration compaction | Frequency | Counterweight (up/down) | Amplitude | Centrifugal force | Vibratory time | Compaction work |
| | 5–50 Hz | 5.5/4.5 kg | Various | Various | 2 min | Various |
| Modified vibration compaction | Frequency | Amplitude | Centrifugal force | Intensity of pressure | Vibratory time | Compaction work |
| | 28–30 Hz | 0.5–2.5 mm | 6000–8000 N | 140 ± 10 kPa | 2 min | 5.881 J |

(a) (b)

Figure 1: Vibration molding test equipment. (a) Traditional single-motor weight loading. (b) Modified synchronous motor pneumatic loading.

the molding methods have the same effect on the density; that is, the ranking of the maximum dry density determined by different molding methods is the traditional vibration compaction > the modified vibration compaction > the practical construction site > the modified Proctor compaction. On the one hand, this is related to the compaction work. On the other hand, the materials fully move in the state of dynamic friction during the compaction process because of the centrifugal force applied by the vibration molding method, which make the structure of the mixture specimen denser. Therefore, the maximum dry density of graded crushed stone mixture is greatly increased based on the vibration compaction method. As for the two kinds of the vibration compaction methods, the difference of maximum dry density with traditional vibration compaction method is larger than that with the modified vibration compaction method, which confirmed that it is difficult for the traditional single-motor counterweight-loading vibration compaction to ensure the consistency of the compaction degree. Besides, comparing to the gradation and material types of mixtures, the molding method has more significant effect on the maximum dry density. Among the three kinds of laboratory compaction methods, the value of maximum dry density with the modified vibration compaction method

Table 3: Maximum dry density of graded crushed stone mixtures with different molding methods.

| No. | Modified Proctor compaction | | Traditional vibration compaction | | | Modified vibration compaction | | Practical construction |
|---|---|---|---|---|---|---|---|---|
| | Maximum dry density (g/cm$^3$) | Difference of maximum dry density (g/cm$^3$) | Maximum dry density (g/cm$^3$) | Difference of maximum dry density (g/cm$^3$) | Average jump time (s) | Maximum dry density (g/cm$^3$) | Difference of maximum dry density (g/cm$^3$) | Maximum dry density (g/cm$^3$) |
| 1# | 2.317 | 0.014 | 2.462 | 0.032 | 137 | 2.357 | 0.013 | 2.366 |
| 2# | 2.297 | 0.011 | 2.433 | 0.038 | 121 | 2.331 | 0.027 | 2.332 |
| 3# | 2.320 | 0.021 | 2.419 | 0.033 | 129 | 2.360 | 0.014 | 2.367 |
| 4# | 2.259 | 0.025 | 2.375 | 0.022 | 136 | 2.307 | 0.016 | 2.307 |
| 5# | 2.201 | 0.019 | 2.257 | 0.027 | 89 | 2.219 | 0.009 | 2.241 |
| 6# | 2.165 | 0.014 | 2.288 | 0.022 | 114 | 2.206 | 0.014 | 2.223 |
| 7# | 2.306 | 0.016 | 2.452 | 0.029 | 137 | 2.359 | 0.018 | 2.358 |
| 8# | 2.274 | 0.022 | 2.327 | 0.054 | 65 | 2.324 | 0.019 | 2.335 |
| 9# | 2.314 | 0.028 | 2.419 | 0.022 | 93 | 2.359 | 0.015 | 2.374 |
| 10# | 2.218 | 0.024 | 2.358 | 0.041 | 118 | 2.252 | 0.024 | 2.274 |
| 11# | 2.223 | 0.017 | 2.350 | 0.034 | 102 | 2.272 | 0.023 | 2.289 |

is closest to that of the practical construction site. Generally, the vibration molding method matches much better with the working of on-site roller and can be used to evaluate the performance of graded crushed stone mixtures.

