Article

Characterization of Properties of Soil–Rock Mixture Prepared by the Laboratory Vibration Compaction Method

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Abstract: This paper presents a study of the properties of soil–rock mixtures (SRM) prepared by the vibration compaction method. First, the results of laboratory experiments and field tests are compared to determine the reasonable parameters of the vibration compaction method (VCM) for soil–rock mixtures. The compaction characteristics, CBR, and resilient modulus of the laboratory-prepared soil–rock mixtures by the static pressure compaction method (SPCM) and vibration compaction method are compared. The effects of the soil to rock ratio and the maximum particle size and gradation on the compaction characteristic, resilient modulus and CBR of soil–rock mixtures prepared by the vibration compaction method are investigated. Finally, field measurements are subsequently conducted to validate the laboratory investigations. The results show that the reasonable vibration frequency, exciting force, and static surface pressure of the vibration compactor for soil–rock mixtures are recommended as 25 Hz, 5.3 kN, and 154.0~163.2 kPa, respectively. Soil–rock mixtures prepared by vibration compaction method has smaller optimum water content and gradation variation and larger density than specimens prepared by the static pressure compaction method, and the CBR and resilient modulus are 1.46 ± 0.02 and 1.16 ± 0.03 times those of specimens prepared by the static pressure compaction method, respectively. The ratio of soil to rock, followed by the maximum particle size, lead obvious influences on the properties of soil–rock mixtures. Moreover, the results show that the CBR and resilient modulus of soil–rock mixtures prepared by vibration compaction method have a correlation of 86.9% and 89.1% with the field tests, respectively, which is higher than the static pressure compaction method.

Keywords: soil–rock mixtures; vibration compaction method; static pressure compaction method; compaction characteristic; CBR; resilient modulus

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1. Introduction

With the construction of highways in the hilly areas of western China, soil–rock mixtures (SRM) after blasting or excavation has gradually used as the main filler of highway subgrades. SRM is composed of coarse rocks and fine soils with a certain gradation, and possesses better water permeability, higher strength and compactness than soil [1]. However, the compaction and mechanical properties of SRM are complicated due to large difference in particle size and uneven gradation [2–5]. Therefore, a lot of research on the influencing factors of SRM road performance has been performed. Kong discovered the compaction density of SRM is related to the mass ratio of soil to rock and the gradation through large-scale compaction tests [6]. Yang et al. used the indoor large-scale direct shear test and PFC discrete element numerical simulation to reveal that the strength of the

rock has a significant influence on the shear characteristics of the SRM [7]. Wang divided SRM into the multi-soil type and multi-rock type by a large number of field test data and established a model for evaluating the compaction quality of the two kinds of SRM [8]. Tu et al. studied the particle crushing characteristics and shear strength characteristics of soil–rock mixtures from macro and meso-level perspectives and revealed the influence of rock content and particle crushing on the shear strength characteristics of SRM [9]. Robert et al. proposed a laboratory compaction standard of SRM [10]. Wang et al. developed a large-scale compaction instrument capable of compacting SRM with a maximum particle size of 120 mm and studied the factors affecting the maximum dry density of SRM [11]. Zhou et al. investigated the effect of freeze–thaw cycles on the mechanical properties of SRM [12]. All the above research discovered that density is an important factor affecting the mechanical properties of SRM, which depends on the maximum dry density measured in the laboratory and the compactness measured in the field. Moreover, the maximum dry density is related to the laboratory compaction methods [13–16].

