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Research Article

Study on the Mechanical Properties and Design Parameters of Floor Slabs Waste Subgrade Filler

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In recent years, there have been more and more studies on the use of construction and demolition waste (CDW) as subgrade filler. The physical performance indexes of a single material of floor slabs waste (FSW) are studied, which meet the requirements of subgrade specification. From the perspective of construction quality control, it is proposed that when FSW is used as subgrade filler, the compaction thickness and the maximum allowable particle size should be controlled according to different layers, and the gradation of subgrade filler is evaluated by using the nonuniformity coefficient (C_u) and curvature coefficient (C_c). The compaction test of FSW shows that the maximum dry density and optimum moisture content of different gradations do not change much. The crushing value under the freeze-thaw cycle is proposed to evaluate the frost resistance of FSW. The crushing value of FSW after water absorption and frost heaving changes a little. The CBR and resilience modulus tests were carried out on the FSW such that the results show that they have a good relationship and the relevant expressions under different compaction degrees are fitted. When performing on-site compaction testing, it is proposed that the upper roadbed adopts the sand replacement method according to the different layers of the FSW subgrade and the settlement discrepancy method should be adopted for other parts. Through laboratory tests and construction field detective, the quality control requirements, road performance indexes, and design indexes of FSW materials are put forward.

1. Introduction

At this stage, resource shortages and environmental pollution have become essential factors restricting the sustainable development of the world [1, 2]. At present, the primary treatment method for CDW is open-air accumulation or landfilling in the ground [3, 4]. Such treatment will not only lead to the occupation of abundant land resources but will also cause a specific impact on the surrounding environment [5]. Therefore, the use of CDW as subgrade filler is an important aspect of resource utilization. The CDW filler is used to fill the subgrade, effectively reducing the excavation of the subgrade filling soil and protecting the ecological environment [6, 7]. CDW is used for backfilling an abutment, soft foundation treatment, roadbed filling, and other engineering parts. It can replace sand and stone materials with better road performance and reduce the use and mining of natural sand and stone [8–10]. In order to analyze the material and mechanical properties of CDW used in the subgrade and ensure its construction quality, its indexes should be studied.

Farias et al. learned compaction and CBR tests that CDW soil can help large particle CDW achieve a better dense state and improve its maximum dry density and CBR [11]. The CBR test of recycled aggregate found that recycled aggregate can be used not only for filling subgrade but also for the base course [12]. At the same time, under the same conditions, the resilient modulus and permanent deformation of processed CDW are better than those of common clay soil [13]. Sharma et al. found that CDW recycled aggregates are better than common lime-stabilized and water-stabilized base materials [14, 15]. Vivian et al. mainly studied the feasibility

and performance of recycling CDW as pavement base and subbase materials under dry and wet conditions [16–18]. The research of Yu et al. shows that CDW is not strong enough when used on the pavement and can only replace part of the pavement aggregate by 20%–30% [19, 20]. In contrast, the performance requirements of subgrade materials are much lower than those of pavement materials, which can be used in a wide range [21]. Leite et al. learned that material particles are broken under the action of external pressure, which increases the content of small particles, which helps to improve the density and bearing capacity of recycled aggregate. From another point of view, the crushing of recycled aggregate particles will also lead to subgrade deformation [22–24]. According to the analysis of Zhe, the main materials contained CDW are bricks, concrete blocks, and mortar [25, 26]; then the properties of the three materials are analyzed. The water absorption and crushing value of brick are the largest, and the concrete block is the opposite [27]. Melbouci et al. explained that the porosity and water absorption of different types of recycled aggregate are generally different, and the moisture content of recycled aggregate is increased compared with natural aggregate, partly due to the existence of small cracks on the aggregate surface [28]. The subgrade in seasonal frozen soil areas will experience one or more freeze-thaw cycles every year [29, 30]. In order to study the damage degree of construction and demolition subgrade caused by the freeze-thaw cycle, Zhang et al. used the van Genuchten model to accurately describe the soil-water characteristics of CDW under different compactness and freeze-thaw cycle times [31]. Thorough field tests researched the application of CDW in the subgrade and determined the optimum loose paving thickness and cycles of strong vibration. And then, the postconstruction settlement monitor was conducted for subgrades filled with CDW to analyze the applicability of CDW further. Compared with ordinary soil subgrade, the deformation of CDW subgrade is small [32], and the recycled CDW aggregate of subgrade performs well when properly compacted [33, 34]. The change of the external environment may significantly impact the long-term deformation of the CDW subgrade, especially the particle lubrication and softening caused by water immersion [35, 36]. Through the laboratory triaxial tests of CDW and clay soil. The results show that CDW has a higher resilient modulus, lower cumulative deformation, and less moisture sensitivity [13]. Therefore, CDW is rated as an excellent subgrade material.

By studying and summarizing the existing technology and scientific research achievements, combined with the laboratory test and field detection of the FSW subgrade, the physical performance indexes of the single material in the FSW are obtained. When filling subgrade with FSW, the compaction thickness and maximum particle size shall be controlled according to different layers of subgrade. C_u and C_c are used to evaluate the large, medium, and small particles of FSW and the gradation under the different proportion combinations of these three particles. During the freeze-thaw cycle, the thawing environment of FSW is changed. The crushing value test was carried out under the two states of thawing at room temperature and water to evaluate its frost resistance. In the process of the CBR test, the compaction forming method and static pressure forming method are compared. The resilient modulus is regressed with the CBR. According to the regression results, the relationship between CBR and resilient modulus under different compactness is fitted. The on-site compactness detection shall adopt sand replacement or settlement difference methods according to different layers of the FSW subgrade.

2. Technical Requirements for Subgrade Filler of FSW

2.1. Material Processing Requirements. Due to the complex composition of FSW, many impurities are unfavorable to the engineering, such as plastic, wood, steel, and foam, which need to be removed by manual and mechanical means [35]. The fixed jaw crusher is used to process FSW after removing the sundries. According to the layer of the subgrade, the diameter is smaller than the corresponding control particle size, which can meet the requirements of subgrade construction.