*3.2. Solid Volume Ratio Test [29].* Under the optimal water content condition, the test specimen was molded by the modified vibration compaction method and the modified Proctor compaction method. The dry density and the bulk density of each graded material were both measured. The solid volume ratio is calculated as follows:

$$V_G = \frac{\rho_{\mp}}{\rho_{sb}}, \tag{1}$$

$V_G$ is the solid volume ratio, $\rho_{\mp}$ is the dry density of compact specimen, and $\rho_{sb}$ is the comprehensive bulk density. According to the standard in Fujian province [30], the solid volume ratio of graded macadam should be larger than 85%.

*3.3. California Bearing Ratio (CBR) Test [31].* The modified vibration compaction method and the modified Proctor compaction method were used to mold the test specimen, and the CBR was calculated after the specimen being saturated with water as required [31]. According to the standard in Fujian province [30], the CBR value of graded macadam should be larger than 100%.

*3.4. Dynamic Triaxial Test.* The dynamic triaxial test was basically carried out in accordance with the test method for the resilient modulus of unbound granular materials [32], where the adjustments were as follows:

(1) The specimens were molded by the vibration with the diameter of 150 mm and height of 300 mm and then cured at room temperature for 24 h to balance the water content.

(2) The vertical partial stress was 460 kPa and the confining pressure was 196 kPa.

(3) The specimens were under the 50,000 times repeat loading.

After the dynamic triaxial test was completed, the resilient modulus under the 20,000 times loading was calculated as the value of the modulus of the mixture. The permanent deformation rate was calculated as the evaluation index of the resistance to deformation according to the difference of the permanent deformation rate of 20,000 to 50,000 times.

*3.5. Static Triaxial Test.* The specimens were molded according to the method of the dynamic triaxial test. The shear test was carried out under the confining pressure of 60 kPa, 90 kPa, and 120 kPa. The friction angle and cohesion could be calculated using the Coulomb model, as shown in equation (2). Further, the shear strength was calculated based on the axial stress of 400 kPa.

$$\tau = \sigma_1 \tan \varphi + c, \tag{2}$$

$\tau$ is the shear strength, $\sigma_1$ is the axial stress, $\phi$ is the internal friction angle, and $c$ is the cohesive force.

## 4. Comparative Analysis of Mechanical Properties

*4.1. Solid Volume Ratio Test Results.* The test specimen was molded by the modified vibration compaction method and the modified Proctor compaction method, respectively. The solid volume ratio was calculated, and the relationship of the solid volume ratio with two molding method is shown in Figure 2. It was found that the solid volume rate value obtained by the modified vibration compaction method was larger than that of the modified Proctor compaction method, with the ratio of 1.02. The correlation coefficient of two test results was 0.9. In addition, the 3# limestone mixture has the best performance in the solid volume ratio test, following by the 2# limestone mixture and the 9# limestone mixture.

*4.2. CBR Test Results.* The value of CBR was calculated and the relationship of the CBR with the two molding methods is shown in Figure 3. It was found that the CBR value obtained by the modified vibration compaction method was larger than that of the modified Proctor compaction method, with the ratio of 1.17. The correlation coefficient of the two test results was 0.87. In addition, the 3# limestone mixture has the best performance in the CBR test, following by the 7# limestone mixture and the 9# limestone mixture.

*4.3. Dynamic Triaxial Test Results.* The mechanical characters of graded crushed stone mixture depended on the applying stress. So, the dynamic triaxial tests were both carried out under the same stress condition, with the vertical partial stress of 460 kPa and the confining pressure of 196 kPa. The permanent deformation rate and resilient modulus of different mixtures are shown in Table 4.

The permanent deformation curves of different mixtures in dynamic triaxial tests are shown in Figure 4. The curve color depended on the raw materials. Among these, the blue, yellow, green, and red one were the limestone, sandstone, tuff, and granite mixture, respectively.

