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Research Article

Study on Compaction Characteristics and Construction Control of Mixtures of Red Clay and Gravel

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Red clay cannot be used as embankment filler directly due to its water-sensitive property. Gravel is usually added into red clay to enhance its performance in engineering practice. In order to investigate the influence of mixtures of red clay and gravel on the road performance, gravitational compaction experiment of red clay and vibratory compaction experiment of mixtures of red clay and gravel were conducted, respectively. The results indicate that compaction curves of red clay have double peak; the second peak is the real maximum dry density, and its corresponding moisture content is the optimal moisture content. The dry density of mixtures of red clay and gravel is influenced by the content of gravel, vibration frequency, and vibration time. The optimal content of gravel is 30%, the best vibration frequency is 45 Hz, and the optimal vibration time is 5 minutes for the mixtures of red clay and gravel in this study. The effectiveness of optimal content of gravel and optimum vibration parameters was confirmed by a CBR test. According to the compaction experiment results and actual situation in the field, a suitable construction method of subgrade using the mixtures of red clay and gravel was put forward. The feasibility of this method was also confirmed by postconstruction deformation data of the field test embankment.

1. Introduction

Red clay is widely distributed in the southwest of China, which is water-sensitive [1]. Because of its large porosity, small density, and high moisture content, it is very easy to lead to roadbed subsidence, shallow sliding collapse, and other engineering disasters if it is used as roadbed filler directly [2, 3]. However, with the development of highways in China, red clay is inevitably used in subgrade construction. There are two kinds of methods to improve its road performance in engineering, such as the chemical method and physical method. The chemical method can cause a series of chemical reactions to absorb soil moisture and create cementitious substances by adding lime, cement, or other chemical materials. It makes the red clay compaction easy and increases its strength [4–8]. But, it is difficult to mix evenly in the construction site by the chemical method. Therefore, the actual effect is not obvious. The physical method often improves the overall strength of the soil by materials with higher strength such as gravel and industrial slag. By contrast, this kind of method has lower cost, simpler operation, and can be used widely [9–11].

In fact, gravel is often used to improve road performance of red clay in construction sites, but laboratory research focused on the effect of gravel on the performance is seldom. In this study, in order to achieve the best compacting effect, a gravitational compaction of red clay and a vibrating compaction of mixtures of red clay and gravel were conducted. According to the compaction experiment results and the actual situation in the field, a suitable construction method of subgrade for the mixtures of red clay and gravel was put forward.

2. Materials and Methods

2.1. Materials

2.1.1. Red Clay. The samples of red clay used in this experiment were taken from the Zun-Gui Highway in China. Clay depth ranges from 5 meters to 10 meters. The appearance is brownish red with white and dark green impurities. The samples are in plastic state with high natural moisture content. Their physical properties and material composition are shown in Tables 1 and 2, respectively.

According to Table 1, red clay has a high natural moisture content and the liquid limit of red clay is 103.1. The plastic limit is 30.6, and the plasticity index reaches to 72.5. Table 1 shows that the physical properties of red clay are quite particular. The reasons for these special properties are mainly related to the material composition and structural characteristics of red clay. It can be seen from Table 2 that there are many fine particles and high content of clay minerals and oxides in red clay. Mineral particles are mainly pellets with mass and fine pores. The free oxides between particles can form a cemented connection with good water stability, and the water in the soil is mainly bound water. The porous space provides a storage space for it [12, 13], so red clay has high natural moisture content and high liquid limit moisture content. In spite of this, the consistency of red clay is 0.94. Its state is plastic state, and some are even solid state. Therefore, red clay has some bad physical properties such as high moisture content, high plasticity index, and high void ratio while it has some good mechanical properties such as high strength and medium compressibility. This also provides a possibility for the application of red clay as roadbed filler.

2.1.2. Gravel. The samples of gravel were also taken from the Zun-Gui Highway in China. It is a type of dolomite with gray colour and hard texture. Its particle gradation curve is shown in Figure 1.