2.2. Technical Requirements for a Simple Substance. When using FSW to fill subgrade, it is necessary to understand the physical performance indexes of its single material, such as water absorption, density, bearing ratio, etc. These indexes are essential in laboratory tests and subgrade construction quality control. In order to use FSW for highway subgrade better, the single material test was carried out first, and the results are shown in Table 1.

It can be seen from Table 1 that FSW has the characteristics of large internal pores and high water absorption. FSW contains waste mortar, which has a strong water absorption capacity. In addition, many small cracks will appear on the surface of FSW during crushing. According to the laboratory test, the CBR of FSW is 185.21%. This value is much higher than the requirements of the specification for the expressway subgrade's bearing ratio, which shall not be less than 8%. Therefore, it is unreasonable to use the existing specifications to evaluate the bearing ratio of the Subgrade of FSW. It is necessary to put forward a new index of the minimum bearing ratio of the FSW subgrade filler. By consulting a large number of references, Know From Technical Specifications for Utilization of Construction Waste in Highway Engineering (JTG/T 2321-2021) and CBR test, it is determined that the CBR of FSW shall not be less than 40%.

3. Test Analysis on Compaction Characteristics of FSW

The particle composition of FSW plays a significant role in the stability of the subgrade. It is necessary to study the influence of different gradations on its road performance to meet the requirements of compaction test and CBR test for material particle size in laboratory soil test, as shown in Figure 1. The sample used for the laboratory test shall be air-dried and then crushed. The maximum particle size after

Table 1: Test results of FSW materials.

Evaluation items	Material		Test result	Specified value	Test method
Impurity content (%)	FSW		—	≤1 (GB/T 14685)	Sorting and weighing
Apparent density (g·cm^{-3})	FSW	Large	2.629	—	Volumetric flask method and basket method
		Medium	2.613		
		Small	2.775		
Water absorption (%)	FSW	Large	6.43	—	
		Medium	6.64		
		Small	8.36		
Plasticity index	FSW		8.9	≤26 (JTG 3430-2020)	Liquid-plastic limit combined test (< 0.075 mm)
CBR (%)	FSW		185.21	≥40	CBR test (maximum particle Size < 40 mm)

Figure 1: Sieving test and compaction test: (a) sieving test; (b) large, medium, and small particles shall be mixed as required by the test; (c) compaction test; (d) sample after compaction.

crushing shall not exceed 40 mm. According to particle size, it can be divided into three particle types: large, medium, and small. Compaction tests were carried out on the subgrade filler of FSW under different proportions to understand the change of its optimal moisture content and maximum dry density.

Firstly, a preliminary sieving test was carried out on the large, medium, and small materials of FSW. In the test, the mass loss of particles is 0.13%, 0.56%, and 0.96%, respectively, which are less than 1%, which meets the code requirement. The average value of the pass rate of each grade was used as the synthetic gradation, as shown in Figure 2. After that, the large, medium, and small particles are combined in different proportions, and each combination is shown in Table 2. A sieving test on the FSW of each proportion was carried out, and its gradation composition was analyzed. The test results are shown in Figure 3.

It can be seen from Figure 2 that the particle size of large particles is quite different from that of small and medium

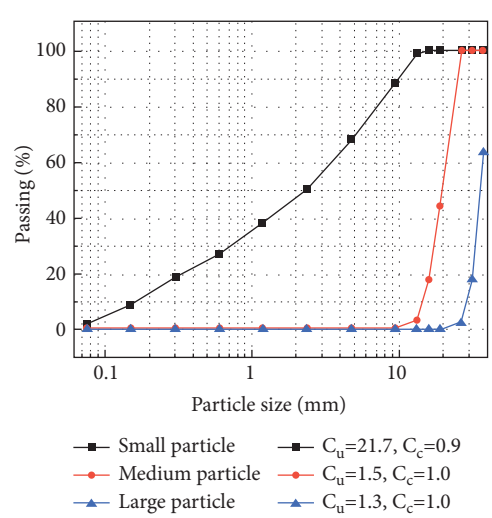

Figure 2: Sieving test of different particles.

Table 2: Proportion of different particle sizes in each group.

Particle size	Proportion of particles (%)					
Large (≤40 mm)	40	10	0	10	20	0
Medium (≤19 mm)	0	30	40	20	0	20
Small (≤13.2 mm)	60	60	60	70	80	80

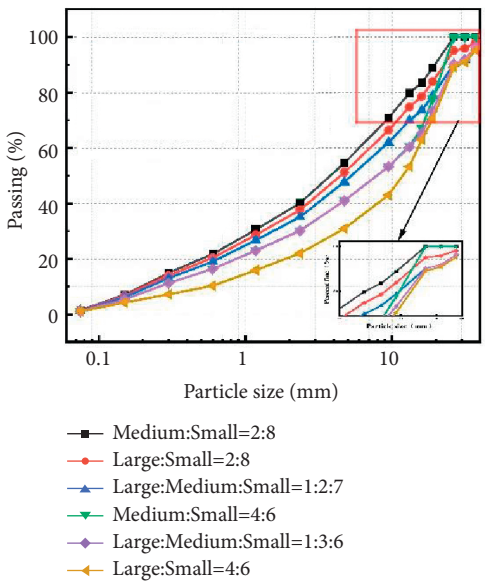

Figure 3: Sieving test of different proportions.

particles. There is little difference in C_u and C_c between large and medium particles, and C_u is less than 5. It shows that the particle size is uniform, and the gradation is poor. C_c of the three particles does not satisfy 1~3, the particle sizes of the three particles are continuous, and there is no disconnection, which can form a gradation curve that meets the requirements of the grassroots specification. It can be seen from Figure 3 that the particle size compositions of different ratios are relatively uniform. In the FSW with the ratio of large: small = 4 : 6, the content of particles smaller than 4.75 mm is 29.5%, which belongs to the skeleton void structure [18]. There are too many large particles that are easily broken in the compacted state, resulting in more small particles, and the structure of FSW is transformed from skeleton voids to skeleton compactness, which meets the requirements for roadbed fillers. The gradation of FSW is evaluated by C_u and C_c under different proportions, and the results are shown in Table 3.