As shown in Figure 4 and Table 4, the permanent deformation of different mixture is quite different. 6# tuff mixture (the green one) had the largest deformation and the corresponding deformation rate was the largest. It indicated that the tuff had poor resistance to permanent deformation. This was mainly due to the porous structure of tuff, which had the characteristics of large pores, low density, and large water absorption. Besides, 5# sandstone mixture, 8# limestone mixture, and 7# limestone mixture had the relatively large permanent deformation rate. 2# limestone mixture performed best and had good resistance to permanent deformation. For the resilient modulus, the performance of 3# limestone mixture was the best, followed by 11# granite mixture and 8# limestone mixture.

The permanent deformation curves of different mixtures basically conformed to the following models:

$$\delta_\alpha N = k_1 e^{-k_2 N^{-a}}, \tag{3}$$

where $\delta_\alpha$ is the permanent deformation, and $N$ is the times of the repeated loading. $k_1$, $k_2$ and $a$ both are the parameters related to the intrinsic characters of the materials.

The material parameters of permanent deformation curves of different graded crushed stone mixtures are shown in Table 5. The fluctuation of the value of the simulated material parameter $a$ was relatively small, which was within 10%, indicating that the material parameter $a$ was not sensitive to the type of material. The material parameters $k_1$ and $k_2$ showed significant changes with the different mixtures, which might be related to the physical and chemical properties of the raw material. It was found that the material parameter $k_1$ had a good relationship with the permanent deformation, with the correlation coefficient of 0.93, as shown in Figure 5. The larger the material parameter $k_1$ was, the greater the permanent deformation rate and the poorer permanent deformation resistance of the corresponding mixture were, such as 6# tuff mixture. In sense, the material parameter $k_1$ could be used to evaluate the permanent deformation resistance of the graded crushed stone mixture. Besides, it can be found that both material parameters $a$ and $k_2$ show weak correlation with the permanent deformation at 50,000 times of loading.

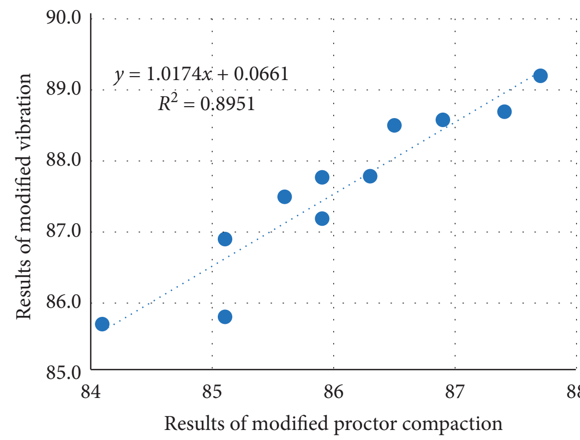


Figure 2: The relationship of the solid volume ratio with two molding methods.

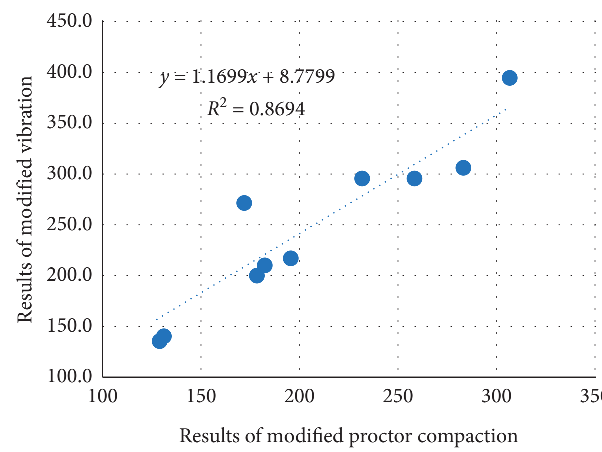


Figure 3: The relationship of CBR with two molding methods.

*4.4. Static Triaxial Test Results.* According to the Mohr–Coulomb model, the shear strength could be calculated under the stress condition of 400 kPa, as shown in Table 6.

Theoretically, the graded crushed stone material is a kind of unbound granular materials with negligible cohesive force. However, the limestone mixtures had large cohesive forces, because the fine aggregate contained some viscous material, while the cohesive force of granite mixture was quite small.

