

Research Article

Properties of Crushed Red-Bed Soft Rock Mixtures Used in Subgrade

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Slaking red-bed soft rocks are widely distributed in the south of Anhui Province, China, and several highways will go through this area. It is important to evaluate their physical and mechanical characteristics for the purpose of using this kind of soft rocks as materials for road construction. In this paper, the compacting tests, the resilient modulus tests, the California bearing ratio (CBR) tests, and permeability tests have been carried out on crushed red-bed soft rock mixtures. The test results showed that, for a given degree of compaction, the resilient modulus decreases linearly with the increase of moisture content. For a given moisture content, the resilient modulus and CBR values increase linearly with the increase of compaction degree, while the soaking swelling, water absorption capacity, and permeability coefficient decrease linearly. In other words, the strength and water stability are enhanced with the increase of the degree of compaction. The results demonstrate that the crushed red-bed soft rock mixtures can be directly used as materials for the highway construction by taking corresponding measures.

1. Introduction

Soft rock is one of the rock types encountered frequently in geotechnical engineering, which is less than the uniaxial compressive strength of 25 MPa, covering a series of sedimentary rocks, such as sandstone, mudstone, argillaceous sandstone, sandy mudstone, and siltstone. Generally, soft rocks are prone to slaking, swelling, collapse, breaking, softening, and argillization in the presence of humidity [1–6]. Such phenomenon can be quite crucial for various geotechnical hazards in roads, slopes, tunnels, and other engineering projects [7–10]. For example, when these soft rocks are used to fill subgrade, it is difficult to ensure the quality of the construction, often leading to excessive settlement, failure of embankments, and slope collapse.

Therefore, soft rocks are considered to be of very poor quality used for subgrade filling materials. In general, the soft rocks should be replaced with soil with better mechanical properties for subgrade filling, but this process will cause additional project costs and possibly extend the construction

duration. Moreover, a large number of such rocks removed as excavated earth have an adverse effect on surrounding environment. Therefore, if soft rocks can be used for subgrade filling, not only can it save a great deal of investment and earthwork, but also substantial economic and environmental benefits can be achieved.

Some studies have focused on the physical and mechanical properties of the crushed soft rocks used as filling materials. The authors of [11] have conducted a staged compression-immersion-direct shear test on the compacted samples of crushed mudstone aggregates, and the compressive and shear behaviors were discussed with attention to cementation effects. The authors of [12] have studied water-induced granular decomposition and its effects on geotechnical properties of crushed soft rocks. The authors of [13] have carried out cyclic loading tests on sandstone and limestone shale aggregates used in unbound forest roads.

Some researchers have paid attention to the techniques to make use of soft rocks as subgrade filling. The authors of [14]

carried out research on the physical and mechanical properties of soft rocks after slaking, and research results show that the indexes of those slaked materials with compacting factor 95% can reach the requirement of embankment. And the subgrade construction technology with the core of “preslaking/raking pressure/rolling pressure,” construction quality control methods and detection measures were adopted in order to ensure the feasibility of using red sandstone as a subgrade filling.

In China, residential land development and transportation networks have been extended to mountainous areas due to rapid economic and population growth. Accordingly, road constructions have been carried out in many soft rock regions. In these regions, many sedimentary soft rocks, such as sandstone or mudstone, are distributed widely. Huangshan city, which exists in the southern mountains of Anhui Province, China, is one of the typical areas covered with many slaking soft rocks. The rocks in this area are red, dark red, or brown resulting from being rich in iron oxides. Some scholars have called them “red-bed soft rocks” [15, 16]. Some construction measures, such as preslaking or adding lime, have been adopted to make full use of the red-bed soft rock as subgrade fillings [14, 17]. But those measures potentially extend the construction duration and increase the costs of the road projects. If the crushed red-bed soft rock in these areas can be directly used as subgrade fillings, the construction duration and investments of the road projects can be reduced.

Accordingly, the purpose of this study is to assess the applicability of crushed red-bed soft rock mixtures to road construction. In particular, the resilient modulus tests, the California bearing ratio (CBR) tests, and permeability tests were carried out on crushed soft rock mixtures with variable moisture contents or compaction degrees.