Currently, the maximum dry density of subgrade soils, granules, and some materials stabilized with inorganic binders is measured mainly by compaction method, which is the static pressure compaction method (SPCM), the shaking table method (STM) and the surface compaction method (SCM). SPCM is the most widely used all over the world, and is applied to the materials with particle sizes of no more than 40 mm. Although the SPCM has been used for road subgrade geotechnical tests for a long time, it still has shortcomings: (1) the standard laboratory density measured by SPCM is low, due to the fact that the compaction energy and method of SPCM are proposed based on the 12–15 tons compaction roller commonly used in the late 1980s and are inconsistent with modern heavy-duty compacting rollers of more than 20 tons; and (2) the SPCM is unsuitable for non-adhesive and free-draining soil, such as sand and pebble. To better simulate the vibration compaction roller, the shaking table method (STM) was developed. Compared with the SPCM, the STM applies vibration force, which can simulate the vibration compaction effect of roller. Therefore, the density of the prepared specimens is improved by 3–5%, and the elastic modulus is improved by approximately 20% [17]. However, the STM applies vibration from the bottom to the top, which is opposite that of the roller in the field. Additionally, due to the limited power of the vibration table, the vibration of heavier specimens cannot be realized. To overcome the limitation of the vibration power, the SCM was developed, which can better simulate the vibration characteristics of the on-site vibratory roller. However, the vibrator motor on the vibratory roller cannot simulate the compaction conditions of multiple compaction parameters in the field, for it has only one frequency and amplitude. The SCM is suitable for non-adhesive, free-draining, and coarse-grained soil with maximum particle diameters of less than 60 mm [18]. In addition, to simulate on-site compaction and obtain information on the compaction process of the asphalt mixture, the Strategic Highway Research Program proposed superior gyratory compaction methods (SGC). This method is mainly for asphalt mixtures, and it is applied rarely in subgrade and cement stabilized macadam base [19,20].

To overcome the shortcomings of these traditional methods, Chinese scholars have developed the laboratory vibration compaction method (VCM). The VCM is performed via the vertical vibration test equipment (VVTE), which can simulate the vibration and oscillation of a vibratory roller [21,22]. The VCM is mainly used for the semi-rigid mixtures, such as cement stabilized gravel. Previous studies showed that the semi-rigid mixtures prepared by VCM has larger density, superior mechanical properties, and better durability than those of mixtures prepared by SPCM [23–25]. The mechanical properties ratio between the laboratory cement-stabilized macadam specimen prepared by the VCM and the on-site specimens is over 90% [26]. In addition, Zvonaric et al. used laboratory vibration compaction methods to study the factors affecting the compaction and strength characteristics of unbonded and cement-bound mixtures and proposed that the compaction and strength characteristics are significantly different due to different compaction methods [27]. The VCM is also used to prepare unbound graded aggregates. Compared with the SPCM, the

unbound graded aggregates prepared by VCM have better mechanical properties [28]. The VCM was gradually applied to the asphalt surface in recent years for its advantages. Oliveira et al. proposed a laboratory VCM that better simulates the conditions of the on-site asphalt mixture [29]. Jiang et al. used the VCM and Marshall methods to design asphalt mixtures and evaluate their road performance, which indicates that the asphalt mixture laboratory prepared by VCM is better than that of the mixture prepared by Marshall method [30,31]. In recent years, the VCM has been also promoted to the subgrade soils, such as loess [32,33], sandy soil [34] and saline soil [35]. These studies illustrate the applicability of the VCM for soil, but whether this method is applicable to SRM has not been studied.

To address this gap in research, this study aimed to: (1) determine the reasonable parameters of VCM for SRM through laboratory experiments and field tests and further compare VCM with the traditional method SPCM, which is most widely used; (2) investigate the compaction characteristic, resilient modulus, and CBR of SRM prepared by the VCM; and (3) carry out on-site investigations to verify the laboratory results.

2. Materials and Testing Methods

2.1. Soil–Rock Materials

SRM was taken from the excavation site of Wuyi County, Zhejiang Province, as shown in Figure 1. The particle composition of SRM is shown in Table 1. SRM is usually divided into soil and rock. Generally speaking, particles smaller than 5 mm in diameter are considered soil, and those larger than 5 mm are considered rock [36]. The soil–rock ratio is the mass ratio of soil to rock. The properties of soil separated from the experimental SRM are presented in Table 2. It can be seen from the uniformity coefficient and coefficient of curvature the soil is a kind of cohesive soil.

Figure 1. SRM used in experiments.

Table 1. Particle composition of SRM.