According to Table 3, it can be found that the FSW with the ratio of large: small = 4 : 6 does not satisfy 1~3. The reason is that there are many coarse particles in the filler. When the compaction test was carried out for this proportion, the coarse particles were easily converted into small particles, and the gradation changed from bad to good. The FSWs in the other four ratios all satisfy $C_u \geq 5$ and $C_c = 1\sim3$, indicating that the gradation is good. In order to satisfy = 1~3, when the compaction test was carried out, the proportion of fine material was at most 80%.

The maximum particle size of the sample in this test is less than 40 mm, which is suitable for heavy II-2 standard compaction. The three-layer method is used for compaction, and each layer is compacted 98 times. The test results of FSW compaction under different proportions are shown in Figure 4.

It can be seen from the test results in Figure 4 when the particle size ratio in the mixture is not the same, the maximum dry density and the optimal moisture content are different. The optimum moisture content range of four proportions of FSW is 9.98%~10.74%, with little difference. Among them, as the proportion of small particle size increases, the optimal moisture content of FSW will be increased. It can be seen from Figure 4 that the moisture content under different ratios is not much different. Therefore, the construction quality is controlled by controlling the content of fine particles, and it is stipulated that the content of fine particles should not be higher than 54.6%.

4. The Relationship between Resilience Modulus and CBR

CBR is an important index to express subgrade strength, which is an important basis for selecting subgrade filler. The resilient modulus indicates that the subgrade filler can recover the deformation property under the action of instantaneous load. In the actual test, it is difficult to measure the resilience modulus. Therefore, scholars at home and abroad are trying to study the relationship between resilience modulus and CBR. The resilience modulus is calculated by CBR [19]. Due to the wide variety of subgrade fillers and the different test conditions, the relationship between resilience modulus and CBR will be different. According to the data, many scholars have proposed that the relationship between resilience modulus and CBR can be expressed by $E_0 = mCBR^n$, and the correlation between the two is better [20, 21]. This relationship is also used when regressing on FSW.

4.1. CBR Test. According to the optimum moisture content and maximum dry density obtained from compaction, the CBR test of FSW under different gradations was carried out, according to which the control parameters at different subgrade positions are analyzed. The compaction degrees are 96%, 93%, and 90%, which represent the roadbed, the upper embankment, and the lower embankment, respectively. Three compaction test specimens were prepared for each group, and the prepared specimens were immersed in water for 4 days and nights. After 4 days, the specimens were subjected to a CBR test. During the test, calculate the bearing ratio when the penetration amount is 5 mm and 2.5 mm, and then take the larger value as the bearing ratio of the material to obtain the CBR and expansion amount of FSW. The test results are shown in Figure 5.

The analysis of the test results shows that the bearing ratio of different proportions of FSW at 5 mm is greater than that at 2.5 mm. Therefore, 5 mm is used as the CBR of FSW during the test. The C_v between the CBRs of the three specimens corresponding to different compaction degrees is all less than 12%, and the average value of the CBRs of the

Table 3: Gradation of FSW under each proportion.

Proportion of large, medium, and small particles	4 : 0 : 6	1 : 3 : 6	0 : 4 : 6	1 : 2 : 7	2 : 0 : 8	0 : 2 : 8
C_u	56.6	48.8	48.04	37.8	34.3	30.6
C_c	5.75	1.57	1.58	1.31	1.13	1.00
Particle content less than 4.75 mm (%)	29.5	41.0	41.0	47.8	51.2	54.6
Gradation situation	Bad	Good	Good	Good	Good	Good

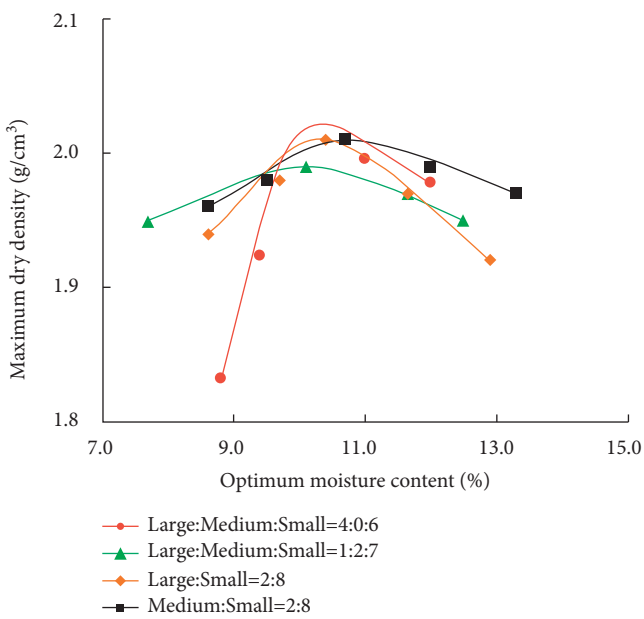

Figure 4: Compaction test results of FSW.

three specimens is finally taken as the bearing ratio of the FSW under this ratio. The variation curves of dry density and CBR of each proportion under different compactness can be obtained. It can be seen from Figure 5, in general, for FSW, as the degree of compaction increases, the value of dry density and the bearing ratio will also increase. When the ratio of large to small is 4 : 6, the content of small particles is less, and the CBR and dry density are the smallest under different degrees of compaction. When the ratio of large: medium: small is 1 : 2 : 7, with the increase of small particle content, CBR and dry density also increase under different compactness. When the ratio of large to small is 2 : 8, the maximum dry density and CBR have a decreasing trend, and the reason is that the support effect is weakened due to the reduction of large particles, which reduces the overall strength of the filler. In the FSW, large particles play a supporting role in the whole filler. With the increase of small particle content, the gap between large particles in friction stir welding can be filled. This can improve the uniformity and compactness of the filler to improve the strength of the sample.