2.2. Experimental Scheme

2.2.1. Gravitational Compaction Experiment. This experiment was strictly referenced to the "standard method for geotechnical test" [14]. According to the method, the gravitational compaction experiment of red clay was carried out. Two methods for sample preparation were used in this experiment. One was the dry method, which dried red clay in the oven and controlled its moisture content by adding water. The other was the wet method, which dried the red clay under the sun and controlled the moisture content through sun-dry time. After sample preparation, loose red clay would be placed in a cylinder whose diameter is 10 cm and height is 12.7 cm for gravitational compaction. The dry density of samples in different moisture content would be recorded. The compaction curve was drawn to obtain the maximum dry density and the optimum moisture content [15–17], and the optimal moisture content was taken as the control index moisture content in the experiment of vibrating compaction.

Table 1: Physical and mechanical properties of red clay.

W_L (%)	W_P (%)	Natural moisture content (%)	Free expansion rate (%)	Plasticity index	Consistency
103.1	30.6	35.0	25.3	72.5	0.94

2.2.2. Vibratory Compaction Experiment. Because both the nature of clay and gravel can be shown in the mixtures of red clay and gravel, the particle diameter of the gravel is larger than the maximum size standard stipulated of gravitational compaction experiment. It is not feasible to research the compaction characteristics of mixtures of red clay and gravel with the gravitational compaction method. Therefore, the experiment of vibratory compaction was conducted. Different amounts of gravel (10%, 20%, 30%, 40%, and 60%) were mixed into red clay in this experiment, and then water was added and the material was choked up for 24 hours. After sample preparation, loose mixtures of red clay and gravel would be placed in a cylinder whose diameter is 28 cm and height is 25 cm for vibratory compaction. The optimal content of gravel was obtained by analyzing the relationship between dry density and gravel content. Then, by changing vibration frequency and vibration time, the relationship between vibration parameters and dry density was analyzed. Finally, the optimal vibration parameters were obtained.

2.2.3. CBR Test. CBR, known as California bearing ratio, is a method of judging the carrying capacity of materials, which is presented by the California Highway Bureau. At present, it has been an important basis for the selection of subgrade filler and the judgement of compaction strength [8, 18, 19]. This test was to process the red clay under the optimum moisture content by gravitational compaction and process the mixtures of red clay and gravel under the optimal gravel content by vibratory compaction. The optimal vibration parameters were used in the vibratory compaction. The size of the CBR test was the same as that of compaction experiment. Then, the strength of these two methods was tested on the CBR tester to validate the effect of gravel treated red clay.

3. Results and Discussion

3.1. Double Peak in the Compaction Curve of Red Clay. In the light of the results of gravitational compaction experiment of red clay, the relationships between dry density and moisture content are shown in Figure 2.

According to the curve in Figure 2, the maximum dry density of the dry method is 1.56 g/cm^3 and the optimal moisture content is 27%. And, the maximum dry density of the wet method is 1.43 g/cm^3, and the optimal moisture content is 28.1%. By comparing the data above, it is obvious

Table 2: Material composition of red clay.

Material composition	Clay mineral (65%)				Free oxide (23%)				Detrital minerals (12%)
	Kaolinite	Chlorite	Illite	Others	Silica	Alumina	Ferric oxide	Others	
Content (%)	8.71	27.75	10.92	17.62	12.02	6.06	2.71	2.14	—

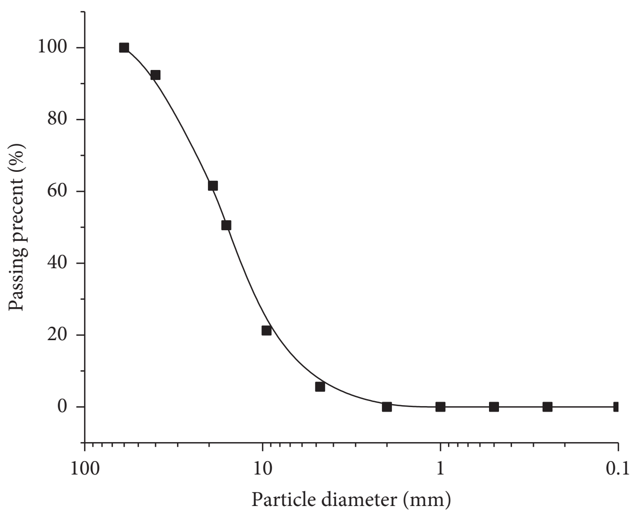

Figure 1: Granular grading of gravel.