The shear strength was related to the internal friction angle, cohesive force, and stress level. As shown in Table 6,

Table 4: Test results of repeated load triaxial test.

| No. | Permanent deformation rate ($10^{-8}$) | Resilient modulus (MPa) | Raw material |
|---|---|---|---|
| 1# | 0.150 | 342 | Limestone |
| 2# | 0.219 | 383 | Limestone |
| 3# | 0.166 | 399 | Limestone |
| 4# | 0.163 | 344 | Sandstone |
| 5# | 0.894 | 341 | Sandstone |
| 6# | 1.712 | 311 | Tuff |
| 7# | 0.277 | 329 | Limestone |
| 8# | 0.486 | 387 | Limestone |
| 9# | 0.231 | 356 | Limestone |
| 10# | 0.118 | 318 | Sandstone |
| 11# | 0.402 | 396 | Granite |

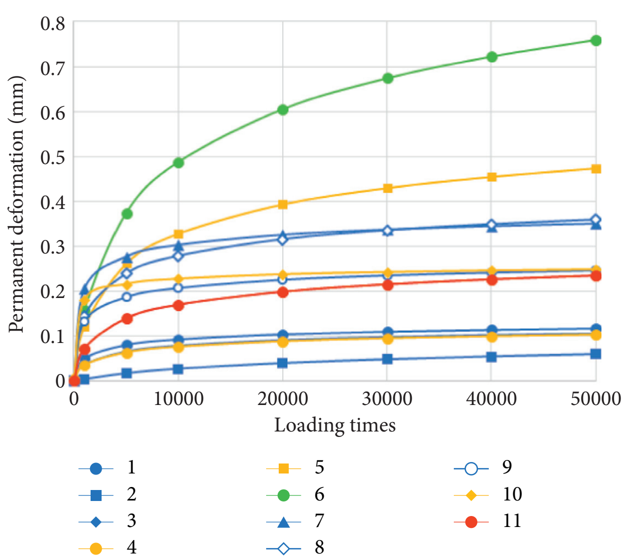


Figure 4: Permanent deformation curves in dynamic triaxial tests.

Table 5: Material parameters of permanent deformation curves of graded crushed stone mixtures.

| No. | $k_1$ | $k_2$ | $a$ | Raw material | Correlation coefficient |
|---|---|---|---|---|---|
| 1# | 0.173 | 9.71 | 0.297 | Limestone | 0.989 |
| 2# | 0.217 | 32.90 | 0.298 | Limestone | 0.997 |
| 3# | 0.169 | 12.97 | 0.307 | Limestone | 0.995 |
| 4# | 0.172 | 11.34 | 0.284 | Sandstone | 0.994 |
| 5# | 0.812 | 17.93 | 0.324 | Sandstone | 0.997 |
| 6# | 1.595 | 17.29 | 0.291 | Tuff | 0.996 |
| 7# | 0.437 | 6.49 | 0.311 | Limestone | 0.988 |
| 8# | 0.546 | 10.14 | 0.294 | Limestone | 0.993 |
| 9# | 0.327 | 6.85 | 0.293 | Limestone | 0.989 |
| 10# | 0.283 | 3.75 | 0.307 | Sandstone | 0.995 |
| 11# | 0.392 | 13.92 | 0.305 | Granite | 0.997 |

the shear strength of each graded crushed stone mixture varied greatly, due to the large difference of the internal friction angle. It proved that increasing the internal friction angle was beneficial to the shear strength due to the stress sensitivity of graded crushed stone materials.

In general, for most limestone mixtures, the permanent deformation and deformation rate were small, while the resilient modulus and shear strength were large. Most limestone mixtures performed well and had the advantages of good resistance to permanent deformation and shear resistance.