The swelling capacity of each proportion of FSW gradually increases with the increase of compaction degrees because when the FSW compaction degree is small, the mass under the same volume is less, and the density is small. When the compaction degree of the sample is too large, the mass increases at the same volume. According to the experimental results, the swelling capacity rate of the sample with a small degree of compaction is small. The swelling capacity of FSW materials is only $0.3 \times 10^{-3} \sim 9.2 \times 10^{-3}$, which shows that the water absorption expansion is small. The reason is that the optimum moisture content is smaller than that of a roadbed of viscous soil, and the FSW belongs to the skeleton structure. The skeleton particles have no water absorption and swell, resulting in small water absorption and swelling amount.

At present, there are two molding methods for specimens in the CBR test. One is the commonly used compaction test method. However, when the three specimens of coarse-grained soil are processed for data, the CBRs are quite different, and the C_v is difficult to meet the requirement of less than 12%. The result is that there are many coarse particles in the specimen, which are not entirely crushed during the compaction process. When coarse particles are subjected to local shear, the stress is not uniform, and the penetrating rod may be pressed on the stone or the gap of the stone, causing large deviations in the CBR results. The other method of CBR specimen forming is provided in Test Methods of Soils for Highway Engineering (JTG) 3430-2020, which calculates the amount of specimen to be used according to its compactness and adopts one-time static pressure forming. The static pressure forming test method is adopted, and the test results are shown in Table 4. The CBRs of the three specimens have little difference, and the C_v is less than 12%, meeting the requirements of the specification. Therefore, in the CBR test, it is recommended to use the static pressure forming method to prepare the test piece.

4.2. Crushing Value Test under Freeze-Thaw Cycle. The water absorption rate of FSW is very high, so it is prone to frostbite. In order to compare the strength changes of FSW before and after freeze-thaw, the following tests were carried out. When simulating the filling of the subgrade with FSW, the subgrade is not always in a dry state. Therefore, some are placed at room temperature during the thawing process and others in water, as shown in Figure 6.

In order to understand the strength change of FSW after many seasonal changes better, the specimens were thawed at room temperature for 0, 10, 50, 100, and 150 freeze-thaw cycles. Under the condition of water, 0, 10, 30, 60, and 90 freeze-thaw cycle tests were prepared. The change of the crushing value of the skeleton after water absorption under the condition of frost heaving is shown in Figure 7.

It can be seen from Figure 7 that with the increase of freeze-thaw cycles, the crushing value of FSW at room temperature and in water tends to increase gradually. Under the same number of freeze-thaw cycles, the crushing value of FSW thawed in water is higher than that of thawing at room temperature. It shows that water has a certain impact on the

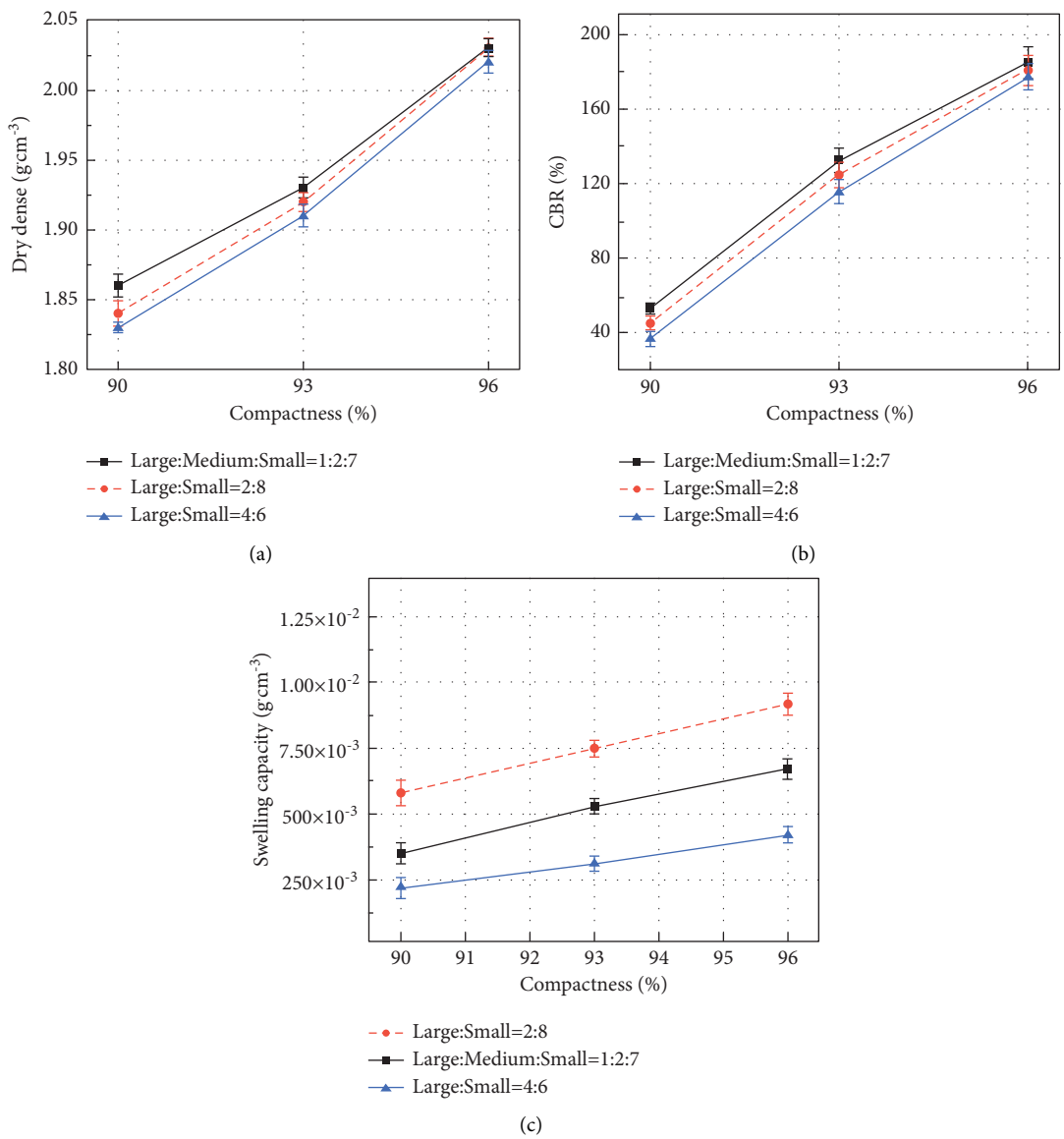

Figure 5: CBR test: (a) relationship between compactness and dry density, (b) relationship between compactness and CBR, and (c) relationship between compactness and swelling capacity. The error bars represent the standard deviation of measurements for 9 particles in three separate sample runs ($n = 27$).