2. Experimental Materials and Experimental Schemes

2.1. Experimental Material. Naturally weathered red-bed soft rocks were obtained from a typical area of the quarry for the Jixi-Huangshan highway, in southern Anhui Province, China, as shown in Figure 1. These soft rocks include argillaceous feldspar quartz fine sandstone, calcareous argillaceous siltstone, argillaceous siltstone, iron-stain argillaceous calcareous siltstone, iron-stain argillaceous calcareous feldspar lithic sandstone, and mudstone.

In natural conditions, uniaxial compressive strength of the red-bed soft rocks generally ranges from 1.24 to 12.32 MPa, and the strength reduces sharply after they are soaked. Large blocks of rock samples were crushed resulting in coarse-grained soils in laboratory.

Due to the differences in their geological locations, the red-bed soft rock’s chemical composition and physical characteristics are different even with the same weathering degree, which directly affect the mechanical properties. The structures of the samples mainly consist of silty-fine structure, silty structure, cryptocrystalline structure, argillaceous structure, pebbly silty-calcareous-argillaceous structure, and argillaceous structure (see Figure 2). The cemented form between the grains is dominated by a basal type cementation.



FIGURE 1: Representative red-bed sandstone sample.

The cementation matters are mainly argillaceous and calcareous, with low strength. The main mineral compositions of the soft rock samples used in this study are summarized in Table 1.

2.2. Experimental Scheme. In the light of the construction duration, it is accepted in the construction process that soft rocks are crushed directly by machine instead of preslaking. For simulating the mechanical crushing process, the soft rock samples were artificially broken with a maximum diameter less than 20 mm (see Figure 3). Then, a series of mechanical tests were carried out according to Test Methods of Soil for Highway Engineering [18].

Firstly, the modified Proctor test compaction was used for the compaction in order to obtain the maximum dry density and optimum moisture content. Then, the resilient modulus test, California Bearing Ratio (CBR) test, and permeability test were carried out with different moisture contents or compaction degrees.

3. Experimental Result

3.1. Compaction Properties. The Proctor compaction test can determine the optimal moisture content (OWC) at which a given soil type becomes the most dense and achieves its maximum dry density. After the obtained rock samples underwent artificial mechanical crushing into small pieces, the aggregates were compacted in the steel mold with an inner diameter of 152 mm and height of 120 mm. The compaction was performed in the way that the aggregates were placed into the mold in three layers; in each layer compaction was conducted using a 4.5 kg rammer, and the compaction energies were 2677.2 kJ/m³.

The relation curve between dry density ρ_d and moisture content w is shown in Figure 4. The maximum dry density is 2.107 g/cm³, and the optimum moisture content, OWC, is 8.8%. Assessment of aggregates compaction is measured by the degree of compaction (K), which is defined as the ratio of the current dry density and maximum dry density.

The coarse aggregates of the red-bed soft rocks will become smaller or transform into fine-grained soil during the rolling process. In this study, in order to investigate the moisture content and compaction effect on grains, particle

TABLE 1: Main mineral composition.

Rock sample number	Main compositions (%)								
	Quartz	Feldspar	Debris	Dolomite	Opaque mineral	Micrite gravel	Calcite	Iron-stain clay mineral + sericite	Calcareous
1#	35	20	5	<1	<1	—	3	30	7
2#	30	15	8	—	<1	3	10	33	—
3#	3	—	—	—	—	—	—	97	—
4#	40	15	5	<1	<1	—	8	31	—
5#	40	10	5	1	1	—	—	30	13
6#	38	12	5	1	<1	—	—	30	13
7#	50	10	—	5	—	—	20	15	—
8#	55	10	1	1	3	—	15	15	—
9#	4	—	—	—	—	—	40	56	—
10#	50	10	—	1	3	1	20	15	—
11#	38	8	19	3	—	—	20	10	—
12#	40	12	23	<1	—	—	15	10	—