Sieve Size (mm)	40	20	10	5	2	1	0.5	0.25	0.075
Passing rate (%)	100	89.5	73.2	54.5	29.2	21.7	11.0	5.1	1.7

Table 2. Soil properties.

Uniformity Coefficient	Coefficient of Curvature	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
13.8	1.4	30	21	9

2.2. Testing Methods

2.2.1. CBR Test

SPCM and VTM were used to form test pieces, respectively, and the test pieces were soaked in water for 4 days and nights, and then the penetration test was performed on the specimens to obtain the relationship curve between unit pressure and penetration amount. Generally, the ratio of the unit pressure when the penetration amount is 2.5 mm to the standard pressure is used as the CBR. At the same time, the CBR when the penetration amount is 5 mm was also calculated. If the CBR when the penetration amount is 5 mm was greater than the CBR when the penetration amount is 2.5 mm, then the test was redone, and if the result was still the same, the CBR at 5 mm was used.

2.2.2. Resilient Modulus Test

The test procedure of the resilience modulus is as follows: pre-compress the specimens formed by the SPCM and VTM methods with the load-bearing plate, and pre-compress 1–2 times for 1 min each time. Divide the predetermined maximum pressure into 4–6 parts, as the loading pressure of each stage, load and unload stage by stage. The time for each loading and unloading is 1 min. Record the displacement after each level of loading and unloading, calculate the rebound deformation under each level of load, and then calculate the resilience modulus under each level of load according to Equation (1).

$$E = \frac{\pi p D}{4l} (1 - \mu^2) \quad (1)$$

where:

P is pressure on the bearing plate;

D is the bearing plate;

l is rebound deformation corresponding to pressure;

and μ is poisson's ratio.

3. Development of the VCM for SRM

3.1. Determination of Work Parameters of the VCM for SRM

To fully simulate the rolling effect of modern heavy vibratory rollers, Chinese researchers have developed a laboratory vibratory compactor based on the principle of directional vibratory rollers. As shown in Figure 2, the vibratory compactor is mainly composed of three parts: the control platform, the rotating device and the vibration system. The vibration system is the most important part of the vibratory compactor, which is mainly composed of the frame, the vibrating entity and the vibrating hammer. Among them, the vibration entity is designed to imitate the vibration device of a vibratory roller, and is divided into vibration exciter, boarding system, and getting off system. The exciter is the core component of the vibration system. It consists of two parallel vibration shafts and a set of eccentric blocks mounted on them. The eccentric blocks on the two vibration shafts are arranged symmetrically. The eccentric blocks on each axis consist of a fixed eccentric block and a movable eccentric block. Composition to achieve the purpose of adjustable eccentricity. The boarding and getting off systems are connected by the vibration damping block, and the getting off system receives regular vibration through the restraining effect of the boarding system [29].

Figure 2. Vertical Vibratory Compactor's Construction Schematic [25].

There are four key parameters affecting the compaction effect, namely vibration frequency, exciting force, static pressure, and compaction time. The theoretical analysis, laboratory experiments, and field testing were conducted to determine the reasonable parameters, including:

Step 1: First, the soil–rock mixture was divided into two parts with a 5 mm sieve. Particles smaller than 5 mm in diameter are considered soil, and those larger than 5 mm are considered rock. Five soil–rock materials with different soil–rock ratios (r) were mixed for experiments, namely 70:30, 60:40, 50:50, 40:60, and 30:70.

Step 2: The vibration frequency was set as 20 Hz, 25 Hz, 30 Hz, 35 Hz, and 40 Hz, and then the maximum dry density of SRM was tested under different vibration frequencies. The frequency with the maximum density was determined as the optimal frequency.

Step 3: Different exciting forces were obtained by adjusting the angle of the eccentric block, namely 1.5 kN, 3.8 kN, 4.6 kN, 6.2 kN, 5.3 kN, 6.0 kN, 7.5 kN, 9.0 kN, and 11.0 kN, respectively. The maximum dry density of SRM under different exciting forces was tested by the VCM. The optimal exciting force was proposed based on the relationship between the density and exciting force.