Table 4: CBR values under different molding methods.

Proportion	CBR/%			C_v	Specimen forming method
	1	2	3		
Large: small = 4 : 6	201.37	165.32	143.36	12.71	Compaction test
	172.57	171.90	187.14	3.97	Static pressure forming

strength of FSW, but generally speaking, frost heave after water absorption does not significantly improve the crushing of FSW. It shows that the strength of the filler after water absorption is relatively stable.

4.3. Resilient Modulus Test. The instrument used in this test is the pavement material strength instrument, the pressure is not less than 50 kN, and the penetration speed can be adjusted to make the penetration of 1 mm per minute. The same specimen was loaded step by step with forces of 4, 8, 12, 16, 20, and 24 kN, respectively, and then the elastic modulus was calculated by unit pressure and rebound deformation. The calculation results are shown in Table 5.

According to the test results, the difference between the results of three specimens corresponding to FSW in each

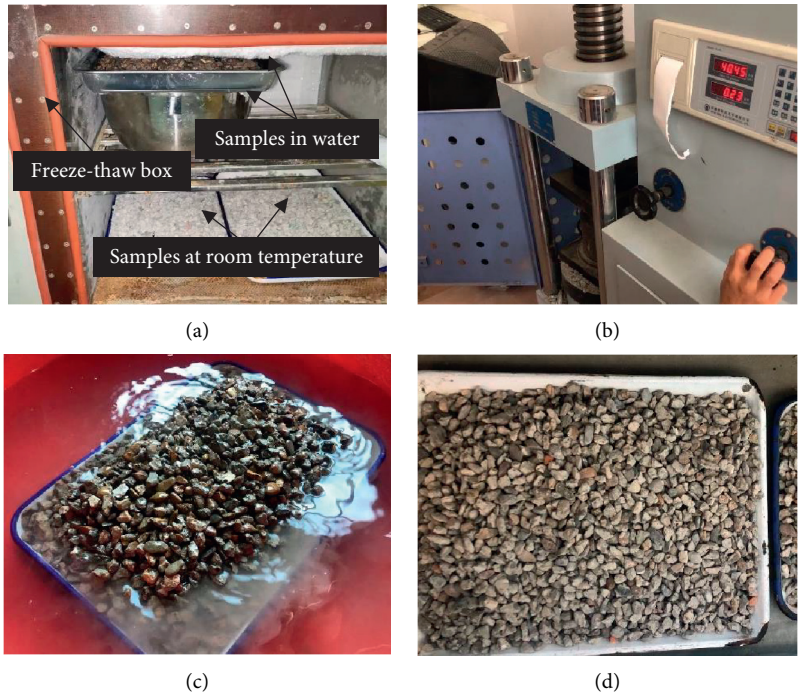

Figure 6: Crushing value test under freeze-thaw cycle: (a) sample in the freeze-thaw box; (b) crushing value test; (c) samples melted in water; (d) samples melted at room temperature.

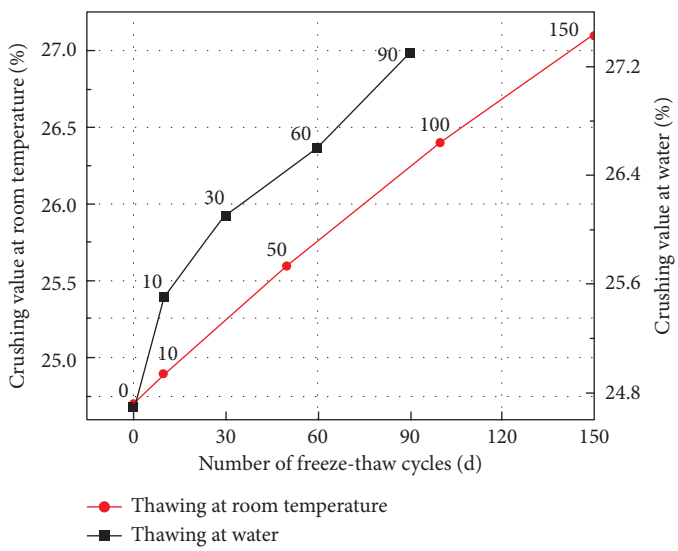

Figure 7: Crushing value of FSW after freeze-thaw.

Table 5: Resilience modulus of FSW in different proportions.

Proportion of large, medium, and small particles	Optimum moisture content (%)	Sample	Resilient modulus (MPa)	Average (MPa)
4 : 0 : 6	10.03	Sample 1	125.1	124.5
		Sample 2	121.4	
		Sample 3	127.1	
1 : 2 : 7	10.13	Sample 1	131.8	130.0
		Sample 2	128.3	
		Sample 3	129.2	
2 : 0 : 8	10.36	Sample 1	130.7	126.7
		Sample 2	125.0	
		Sample 3	124.4	

proportion and its average resilient modulus is no more than 5%, so the average value is taken as the resilient modulus of FSW in this proportion. It can be seen from Table 5 that the resilience moduli of different proportions of FSW are not much different. When the ratio of large: small is 4 : 6, the modulus of resilience is the smallest. When large: medium: small is 1 : 2 : 7, the modulus of resilience increases as the content of small particles increases. When the ratio of large to small is 2 : 8, the reduction of large particle content reduces the support effect, strength, and resilience modulus in the filler.

4.4. Study on the Relationship between Resilience Modulus and CBR. The standard load strength and standard load corresponding to different penetration are shown in Figure 8.