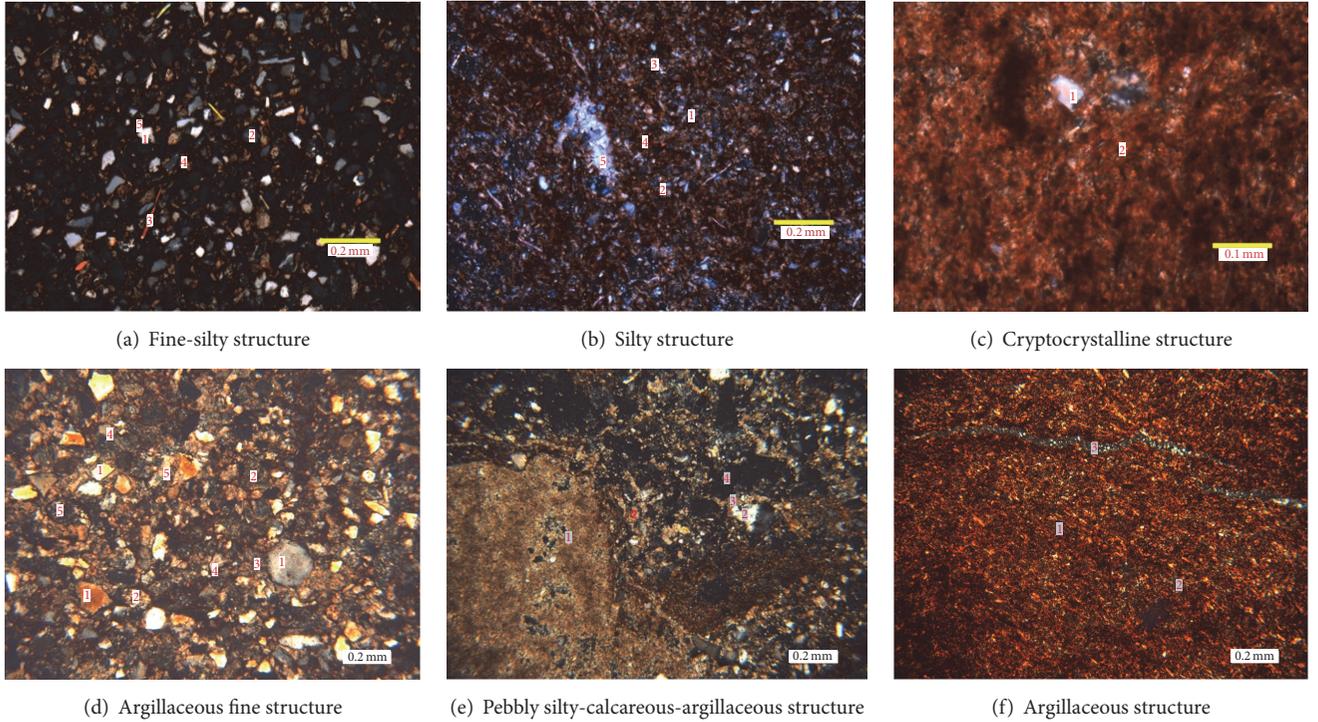


FIGURE 2: Microscopic structure diagram of representative red-bed soft rock.

size distribution tests were performed for the dry crushed soft rock mixtures and three compacted specimens with the moisture content of 5%, 8%, and 9% respectively, as shown in Figure 5. And the uniformity coefficient C_u and gradation coefficient C_c of each curve were calculated, as shown in Table 2.

The uniformity coefficient C_u is defined as

$$C_u = \frac{D_{60}}{D_{10}}. \quad (1)$$

The gradation coefficient C_c is defined as

$$C_c = \frac{(D_{30})^2}{D_{60} \cdot D_{10}}, \quad (2)$$

where D_{60} , D_{30} , and D_{10} are diameter through which 60%, 30%, and 10% of the total soil mass are passing, respectively.

It can be seen from Table 2 that the coarse-grained soil has the uniformity coefficient C_u greater than 5, and the gradation coefficient C_c is in the range 1–3 after compaction,



FIGURE 3: The crushed red-bed soft rock mixtures.

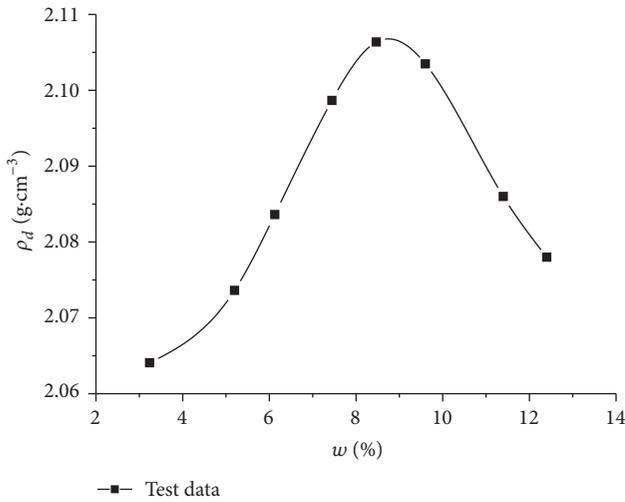


FIGURE 4: Relation between dry density ρ_d and moisture content w .