Step 4: Different static pressures were obtained by adjusting the number of counterweights, namely 122.7 kPa, 139.9 kPa, 154.0 kPa, 163.2 kPa, and 169.4 kPa, respectively. The maximum dry density of SRM under different static pressure was tested. The optimal static pressure was recommended according to the results.

Step 5: VCM was used to perform indoor vibration compaction at different times (35 s, 45 s, 55 s, 65 s, and 75 s), and the results were compared with the density of the SMR subgrade after on-site compaction. The recommended vibration compaction time was determined as the time when the indoor density reaches the on-site density. A 20 t single-drum vibratory roller was used for on-site compaction, and the rolling process was follows: static pressing 1 pass and then vibrating pressing 6 passes.

3.1.1. Vibration Frequency

The vibration frequency f is the rotational frequency of the eccentric block, as in Equation (2) [37].

$$\omega = 2\pi f \quad (2)$$

where ω is the speed of the vibration exciter, rad/min.

The vibrating hammer can vibrate up or down under the action of the transfer of the eccentric block, and it applies a periodic vibration force to the material to be compacted. The frequency is related to the natural frequency of the material to be compacted. The vibration frequency was varied to compact SRM with different soil–rock ratios (r), and

the maximum dry density was obtained. The results were shown in Figure 3. It can be seen from the results that the maximum dry density of SRM increases rapidly with the increasing vibration frequency when the frequency is rather small, achieves the maximum peak when the frequency is 25 Hz, and then gradually decreases to a small valley when the frequency is 28 Hz. Then, it increases to a second peak at 35 Hz and, finally, quickly decreases. Previous research showed that when the vibration frequency of the road roller is $\sqrt{2}$ times of natural frequency of the compacted materials [38], resonance easily occurs, and the compaction effect is best. The natural frequency of SRM is approximately 17~20 Hz, and thus the corresponding optimal vibration frequency of the equipment for SRM is 24~28 Hz. When the vibration frequency is small, the compaction effect increases with the frequency, and the maximum dry density becomes larger. When the vibration frequency exceeds 28 Hz, the difference between the vibration frequency and the natural frequency of SRM is large, and the compaction effect is weakened. In summary, in order to achieve higher maximum dry density, the vibration frequency is recommended as 25 Hz for SRM.

Figure 3. Maximum dry density at different frequencies.

3.1.2. Exciting Force

The exciting force F_0 is formed by the centrifugal force of the eccentric blocks rotating at a high speed, which is related to the static eccentricity M_e and the speed of the vibration exciter, as in Equation (3) [37]. The exciting force is a key factor affecting the interaction force between the particles of the compacted material, which, in turn, influences the effect of compaction.

$$F_0 = M_e \omega^2 = m_d A_0 (2\pi f)^2 \quad (3)$$

where:

m_d is the quality of vibrating system, kg;
and A_0 is the vibrating amplitude, mm.

It can be known from Equation (3) that there is a power function relation between the exciting force and the frequency. However, the high frequency not only reduces the vibration force of the vibrometer on the compacted material but can also damage the machine.

Different exciting forces can be obtained by adjusting the angle of the eccentric block. The maximum dry densities of SRM under different exciting forces were shown in Figure 4. It can be seen from Figure 4 that the maximum dry density of SRM increases rapidly with increasing exciting force when the exciting force is small and increases gradually as the exciting force further increases. When the exciting force exceeds 5.0 kN, the increase in maximum dry density is extremely gentle. A large exciting force does not mean that the compaction effect is good. Only the appropriate exciting force with the correct amplitude

and frequency can achieve a better compaction effect. In general, the larger the angle of the eccentric block, the larger the amplitude, which not only affects the service life of the device but also causes the surface of the specimens to be uneven. Through experiments, it is found that when the angle of the eccentric block is $0\sim 30^\circ$, the amplitude is within the optimal range of 1.25 ± 0.05 mm, the surface of the specimens is flat, and the compaction effect is well guaranteed. Therefore, the angle of the eccentric block is recommended as zero, and the corresponding exciting force is determined as 5.3 kN.