The fitting can be performed according to the data in Figure 8, and the fitting relationship is as follows:

$$p = 4018.5 \times L^{0.601}, \tag{1}$$

where p is the standard load strength and L is the penetration.

In order to analyze the relationship between resilience modulus and CBR of FSW, the ratio of large: small = 4 : 6 was selected for the test. During the test, two dial gauges of the penetration amount were recorded at the same time. In order to express the resilience modulus value more accurately, when the penetration amount reached 5 mm, the test was not stopped, and the penetration amount was continued to be recorded. In the CBR test, the penetration amount is also changed under stress, but the modulus of resilience cannot be obtained directly calculated in this way. The modulus of resilience is the stress ratio to the corresponding resilience strain. Therefore, the resilient modulus cannot be calculated directly through the CBR test. Through the CBR test, the change curve of stress and strain can be known, from which we can obtain the slope of each point on the stress-strain curve which is called the tangent modulus. The relationship between the modulus of resilience E_t and the modulus of tangent is shown in Figure 9.

It can be seen from Figure 9 that with the increase of penetration, the resilient modulus and tangent modulus increase, and the changing trend between them is basically the same. A fitting is performed on the resilient modulus and the tangent modulus, and the fitting relationship is as follows:

$$E = 1.32 \times E_t - 98733, \tag{2}$$

where E is the resilient modulus and E_t is the tangent modulus.

Through the tangent modulus of each penetration and in combination with formulas (1) and (2), the resilience modulus corresponding to each penetration is calculated, and then the bearing ratio of each point is analyzed. The results are shown in Figure 10.

The resilient modulus of FSW in Figure 10(a) increases with the increase of CBR. When the penetration reaches about 3 mm, the resilient modulus declines. The changing trends of Figures 10(b) and (c) are basically similar to Figure 10(a), but there is a difference in the turning point of the downward trend of the elastic modulus. The turning point in Figure 10(b) is when the penetration amount reaches about 3.5 mm, and the penetration amount in Figure 10(c) reaches 6 mm. No matter the compaction degree is 96%, 93%, or 90%, the point of CBR drop is about 5 mm, so the CBR of FSW can reach the maximum value at about 5 mm. According to Test Methods of Soils for Highway Engineering (JTG) 3430-2020, when the penetration amount is 2.5 mm and 5 mm, the bearing ratio is calculated, and the larger one is taken as the CBR value of the material. The test shows that the maximum CBR of FSW is obtained when the penetration reaches about 5 mm. Therefore, when carrying out the bearing ratio test, the reading can reach 500×10^{-2}mm. As shown in Figure 10, the resilient modulus and CBR of FSW have a reasonable correlation. When the resilient modulus test is limited, the CBR can be used to preliminary calculate the resilience modulus. The fitting results of resilient modulus and CBR for different compactness are shown in Table 6.

5. Quality Control of Subgrade Filled with FSW

When using FSW to fill the roadbed, it is necessary to control the construction quality strictly. Through the construction of experimental roads, the quality control and detection methods of FSW are summarized. In order to reflect the road performance of FSW as a subgrade filler better, its construction technology should be proposed in combination with different layers of subgrade. Combined with the laboratory test and the construction field conditions, the requirements for the maximum particle size and layered filling thickness of the FSW subgrade are put forward.

5.1. Site Description. The test section of the project is located in Tongyu County, Baicheng City, Jilin Province. It belongs to bid section 03 of the 2020 rural highway old reconstruction project in Tongyu County. The specific section is from Yuejin to Xitai, and FSW replaces gravel for soft foundation treatment. The total length is 200 m, and the section number is $K1+600$ ~$K1+800$. The photos of the construction site are shown in Figure 11.

5.2. Design Index. The FSW filler shall be filled in layers according to different layers of subgrade, and the maximum allowable particle size of each layer shall be controlled accordingly so that it can achieve a good compaction effect after rolling. In order to explain the compaction state of different layers, the compaction degree of the FSW subgrade is measured by the sand replacement method and settlement discrepancy.

5.2.1. Sand Replacement Method to Measure the Degree of Compaction. Sand replacement is a method of replacing the volume of the test hole with the volume of sand, which is commonly used to test the degree of compaction.

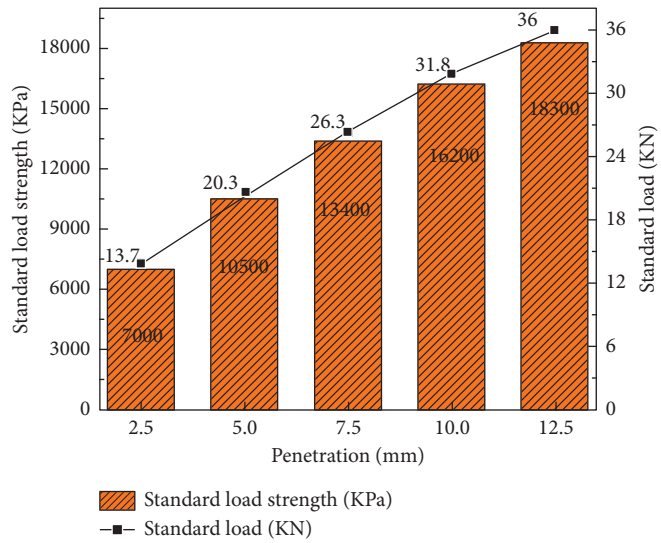

Figure 8: Standard load strength and standard load under different penetration.

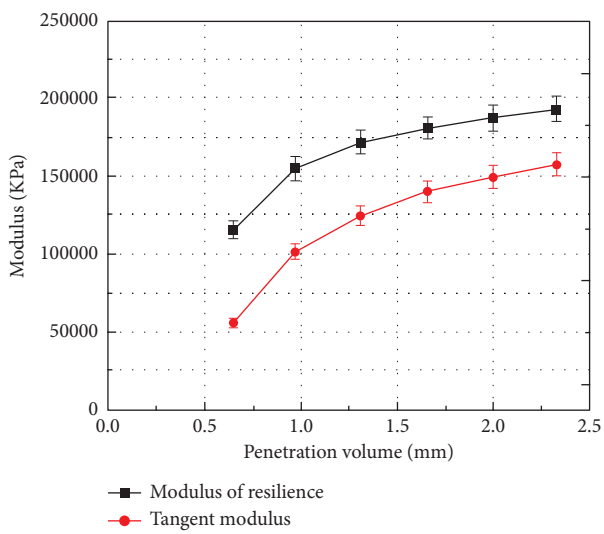

Figure 9: Relationship between resilience modulus and tangent modulus of FSW. The error bars represent the standard deviation of measurements for 18 particles in two separate sample runs ($n = 36$).