TABLE 2: Uniformity coefficient C_u and gradation coefficient C_c .

Test group	D_{60}	D_{30}	D_{10}	C_u	C_c
Before compaction	9.4	5.3	1.2	7.83	2.49
$w = 9\%$	4.8	1.8	0.23	20.87	2.93
$w = 8\%$	4.1	1.3	0.16	25.63	2.58
$w = 5\%$	3	0.55	0.09	33.33	1.12

which shows the aggregates have a good size distribution. It is worthwhile to note that the uniformity coefficients of compacted crushed rock mixtures have become greater than that without compaction. In other words, the compaction and other construction technologies executed on broken soft rock mixtures can improve the particle grading, which leads to good engineering properties, such as smaller porosity, higher density, and large bearing capacity.

3.2. *Test on Resilient Modulus.* Resilient modulus E_r is one of the mechanical parameters used to characterize subgrade soil strength, which is a vital parameter for pavement design. The most commonly applied resilient modulus models are the so-called universal models that relate the modulus to the deviatoric stress, confining pressure, or a combination

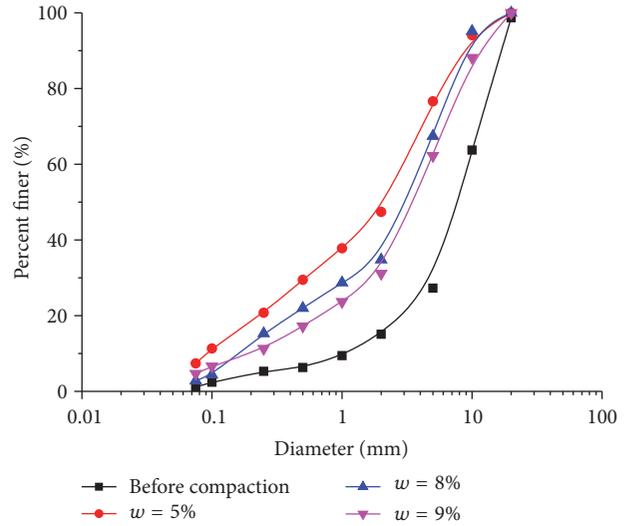


FIGURE 5: Particle size grading of crushed red-bed soft rock mixtures before and after compaction.

of them [19]. In this paper, the resilient modulus model in China’s specification [18] is adopted and the modulus of the soil can be obtained by the Plate Load tests. The relationships between the resilient modulus and moisture content, as well as the compaction degree, are discussed.

Moisture is one of the main factors affecting the subgrade resilient modulus. The specimens with a compaction degree of 96% and moisture contents of 4.8%, 7.0%, 8.3%, 7.0%, and 12.4% were prepared for the tests on resilient modulus. The results are shown in Figure 6.

Figure 6 reflects the influences of moisture content (w) on the resilient modulus (E_r). It can be seen that the resilient modulus has close relation with moisture content, decreasing with the increase of moisture content, and the general decline trend is approximately linear; around the optimum moisture content $w = 8.8\%$, the resilient modulus is not less than 90 MPa, which meets the requirement of national standard [20], in which the resilient modulus larger than 40 MPa is demanded. However, the resilient modulus is 13.69 MPa in the case of moisture content of 12.4%. Therefore, the moisture content should be controlled close to the optimum moisture content. Based on the test results, the moisture content in the construction period is suggested to be no more than 11%, so as to fulfill the strength performance of the subgrade filling required.

With the same moisture content of 9.0%, the specimens with a compaction degree of 99.7%, 97.1%, and 95.0% were prepared for the tests on the resilient modulus. Figure 7 illustrates the relation between the resilient modulus (E_r) and the degree of compaction (K). It can be seen that the resilient modulus gradually increases with the increase of the compaction degree.

3.3. *Test on CBR.* CBR is used to assess the strength indexes of subgrade and pavement materials. In the CBR test, load and penetration reading of plunger were observed at a rate of 1.25 mm/minute; the load for 2.5 mm and 5 mm were

TABLE 3: The results of CBR tests under different degrees of compaction.