Figure 4. Maximum dry density of SRM under different exciting forces.

3.1.3. Static Pressure

The static surface pressure is mainly from the upper system, the nether system, the pressure head, and the clump weight. To increase the vibration force on the material to be compacted, the quality of the nether system is selected to be lower. To increase the impact energy of the material to be compacted, it is desirable to select a nether system with a higher quality.

Different static surface pressures can be obtained by adjusting the number of clump weights [37]. The maximum dry densities of SRM under different static surface pressures are shown in Figure 5. It can be seen from Figure 5 that the pattern of maximum dry density of SRM is shown as a convex type of parabola with the increasing static pressure. A peak occurs at the weights of S4X7 and S5X9 (S4X7 represents four and seven clump weights, respectively, on the upper system and nether system). At the same time, it is found during the test that the vibratory compactor shakes sharply when the counterweight is small. As the number of clump weights increases, the body of the vibratory compactor jumps smoothly and is in a stable working state. If the number of clump weights or static surface pressures is too large, it is difficult for the nether system to jump, and the decrease in amplitude is too large, resulting in poor contact between the pressure head and the specimens. For comprehensive consideration, the recommended weight is S4X7 or S5X9, and the recommended static surface pressure is 154.0~163.2 kPa.

Figure 5. Maximum dry density of SRM under different static surface pressures.

3.1.4. Compaction Time

To simulate the compaction characteristics of SRM at the construction site, it is necessary to determine a reasonable compaction time. The vibration time is closely related to the compaction energy. The longer the time is, the greater the compaction energy and the better the compaction effect. When the compaction of SRM increases to a certain extent, the material tends to be in close contact, causing friction between the particles. Most of the compaction energy is converted into heat energy, and the effect of increasing is poor when the compaction time is prolonged. Therefore, it is necessary to determine a reasonable vibration time, and the dry density obtained in the laboratory is basically consistent with the dry density under the representative rolling process in the field. SRM at the construction site of the test section was obtained, and the VCM was used to test the relationship between the dry density and the laboratory vibration compaction time. The results are shown in Figure 6.

Figure 6. Relationship between vibration time and on-site dry density.

It can be seen from the results that the dry density of SRM increases first with the increase in the vibration time and then gradually stabilizes. If the maximum dry density of SRM is equal to the dry density at the site, then the vibration compaction time of SRM is 75 s. Therefore, it is determined that the laboratory vibration compaction time of SRM is 75 s. To facilitate the control of the compaction degree at the construction site, the relationship between the compaction degree and the vibration compaction time was studied in the

laboratory. The vibration time of specimens required for different compaction degree were presented in Figure 7 and Table 3.

Figure 7. Relationship between vibration time and compaction degree.

Table 3. Compaction time required for different degrees of compaction.

K (%)	≥96	≥95	≥94	≥93	≥92	≥90
Vibration time (s)	67	65	64	62	60	58

3.2. Detail Procedures of the Established VCM for SRM

According to the determined work parameters, the VCM for SRM was proposed, which includes two procedures: determining the maximum dry density and optimum water content, and preparing the specimens.

3.2.1. Determining the Maximum Dry Density and Optimum Water Content

The SRM was heated in a constant temperature oven with a temperature of 105 °C for 4–6 h. Then, five specimens from the same SRM were obtained by the quartering method, and then water was added to each specimen at intervals of 2–3% water content and mixed uniformly. After a night of curing, the SRM was poured into a Φ150 mm and h230 mm mold. The testing molds were fixed on a vibrating compactor and vibrated for 75 s. The parameters of the vibrating compactor were summarized Table 4 according to the above investigations. The height of the prepared specimen was required to be at the range of 115–125 mm. The experiments were completed on five SRMs added with different water weight. Water content–dry density was plotted as an X–Y coordinate curve. The peak of the curve in the Y axis was the maximum dry density of SRM, and the corresponding water content was the optimum water content.

Table 4. Parameters of the vibration compactor.