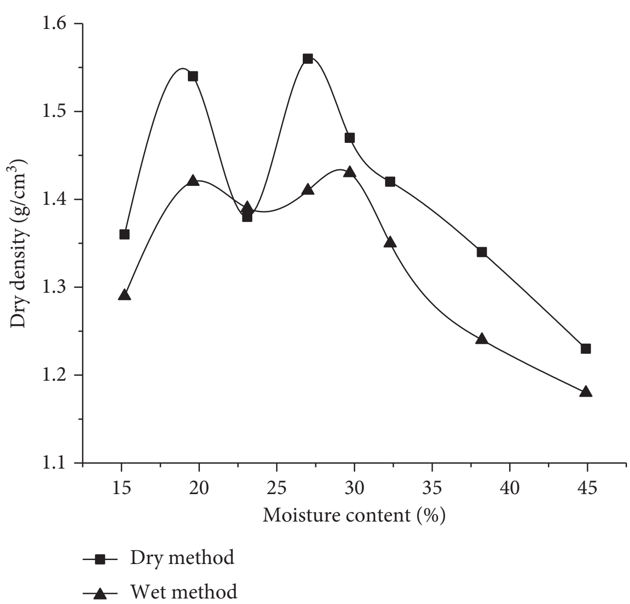

Figure 2: Relationship between dry density and moisture content.

that the maximum dry density of the dry method is larger than that of the wet method, while the optimal moisture content of the dry method is smaller than the wet method. After the analysis of this phenomenon, one of the important reasons discovered is that red clay is irreversible. The dry method compaction is equivalent to a dry-wet circulation [20–22]. The structure of the red clay is destroyed, and it results in the loss of bound water. But, the wet method compaction helps keep the bound water. Therefore, it is concluded that the optimal moisture content is higher than that of the dry method.

Actually, the results of the dry method are inapplicable in the construction sites. This is because its maximum dry density is higher and optimum moisture content is lower. The moisture content of natural red clay is high; the cost of the dry method is much higher than that of the wet method. Therefore, the result of the wet method is more conducive to guide engineering practice.

According to Figure 2, it can also be found that the curve of gravitation compaction appears as a double peak. It is obvious that the first peak is lower than the second peak. When it comes to this phenomenon, reasons can be found in the following aspects. First, the soil structure of red clay is too strong to destroy by compaction energy when it is of low moisture content. Therefore, the first peak appears. Second, red clay is softening gradually while increasing the moisture content; the heavy hammer of gravitation compaction energy can destroy its structure, and then red clay is recompacted. The dry density becomes largest when the moisture content reached a critical value. So, another peak appears. Although there are two peaks of dry density in the compaction curve, it is known from Table 1 that the moisture content of the red clay in the natural state is high. It is difficult to reach the low moisture content without manual control. Therefore, it is considered that the second peak is the real maximum dry density, and its corresponding moisture content is the optimal moisture content.

3.2. Vibration Compaction Characteristics of Mixtures of Red Clay and Gravel

3.2.1. Effect of Gravel Content on Dry Density. Because of the difference between red clay and gravel in material density, the dry density can vary with the change of content of clay and gravel under certain conditions. The relationship between content of gravel and dry density is shown in Figure 3.

It can be seen from Figure 3 that the dry density of samples increases with the increase of gravel content in the same vibration parameters, but they are not linear. The curve can be roughly divided into three sections. Firstly, when the gravel content is less than 20%, the slope of curve is low and dry density increases slowly. Secondly, when the gravel content is between 20% and 40%, the slope rises sharply. At the same time, the value of dry density increases sharply. Finally, when gravel content is between 40% and 60%, with the increase of gravel content, dry density is still rising, but it rises slowly again.