Sample number	Number of blows	Dry density $\rho_d/(\text{g}\cdot\text{cm}^{-3})$	Compaction degree $K/\%$	CBR %	Soaking swelling $Q/\%$	Water absorbing X/g
(1)	98	2.104	99.9	61.24	0.088	28
(2)		2.102	99.7	57.14	0.074	25
(4)	50	2.060	97.7	49.71	0.108	49
(5)		2.053	97.5	48.76	0.102	48
(7)	30	2.010	95.4	35.14	0.164	108
(8)		2.006	95.2	34.00	0.155	99

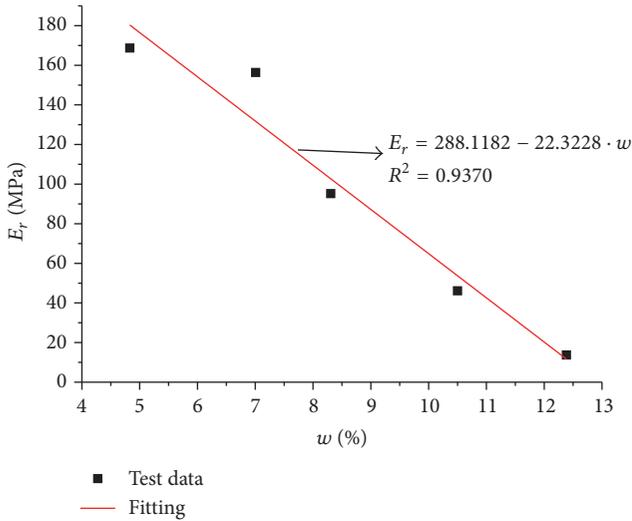


FIGURE 6: Relation between resilient modulus E_r and moisture content w .

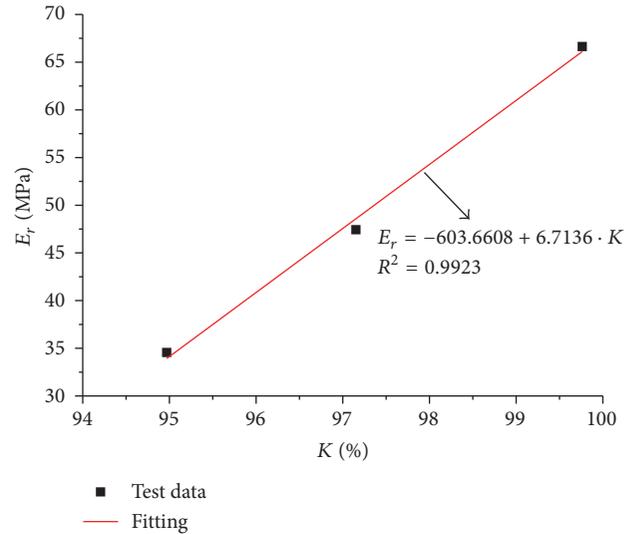


FIGURE 7: Relation between resilient modulus E_r and compaction degree K .

observed. CBR value is the comparison between applied piston loads on a soil sample and the standard loads.

Typically, CBR value is calculated by the load for 2.5 mm as follows:

$$\text{CBR} = \frac{P}{7000} \times 100, \quad (3)$$

where p is applied stress, kPa.

At the same time, CBR value is calculated by the load for 5 mm as follows:

$$\text{CBR} = \frac{P}{10500} \times 100. \quad (4)$$

If the value from (4) is greater than that from (3), the test should be carried out once more. If the result is still like that, CBR value calculated by the load for 5 mm would be adopted.

The specimens with different degrees of compaction were prepared with each layer having blows of 30, 50, and 98 with the same moisture content 9.0%, to explore the influences of compaction degree K on CBR, the soaking swelling Q , and water adsorption X , which were evaluated by the Chinese Industrial Standard [18]. The test results are shown in Table 3 and Figures 8–10.

Figure 8 shows the relationship between CBR and compaction degree (K). It can be seen that (1) all the compacted

specimens with different dry densities have higher CBR values; for example, the CBR value of the specimen with 95% compaction degree can reach up to 30% or more, which shows that the compacted specimens have a strong ability to resist damage; (2) with the increase of the compaction degree, the CBR value presents a linear increasing trend. According to the national standard [20] of China, the CBR of the fillings for highway should not be lower than 8% when the 96% degree of compaction is proposed. The results suggest that the compacted specimens fully meet the requirements of national standard [20].