It can be seen from Table 7 that the compaction degree of the first layer and the second layer of the filler on the roadbed after 10 times of rolling meets the requirement that the degree of compaction is not less than 95%. Therefore, *t* the sand replacement method can detect the compaction degree of the subgrade above the FSW filler.

Due to the large particle size of FSW, according to Test Methods of Soils for Highway Engineering (JTG) 3430-2020, when the content of particles with the maximum particle size exceeding 40 mm is greater than 30%, the sample cannot obtain the maximum dry density through compaction test, the maximum particle size of FSW filler below the upper roadbed is basically greater than 40 mm. Therefore, it is impossible to accurately calculate the degree of compaction by using the maximum dry density measured in the compaction test. When the sand replacement method is difficult to measure the degree of compaction, the settlement difference method can be considered, which is more intuitive.

5.2.2. Settlement Difference Method to Measure the Degree of Compaction. In order to obtain the rolling quality of the subgrade below the upper roadbed of the FSW, after the last two passes of rolling, the difference between the measured elevations cannot be greater than 2 mm, the settlement difference test was carried out under different rolling times. During the rolling process of FSW subgrade filler, the state of filler changes from loose to dense, and the thickness of filler is gradually stable. During the rolling process, the subgrade settlement shall be measured in time, and the rolling quality can be judged according to the settlement difference. Table 8 shows the subgrade settlement results measured during rolling.

The analysis of the settlement difference shows that for the FSW subgrade with a loose thickness of 30 cm, the settlement difference gradually decreases with the increase of the rolling times when the layers are filled. When the number of rolling compaction reaches more than 8 times, the settlement difference of FSW gradually tends to a stable state, and all of them are less than 2 mm. According to the change of settlement difference of FSW subgrade filler, this paper suggests that the number of rolling passes should not be less than 8 times, and the settlement difference of two adjacent passes should not be greater than 2 mm. At this time, the subgrade settlement is basically stable, and the filler has reached a relatively dense state. Therefore, in the course of the test, the sand replacement method or settlement difference method is used to detect the compactness according to the different layers of the FSW subgrade.

5.2.3. Control of Compaction Thickness and Maximum Particle Size at Different Parts of Subgrade. According to the specification requirements, the filling thickness of the upper roadbed ranges from 0 to 0.30 m. When the compaction

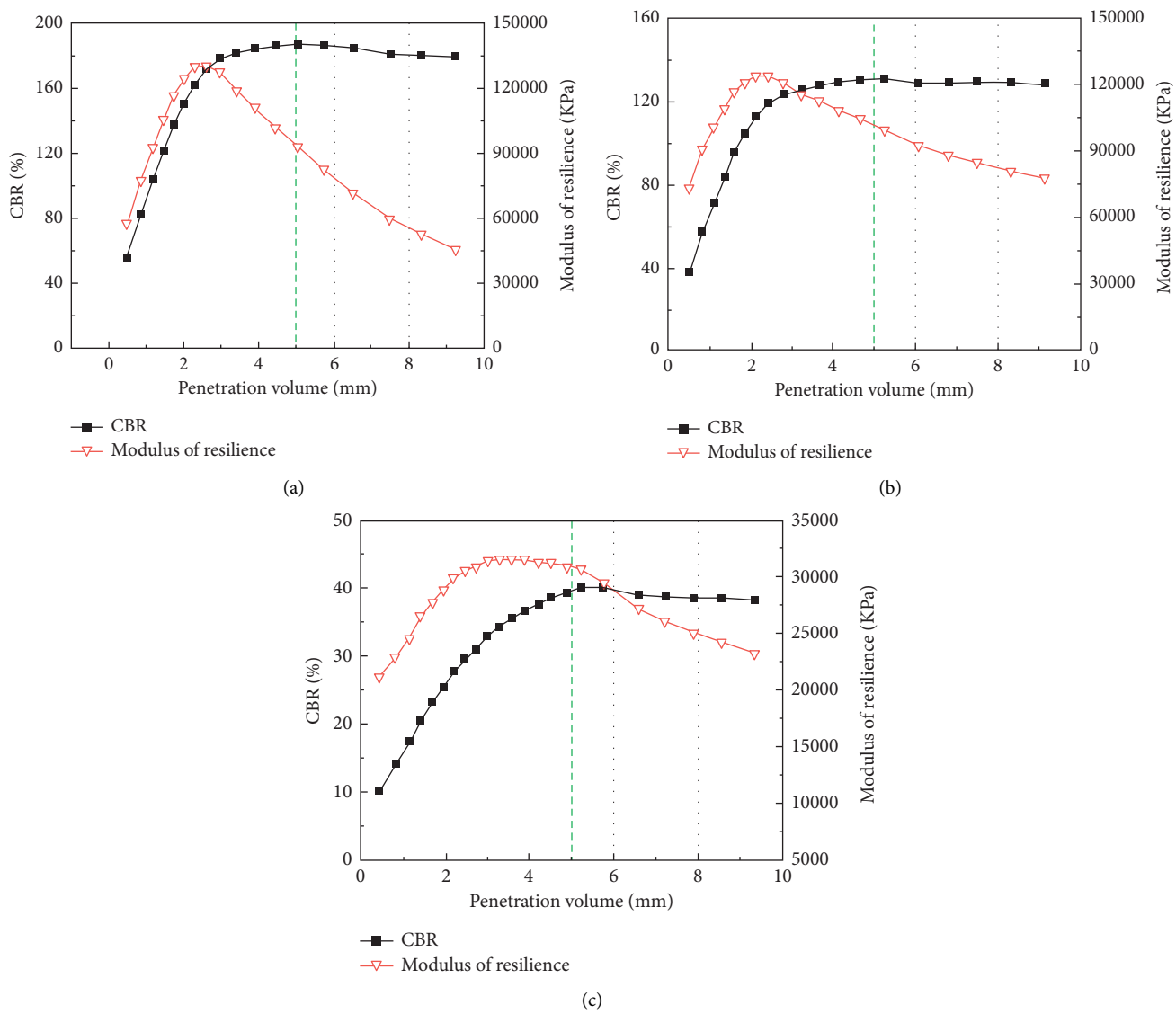

Figure 10: Relationship between CBR and modulus of resilience: (a) 96% compaction, (b) 93% compaction, and (c) 90% compaction.