The main reason for this phenomenon is that the red clay has larger specific surface area, larger void ratio, and smaller quality [23].Therefore, with the increase of gravel

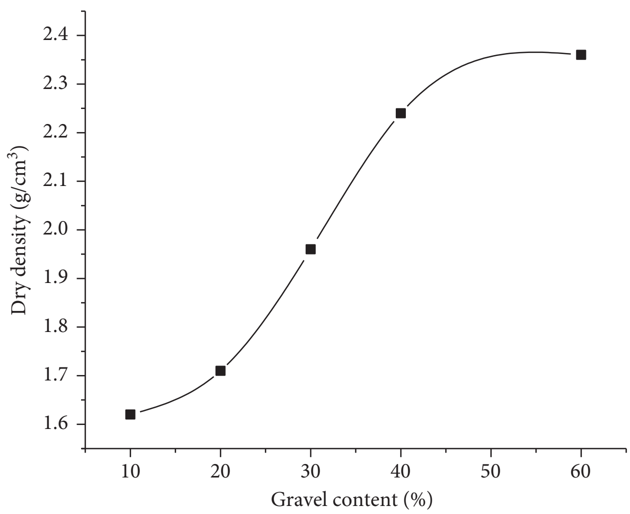

Figure 3: Relationship between dry density and gravel content.

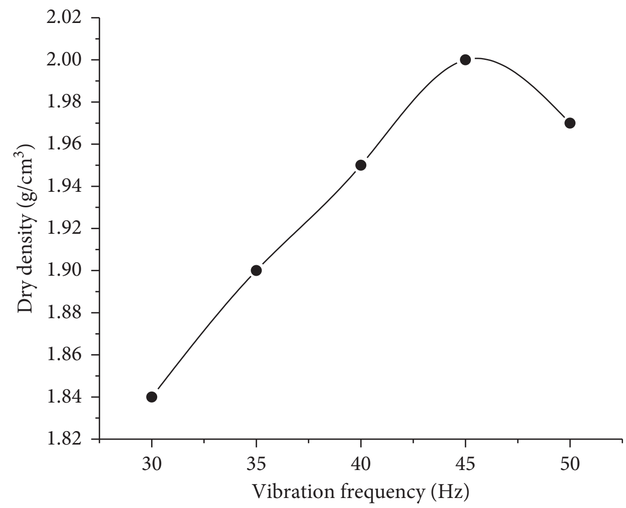

Figure 4: Relationship between dry density and vibration frequency.

content, the dry density of filler increases gradually. When the content of gravel is low (<20%), the gravel fails to form a skeleton in the red clay. The gravel is suspending in the red clay. It can be called as "supension-compaction structure." The dry density increases slowly because the red clay still plays a major role. With the increase of gravel content (20%–40%), gravel plays a role of skeleton in the soil gradually. The red clay can be used as fine material filling to skeleton pores, crude and fine material squeeze each other, and the degree of compaction is further enhanced. The mixtures of red clay and gravel reached a densest state. When the content of gravel is large (40%–60%), gravel continues to play a role of skeleton. However, the vibration parameters are defined, and there is not enough energy to squeeze the mixtures. Although the dry density results in an enlarged appearance, the degree of compaction is actually reduced when compared with the preceding stage (20%-40%). There are similar phenomena in the construction site; when the vibration parameters are certain, it is uneconomical and unscientific to improve the compaction quality by increasing the content of gravel simply. With the increase of gravel content, the construction cost and construction difficulty would increase step-by-step, respectively, and it would not improve the degree of subgrade compaction obviously. It is defined that the optimal gravel content is 30% based on a comprehensive consideration of experimental data and the actual situation of engineering.

3.2.2. Effect of Vibration Frequency on Dry Density. Vibratory compaction is a resonance of the mixtures through high frequency vibration produced by the vibrating compaction instrument. When the vibratory frequency is close to its own natural frequency of the mixtures, the particles will rearrange and squeeze each other. At the same time, small particles will be embedded in the pores of large particles to increase the degree of compaction. Therefore, the frequency of vibration has a great influence on the dry density and compactness of the mixtures. According to the experiment scheme, the relationship between vibration frequency and dry density is shown in Figure 4.