## 5. Standard for Design of Graded Crushed Stone Based on Vibration Molding Method

The reasonable mechanical indicators are extremely important for the quality control of the graded crushed stone mixture. It will be of benefit to guide the design and construction performance of graded crushed stone mixture and ensure the quality of the practical project. However, when the standard is too low, the performance of asphalt pavement with the graded crushed stone layer cannot meet the actual mechanical requirements, which will cause pavement damage. Similarly, when the standard is too high, it is difficult to meet the requirements and practically apply in the practical project. Therefore, the reasonable theory and the simple experiment is the basis for ensuring the road performance of the asphalt pavement with the graded crushed stone layer.

*5.1. Solid Volume Ratio.* The solid volume ratio is an important design index of the graded crushed stone, which is generally considered to be related to the permanent deformation and resilient modulus. In the technical guidance in Fujian Province [30], the solid volume ratio should be larger than 85% based on the modified Proctor compaction method. According to the linear regression equation of the measured solid volume ratio values of the two methods, it was recommended that the solid volume ratio be not less than 86.5%.

*5.2. CBR.* For the modified Proctor compaction molding method, it is generally required that the CBR of the graded crushed stone for the base layer be not less than 80% in the world, while in the Chinese construction technical specification, the standard of the CBR index is determined according to the traffic load. For the medium traffic, the CBR value is not less than 160%. But for heavy and extremely heavy traffic, the index changes to be 180% and 200%, respectively. Therefore, the CBR value based on the modified

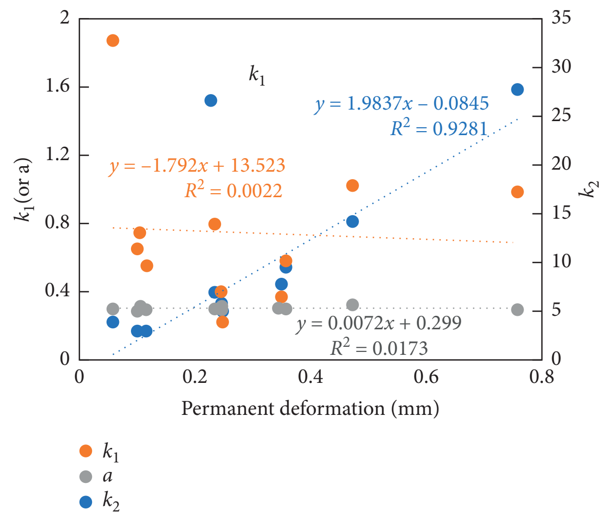


Figure 5: Relationship between the material parameters and the permanent deformation at 50,000 times of loading.

Table 6: Test results in the static triaxial test.

| No. | Internal friction angle (°) | Cohesive force (kPa) | Shear strength (kPa) | Raw material |
|---|---|---|---|---|
| 1# | 48.7 | 40.1 | 495 | Limestone |
| 2# | 49.5 | 51.9 | 520 | Limestone |
| 3# | 51.1 | 39.2 | 534 | Limestone |
| 4# | 45.6 | 20.3 | 428 | Sandstone |
| 5# | 44.9 | 13.7 | 412 | Sandstone |
| 6# | 44.8 | 6.9 | 404 | Tuff |
| 7# | 48.4 | 49.3 | 499 | Limestone |
| 8# | 49.1 | 37.8 | 499 | Limestone |
| 9# | 48.9 | 46.1 | 504 | Limestone |
| 10# | 47.2 | 8.4 | 440 | Sandstone |
| 11# | 51.2 | 9.5 | 507 | Granite |

Proctor compaction molding method should be larger than 180%. Among the 11 kinds of mixtures in this study, 5 mixtures did not meet the requirements, which mainly were granite, tuff, and sandstone mixtures. Most of the limestone mixtures met the requirements. So, the current technical standard of CBR was too high.

The higher CBR value does not mean the better performance of the graded crushed stone mixture. According to the correlation analysis, the CBR value, which was an empirical indicator, was poorly correlated with the shear strength, dynamic modulus, and permanent deformation of the graded crushed stone mixture. The previous engineering practice showed that it was difficult to obtain the suitable engineering materials if the CBR value was too high. This was because the CBR value was mainly determined by the material type, rather than the gradation of mixtures. So its requirement should not be too high. According to the engineering practices, the CBR value of the graded crushed stone mixture based on the modified Proctor compaction molding method should be 120%. It was deduced that the CBR value based on the modified vibration compaction molding method was not less than 150% from the CBR correlation of the two molding methods.