Figures 9 and 10 give the relationship of the soaking swelling (Q) and the water adsorption (X) with the degree of compaction (K), respectively. It can be seen that the compaction degree has basically the same influence on the soaking swelling and the water adsorption. The higher the compaction degree is, the smaller the soaking swelling and water adsorption become, which show that the water stability is gradually enhanced with the increase of compaction degree. This is mainly due to higher compaction degree leading to a decrease of porosity among the soil particles. In other words, the water storage space of specimens is reduced, characterized by declining of the water absorbing capacity.

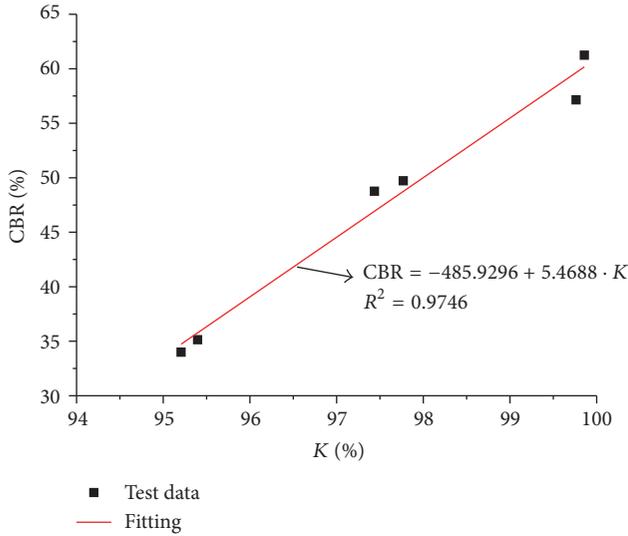


FIGURE 8: Relation between CBR and compaction degree K .

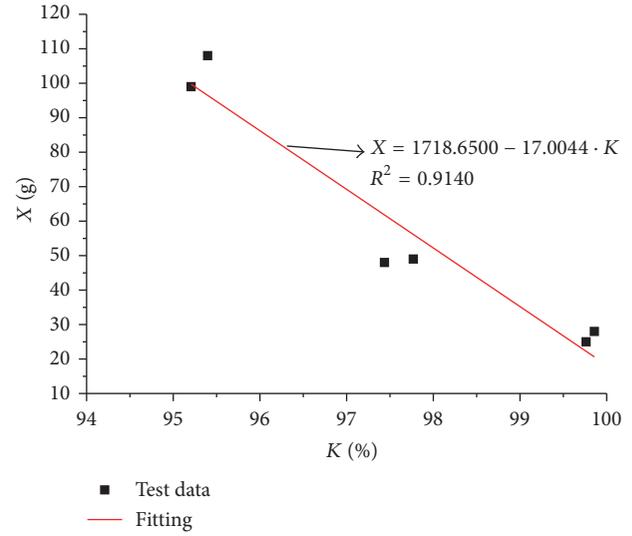


FIGURE 10: Relation between water absorbing X and compaction degree K .

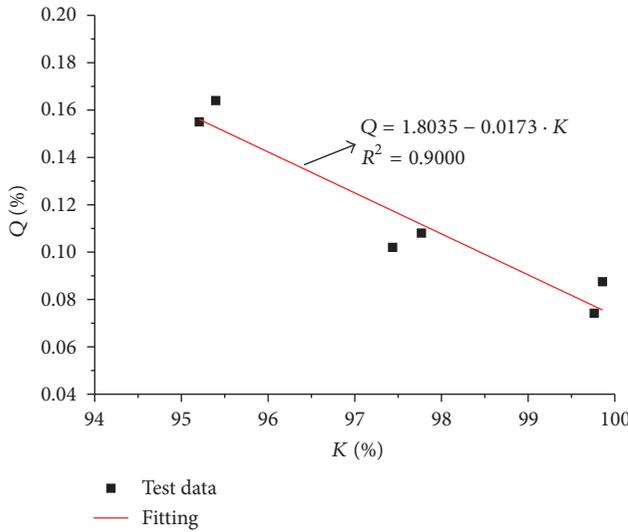


FIGURE 9: Relation between soaking swelling Q and compaction degree K .