It can be concluded from Figure 4 that, when the time of vibration and the content of gravel are certain, the dry density of the mixtures of red clay and gravel increases at first and then decreases. There is a peak on the curve. Based on the analysis, this phenomenon can be explained from the respect of energy. With the increase of frequency, the original stress of the mixtures of red clay and gravel is damaged, and then the particles are rearranged. Under the effect of vibration and pressure, the vibrating energy is absorbed by filler, and the filler is compacted gradually until the optimal frequency occurs, the absorbing energy reaches the maximum value. If the frequency continues to increase, the excess energy cannot be absorbed by filler. What's more, it can destroy the filler which has been compacted. So, there is a downward trend in dry density. Similar situation will appear on the construction site. When the intensity of the vibratory roller is too large, it not only fails to compact subgrade but also can damage the structure of subgrade filler, resulting in irregular impact or excessive compaction. According to the experimental results, the optimal vibration compaction frequency of the mixtures is 45 Hz.

3.2.3. Effect of Vibration Time on Dry Density. During the vibration compaction experiment, the dry density of mixtures of red clay and gravel not only relates to gravel content and vibration frequency but also has a close relationship with vibration time. The relationship between vibration time and dry density is shown in Figure 5.

It can be seen that when the content of gravel and vibration frequency are certain, the dry density of mixtures of red clay and gravel increases with the increasing vibration time. As shown in Figure 5, the relationship between vibration time and dry density is close to linear when the

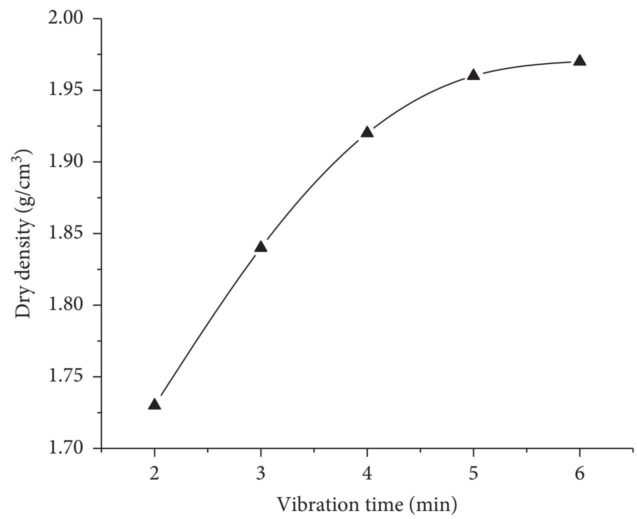

Figure 5: Relationship between dry density and vibration time.

Table 3: Minimum strength and compaction degree of highway subgrade construction.

Project classification	Subgrade part	Depth (m)	CBR (%)	Maximum particle size of packing (mm)	Compactness (%)
Fill subgrade	Upper roadbed	0–0.3	8	<100	>97
	Lower roadbed	0.3–0.8	5	<100	>97
	Upper embankment	0.8–1.5	4	<150	>95
	Lower embankment	>1.5	3	<150	>93

vibration time is less than 4 min. If the vibration time continues to increase, the slope of the curve becomes lower gradually and dry density increases slowly. With the increase of time, dry density changes little when the vibration time is more than 5 min. So, it is concluded that the compaction efficiency is best when the vibration time is 5 min.

3.3. CBR Test. The current standard "technical code for construction of highway subgrade" clearly stipulates the minimum strength and compactness of the subgrade, and the specific parameters are shown in Table 3 [24]. The results of the CBR test are shown in Table 4. It can be seen that the modified red clay is better than the pure red clay in the CBR value, water absorption, and swelling capacity. In particular, the improvement of the CBR value makes the subgrade strength increase about 3 times, which can come to the standard requirement of the CBR value of the filler in each position of the roadbed. Therefore, the compaction properties and strength properties of the compacted mixtures of red clay and gravel under the optimal gravel content and the optimal vibration parameters have been significantly improved in the CBR test.

4. Field Application

From the results of the vibration compaction experiment, the optimum vibration frequency of the mixtures of red clay and gravel is 45 Hz and the optimum vibration time is 5 min. Too high or too low vibration frequency and too long or too short vibration time is not conducive to the compaction of filler. According to the comparison and selection of the road roller on the construction site, the rolling effect of the "YZC10J double-steel wheel vibratory roller" is similar to that of the indoor test parameters, so this road roller is adopted to compact the filler. Some field tests were conducted for ensuring the optimal compaction time of 5 min. It is found that the compacting effect is the same as 5 min indoor compaction when the speed of the roller is 4.8 km/h and the rolling times are 4. The specific working parameters are shown in Table 5.