Frequency (Hz)	Amplitude (mm)	Working Weight (kg)			Exciting Force (kN)
		Upper System	Nether System	Total Weight	
25	1.2~1.3	107.08~115.01	170.69~179.33	277.77~294.34	5.3

3.2.2. Specimen Preparation

A cylindrical specimen with Φ150 mm and h150 mm was prepared via the VCM. The weight of a specimen was determined by Equation (4), in accordance with the maximum dry density, optimum water content, and compaction degree. The vibration compaction time was determined by Table 3 (see also Figure 7) according to the compaction degree.

$$m_0 = V \times \rho_d \times (1 + w_o) \times K \quad (4)$$

where:

m_0 is the specimen weight, g;
 V is the specimen volume, cm^3 ;
 ρ_d is the maximum dry density, g/cm^3 ;
 w_o is the optimum water content, %;
 and K is the compaction degree, %.

3.3. Verification of the VCM

The compaction characteristic, resilient modulus, CBR, and gradation variation of SRM laboratory prepared by the SPCM and VCM were compared to verify the applicability of the VCM. The detailed procedures of SPCM, CBR, and resilient modulus tests were taken from the Chinese specification of JTG E40–2007 [39]. Three parallel experiments are required in CBR and resilient modulus tests.

3.3.1. Compaction Characteristics

The specimens with different mass ratios of soil to rock were produced using the VCM and SPCM, and the results of optimum moisture content and maximum dry density are shown in Figure 8. As shown in Figure 8, the maximum dry density of SRM specimens produced using VCM is 1.021 ± 0.005 times that of the specimens produced using SPCM, and the optimum moisture content of the specimens produced using VCM is 0.84 ± 0.01 times that of the specimens produced using SPCM. The reason for this result is that, under the impact of vibratory compaction, the compacted granular materials transition from the initial stationary state to the moving state, the interaction between the particles transitions from static friction to dynamic friction or sliding friction, and the particles move relative to each other. The coarse particles are in closer contact, and the fine aggregate fills the voids made by the coarse aggregate; at the same time, under the action of the vibration force, the water aggregates to form a water film to provide lubrication for the relative motion between the particles, resulting in the particles being more easily compacted.

Figure 8. Comparison of the optimal moisture content and maximum dry density.

3.3.2. Resilient Modulus

The specimens were prepared with the SPCM and VCM for soil–rock ratios of 60:40, 50:50, and 40:60. The resilient modulus of the specimens was measured, and the results are shown in Figure 9. As shown in Figure 9, the resilient modulus of the specimens prepared by the VCM is approximately 1.16 ± 0.03 times that of the specimens prepared by the SPCM. This reason is that the mechanical strength of SRM is closely related to the compaction degree.

Figure 9. Comparison of the resilient modulus.

3.3.3. CBR

The specimens were prepared by the SPCM and VCM and the CBR test of the prepared specimens was carried out. The results are shown in Figure 10. As shown in Figure 10, the CBR of the specimens prepared by the VCM is approximately 1.46 ± 0.02 times that of the specimens prepared by the SPCM. The higher the maximum dry density, the less it will be affected by water, the stronger the resistance to unit load penetration, and the greater the CBR.

Figure 10. Comparison of test results of the CBR.

3.3.4. Gradation Variation

The gradations of SRMs before compaction and after compaction by the VCM and SPCM were compared to investigate the influence of the different methods on the gradation variation, which was assessed by the deviation coefficient S , shown as Equation (5). The larger the S , the greater the difference in the pass rate of the same sieve before and after the compaction, which means that the compaction has a more significant crushing effect on the SRM coarse particles.

$$S = \sqrt{\frac{(P_{b,i} - P_{a,i})^2}{n - 1}} \quad (5)$$

where:

$P_{b,i}$ is the passing rate at the sieve i before compaction, %;

$P_{a,i}$ is the passing rate at the sieve i after compaction, %;

and n is the number of sieves.