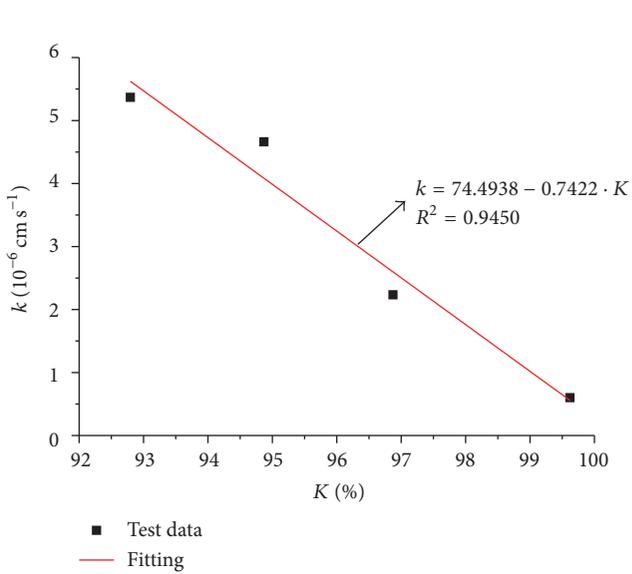


FIGURE 11: Relation between permeability coefficient k and compaction degree K .

From the long-term stability of the roadbed, the compaction of red-bed sandstone fillings should be controlled as well as possible. In this condition, the adverse effect of water on the strength of the roadbed can be reduced significantly.

3.4. Test on Permeability. In order to study the relationship between the permeability coefficient (k) and the compaction degree (K), a variable water head method was adopted for the seepage experiment of the saturated specimens with varied compaction degrees ($K = 99.6\%$, 96.9% , 94.9% , and 96.9%). The results are shown in Figure 11.

Figure 11 reflects the influences of compaction degree on permeability. It can be seen that (1) the permeability coefficients of the filling decrease linearly with the increase of the compaction degree; with the increasing of the compaction degree, the porosity becomes smaller, and the pore water

pressure increases; so, the flowing of free water among soil particles slows down or even stops due to the capillary effect, which leads to the decreasing of the permeability coefficient; (2) with the compaction degree of 92% to 100%, the permeability coefficients k are less than $1.0 \times 10^{-6} \text{ cm/s}$, showing a good antipermeability performance and thus proving that the compaction degree has an effective controlling effect on the porosity and permeability coefficients.

4. Discussion

The special properties of red-bed soft rocks, such as slaking or softening in water, should be full considered in materials for road construction. Based on the above physical and

mechanical properties of crushed soft rock matrix, the red-bed soft rocks have good engineering properties for subgrade after being crushed and compacted. The red-bed soft rocks mixtures become fine-grained soil during the rolling process. The compaction and other construction technologies can improve the particle grading, which leads to good engineering properties.

Compaction degree is a key factor to ensure that the mechanical properties of the crushed rock mixtures meet the requirements. So, the compaction degree should be selected as the main quality control index for the red-bed roadbed construction in practice.

When the compaction degree of the crushed red-bed rock mixtures is above 90%, the permeability is very small, similar to that of clay. The moisture has great influences on the mechanical properties, and some waterproof measures should be taken on the subgrade slope in the actual highway construction project.

5. Conclusions

- (1) The red-bed soft rocks in the southern mountains of Anhui Province, China, have complex and diversified lithology and structure. The clay mineral contents are higher with a mud-calcium cementation, minimal strength, and weak weathering resistance.
- (2) The moisture has great influences on the resilient modulus of the red-bed crushed soft rock mixtures. The resilient modulus decreases with the increase of moisture content. Therefore, the moisture content of the mixtures should be controlled close to the OWC when rolling to ensure the subgrade resilient modulus meeting the requirements of road construction.
- (3) The compaction degree has close relationship with the filling's strength and water stability. With the increase of the compaction degree, the resilient modulus and CBR of the compacted specimens show linear increasing trends, while the soaking swelling, water absorbing capacity, and permeability coefficient present linear decreasing trends.
- (4) The laboratory experimental results show that, under certain key control indices such as moisture content or degree compaction, the engineering properties of the crushed red-bed soft rock mixtures can meet the demands of highway construction.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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