In the filling process of subgrade, there is also a very important issue to consider, that is, the "loose paving thickness" of the mixtures of red clay and gravel [25]. In fact, there is no large type of clay and gravel mixing equipment, which is the reason why the clay and gravel mixed embankment cannot be used widely [26, 27]. Therefore, this paper proposes to use the rotary tiller to mix red clay and gravel. Red clay and gravel are used in different levels. The operation depth of the rotary tiller is 25 cm, so the depth is used to control different content of red clay and gravel, that is, first spreading about $25 * 0.7 = 17.5$ cm thickness of red clay, and then spreading about $25 * 0.3 = 7.5$ cm of gravel, afterwards, using the rotary tiller for ploughing. The mixing process can not only reduce the natural moisture content of red clay but also makes the mixtures evenly distributed and easy to compaction. Use the road roller to compact it after mixing. When a layer of filler is compacted, repeat the above operation. This method has good effect on practical use. The compaction degree is tested by using the sand replacement method. The results show that the compaction degree is above 94%, which is much higher than that of filling with red clay directly.

Table 4: The results of CBR test.

Filler	Gravel content (%)	Compaction method	CBR (%)	Water absorption (g)	Swelling capacity (%)
Red clay	0	Heavy compaction	3.5	110	1.58
Mixtures of red clay and gravel	30	Vibratory compaction	11	80	0.5

Table 5: The working parameters of YZC10J roller.

Model type	Weight (kg)	Vibration force (kN)	Vibration frequency (Hz)	Speed (km/h)			Width (mm)
YZC10J	10000	98	42	2.4	4.8	8.4	1700

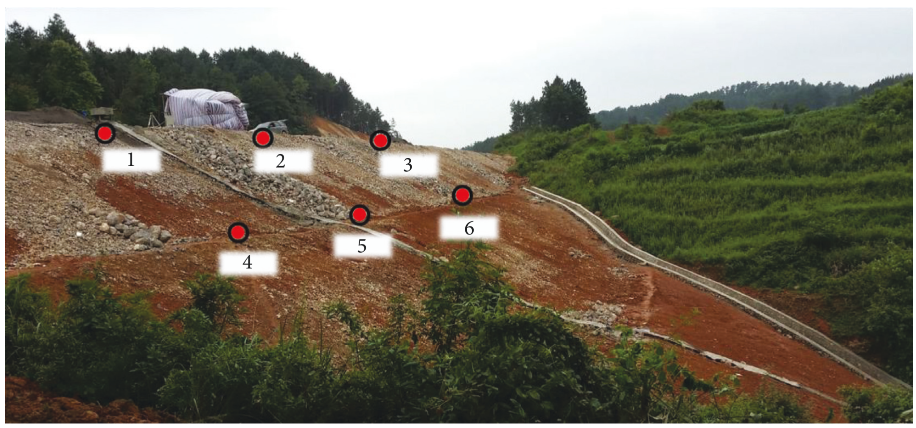

Figure 6: The schematic diagram of the location of the settlement monitoring point.