Table 6: Calculation formula of resilient modulus and CBR under different compactness in FSW.

Position of filler application (below the top of roadbed) (m)	Compactness (%)		
	Expressway and first-class highway	Second-class highway	Third- and fourth-class highway
Upper roadbed	≥96	≥95	≥94
Lower roadbed	≥96	≥95	≥94
Upper embankment	≥94	≥94	≥93
Lower embankment	≥93	≥92	≥90

Note: $E_{96} = 2.8 \times \mathrm{CBR}^{0.75}$ $(40\% \le \mathrm{CBR} \le 170\%)$, $E_{96} = 5.1 \times \mathrm{CBR} - 877.0$ $(170\% < \mathrm{CBR} \le 190\%)$, $E_{93} = 13.6 \times \mathrm{CBR}^{0.47}$ $(30\% \le \mathrm{CBR} \le 120\%)$, $E_{93} = 8.2 \times \mathrm{CBR} - 966.2$ $(120\% < \mathrm{CBR} \le 140\%)$, $E_{90} = 10.9 \times \mathrm{CBR}^{0.29}$ $(10\% \le \mathrm{CBR} \le 30\%)$, $E_{90} = 3.5 \times \mathrm{CBR} - 108.6$ $(30\% < \mathrm{CBR} \le 40\%)$, where E_{96}, E_{93}, and E_{90} are the resilient modulus values of the test piece when the compactness is not less than 96%, 93%, and 90%, respectively.

thickness of the upper roadbed reaches the requirement of 0.30 m, it can be filled twice in layers, and 150 mm can be filled each time. The lower roadbed is also filled in layers. If the traffic is extremely heavy, the filling thickness of the lower roadbed ranges from 0.30 to 1.20 m according to the specification requirements. Therefore, the compaction thickness at the construction field shall be determined as 300 mm and filled in three times. For light, medium, and heavy traffic, the filling range of the lower roadbed is 0.30~0.80 m, and the compaction thickness can be set as 250 mm, which can be filled in two times. As the FSW belongs to soft rock, the compaction thickness shall be controlled according to the requirements of filling embankment with soft rock. Since the particle size of FSW

(a) (b) (c)

Figure 11: Construction process of the FSW subgrade: (a) roughly leveling with a bulldozer; (b) watering with a sprinkler; (c) static compaction and weak vibration.

Table 7: Test results of compactness of FSW.

Number of layers	The number of compaction times	Stake	Loose laying depth (cm)	Wet density ($g{\cdot}cm^{-3}$)	Dry density ($g{\cdot}cm^{-3}$)	Degree of compaction (%)
The first layer	10	$K1+40$	30	1.96	1.85	97.51
		$K1+50$		1.92	1.81	95.25
The second layer	10	$K1+40$	30	1.95	1.84	96.59
		$K1+50$		1.93	1.82	95.62

Table 8: Subgrade settlement observation index.

Subgrade filler	Number of layers	Compaction times	Loose laying depth (cm)	Settlement difference (mm)	Testing equipment
FSW	The first layer	2	30	9.8	22t Vibratory roller, level, level ruler, tape measure, and spray paint
		4		9.0	
		6		3.0	
		8		1.5	
		10		0.8	
	The second layer	2	30	5.3	
		4		2.5	
		6		2.1	
		8		1.2	
		10		0.6	

Table 9: Requirements for layered filling thickness and maximum particle size of FSW and detection methods of compaction degree.

Subgrade position	Compacted thickness (mm)	Maximum particle size (mm)	Detection methods of compaction degree
Upper roadbed	150	≤50	Sand replacement method
Lower roadbed	≤300	≤100	Settlement difference method
Upper embankment	≤300	≤300	
Lower embankment	≤400	≤300	

particles reaches about 300 mm, the particles become flakes, which can be used to fill the embankment and is not suitable for filling the roadbed. Combined with the compaction thickness, the maximum particle size is controlled.

5.2.4. Design Index Requirements. The layered filling thickness, maximum particle size requirements, and detection methods of compaction degree of FSW are shown in Table 9.

6. Conclusion and Suggestions

Combined with many laboratory tests and field tests, this paper puts forward various road performance indexes and design indexes when FSW fills subgrade through analysis and summary. The main conclusions are as follows:

(1) Different specimen forming methods have a certain impact on the CBR results. In the CBR test of FSW, the standard compaction forming method has great discreteness, while the CBR value is relatively

uniform in static pressure forming. Therefore, it is suggested to prepare FSW specimens by static pressure forming;

(2) The CBR of FSW has a good correlation with the resilience modulus, and the relationship between them under different degrees of compaction is fitted. The modulus of resilience can be estimated by CBR test;

(3) FSW has high water absorption and a small amount of swelling. Therefore, the crushing value after the freeze-thaw cycle is proposed to evaluate the frost resistance of FSW. The results show that the crushing value of FSW changes little after water absorption and frost heaving. FSW strength is relatively stable after water absorption, which can replace sand and gravel materials for special subgrade treatment;

(4) Through the research on the characteristics of FSW, combined with the design and construction of the subgrade test section, this paper puts forward the design indexes such as compacted thickness, maximum particle size requirements, and compactness detection method of different layers as subgrade filler.

Data Availability

Data used to support the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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