*5.3. Permanent Deformation.* The permanent deformation of the graded crushed stone is very critical to control the rut depth in asphalt pavement structure. According to the standard load [30], for typical structures in Fujian province, the deformation rate of the graded crushed stone mixture should not be greater than $10^{-8}$. As shown in Table 4, it was found that 90% of the mixture met the performance index requirements based on the vibration molding method. So, it was reasonable that the deformation rate of $10^{-8}$ in the dynamic triaxial test could be used as the performance indicators of the antideformation ability based on the vibration molding method.

*5.4. Resilient Modulus.* According to JTG D50-2017 [32], the range of the resilient modulus of the graded crushed stone is 200–400 MPa. Generally, the value is 300 MPa in engineering. According to the test results in the dynamic triaxial tests, the values were both greater than 300 MPa, so the resilient modulus of 300 MPa under the vertical partial stress of 460 kPa and the confining pressure of 196 kPa could be used as the performance indicators of the bearing capacity ability.

*5.5. Shear Strength.* According to the literature [30], the maximum shear strength of the grade crushed stone in Fujian typical structure was calculated to be 332.8 kPa. Considering the reliability factor of 1.2, 395 kPa was taken as the shear strength standard of the grade crushed stone mixture based on the modified Proctor compaction molding method. In this study, the shear strength of 400 kPa in the static triaxial test could be used as the performance indicators of the shear failure resistance, which was convenient for engineering applications.

## 6. Conclusion

Aiming to solve the problems, such as cracking, rutting, and structural water damage, appeared on the asphalt pavement under the combined effect of the high-temperature and rainy climatic condition and heavy loading in Fujian province, 11 kinds of graded crushed stone mixtures were selected in this study to compare the two experience indexes (solid volume ratio, CBR) and three performance indicators (resilient modulus, permanent deformation, and shear strength) of the specimens. Two laboratory compaction methods, namely, vibration compaction and modified Proctor compaction, were adopted to study the effects and the relationship of compaction methods on the stress-strain characteristics and shear strength of graded crushed stone mixtures. Results lay an experimental foundation for the mix design and engineering application of graded crushed stone mixture in Fujian province. Conclusions are listed as follows:

(1) It was confirmed that the vibration molding method could be used to evaluate the performance of graded crushed stone mixtures. In addition, the standardization for mix design based on vibration compaction was proposed to guide the mix design of graded crushed stone mixture in Fujian province. The results indicated that the vibration molding method matched much better with the working of on-site roller. Comparing with the modified Proctor compaction, the maximum dry density designed by the vibration molding method was improved remarkably. Further, the mechanical indexes of graded crushed stone got by the synchronous motor pneumatic loading vibration molding, including CBR, the antideformation ability, and the shear failure resistance, were much better. At the same time, the results obtained by the synchronous motor pneumatic loading vibration molding method were more stable, which was an advantage over the traditional vibration molding method.

(2) The performance indexes of vibration molding method, such as the solid volume ratio and CBR, had strong correlations with the corresponding parameters of the modified Proctor compaction. It was recommended that the solid volume ratio be not less than 86.5% and CBR be not less than 150%.

(3) Based on the vibration molding method, the resilient modulus of 300 MPa and the deformation rate of $10^{-8}$ in the dynamic triaxial test could be used as the performance indicators of the bearing capacity and the antideformation ability; the shear strength of 400 kPa in the static triaxial test could be used as the performance indicators of the shear failure resistance. These performance indexes need further verification in road engineering.

(4) Besides, for most limestone mixtures, the permanent deformation and deformation rate were small, while the resilient modulus and shear strength were large. Most limestone mixtures performed well and had the advantages of good resistance to permanent deformation and shear resistance.

## Data Availability

Data used in this paper are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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