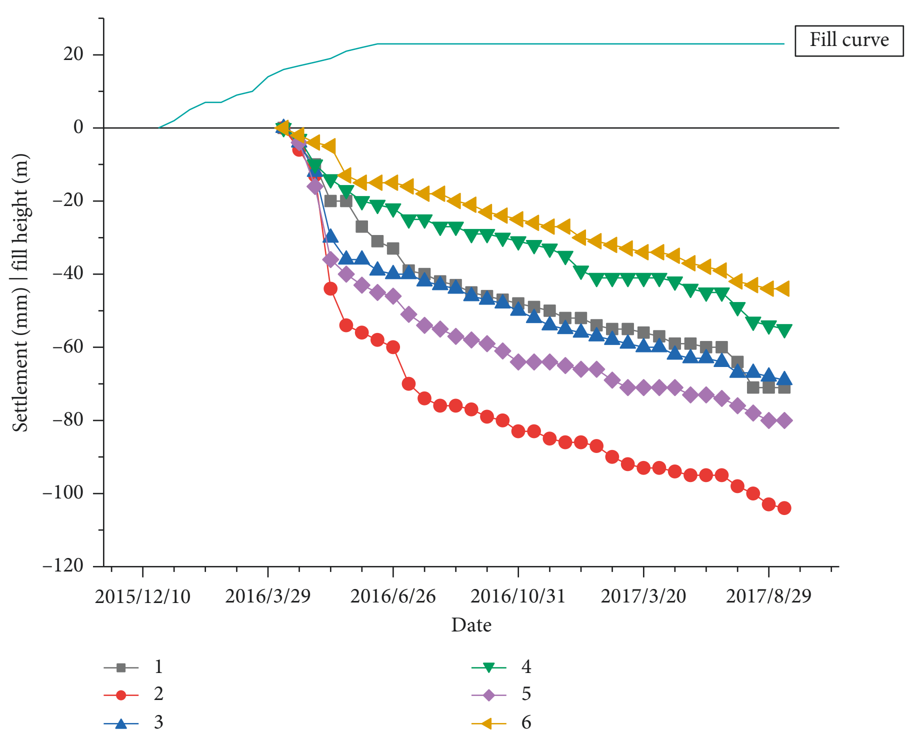

Figure 7: The relation curve between settlement and time in subgrade monitoring point.

In order to verify the actual improvement effect of the optimum gravel content and the optimum vibration parameters, a field test embankment was filled by using the road roller and compaction method. And, a real time monitoring of the typical section in the field test embankment was conducted. The field test embankment was filled with 23 m height. The embankment began to be filled in December 2015 and completed in June 2016. The schematic diagram of the location of the settlement monitoring point is shown in Figure 6.

As shown in Figure 7, the slope of the settlement curve is high in the first three months and then slows down. It shows that the early settlement of the roadbed is large, and then, the settlement decreases gradually. The settlement increment is approximately 20 mm in May, and settlement increment of some point is over 40 mm. The settlement increment is 8 mm in June, and it slows down gradually. The settlement increment is 7 mm in July, and the monthly settlement increment is maintained within 5 mm until May 2017. After that, the settlement increment is about 1 to 2 mm, the settlement gradually converged. Finally, the total settlement of each monitoring point is between 40 mm and 110 mm. It is much lower than the allowable settlement of expressway subgrade which is 300 mm. Therefore, with the appropriate construction parameters, the compactness and settlement of mixtures of red clay and gravel can reach the standard. It can be used as roadbed filler. It shows that the application of this method is successful.

5. Conclusions

This paper focuses on the compaction characteristics of red clay and mixtures of red clay and gravel. The effectiveness of optimal content of gravel and optimum vibration parameters is confirmed by the CBR test. A suitable construction method of subgrade for the mixtures is put forward. Some conclusions drawn from this study are as follows:

(i) There are two peaks in the compaction curve of red clay. This phenomenon is caused by strong structural property of red clay with low moisture content. It is considered that the second peak is the real maximum dry density; its corresponding moisture content is the optimal moisture content in a comprehensive consideration of the actual situation of engineering.

(ii) In the experiment of vibratory compaction, the dry density of mixtures increases with the increase of gravel content under the condition of the same vibration parameters. However, there is an optimum content of gravel in the mixtures of red clay and gravel. When the gravel content is 30%, it can control construction cost while ensuring compaction quality.

(iii) The change of vibration parameters leads to the change of vibration energy in the experiment of vibratory compaction. The energy absorbed by mixtures has a threshold value. There are optimum vibration parameters in this experiment. When the vibration frequency is 45 Hz and the vibration time is 5 min, the compaction efficiency of the mixtures of red clay and gravel is the best.

(iv) The compaction properties and strength properties of the compacted mixtures of red clay and gravel under the optimal gravel content and the optimal vibration parameters are significantly improved in the CBR test.

(v) According to the indoor compaction experiment results and the actual situation in the field, a suitable construction method of subgrade for the mixture of red clay and gravel is put forward. The feasibility of this method is also confirmed by postconstruction deformation data of the field test embankment.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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