Table 5 shows the gradation variation of SRM compacted by the VCM and SPCM. It can be seen from Table 6 that the S of SRM compacted by SPCM was bigger than that of SRM by the VCM, which indicates that the fragmentation on particles caused by the VCM is relatively weak. The reason for this phenomenon is that the particles are prone to becoming crushed to smaller particles as the number of compactations increases. The exciting force of VCM makes the relative movement between the particles is smaller than the SPCM and to achieve a denser effect; thence, the fragmentation of particles is relatively slight [22].

Table 5. Effect of the compaction method on gradation.

Soil-Rock Ratio	Method	Passing Rate (%) at Different Sieve Size (mm)					S
		40	20	10	5	2	
60:40	Pre-compaction	100	90	80	60	30	/
	SPCM	100	94.2	86.8	70.2	40.4	8.31
	VCM	100	91.8	82.4	64	31.3	2.58
50:50	Pre-compaction	100	80	65	50	25	/
	SPCM	100	89.3	79.7	67.9	45.1	16.02
	VCM	100	85.2	72.5	56.2	31.1	6.30
40:60	Pre-compaction	100	70	50	35	15	/
	SPCM	100	85.3	63.4	57.4	29.3	16.73
	VCM	100	81.7	59.3	49.2	23.4	11.13

Table 6. Correlation of CBR.

Measuring Point	CBR of Laboratory Specimens (%)		CBR of on-Site Subgrade (%)	Correlation (%)	
	SPCM	VCM		SPCM	VCM
Measuring point 1	35.91	52.51	60.38	59.5	87.0
Measuring point 2	32.47	53.32	61.44	52.8	86.8

4. Engineering Properties of SRM Prepared by the VCM

It can be concluded from the above investigations that the VCM does not only simulate the field roller compaction better, but also improves the engineering of SRM. It is very meaningful to promote the application of VCM for SRM. It is fundamental to explore the engineering properties of SRM prepared by the VCM, which are obviously influenced by the soil–rock ratio, maximum particle size, etc.

In order to investigate the influence of soil–rock ratio, nine different ratios of soil to rock were utilized, namely 100:0, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80, and 0:100, respectively. For each soil–rock ratio, the soil particles were divided into two groups,

≤ 2 mm and 2–5 mm, and their mass ratio was designated as 55:45. The rock particles were divided into three groups: 20–40 mm, 10–20 mm, and 5–10 mm, and their mass ratio was designated as 25:35:40. Three SRMs with the maximum particle size of 40 mm, 20 mm, and 10 mm and with a fixed soil–rock ratio of 50:50 were selected, respectively, to explore the influence of maximum particle size on the engineering properties of SRM.

4.1. Effect of the Soil–Rock Ratio

Figure 11 shows the maximum dry density and optimum moisture content of SRM with different ratios of soil to rock produced by the VCM. The results show that the optimum moisture content gradually decreases as the rock content increases, which is caused by the reason that the soil particle has bigger specific surface area than rock particle. The maximum dry density initially increases and then decreases with the increasing the rock content and achieves the peak when the rock content is 60%. This phenomenon can be attributed to the spatial structure of SRM [16]. When the soil ratio in SRM is larger, the rock particles do not mutually contact with each other and are surrounded with soil particles, and a called suspended dense structure appears in SRM. When the soil ratio in SRM is 30–50%, the voids between the rock particles are completely filled by the soil particles, and the rock particles are close to or in contact with each other, finally, a called skeletal dense structure appears in SRM. When the soil ratio in SRM is smaller than 30% and the voids between the rock particles cannot be completely filled by the soil particles, a called skeletal void structure appears and the density decreases.

Figure 11. Optimum moisture contents and maximum dry densities of SRM with different rock content.

Figure 12 shows the resilient modulus and CBR of SRM produced by the VCM with different soil–rock ratio. It can be seen from Figure 12 that the resilient modulus and CBR of SRM with a rock content of zero is larger than that of SRM with a rock content of 20%. When the rock content exceeds 20%, the resilient modulus and CBR of SRM vary in a convex curve with the increasing the rock content and achieve the maximum peak when the rock content is 80%. The mechanical strength of SRM is closely related with the density and structure of SRM. It can be known from Figure 11 that the density of SRM increases initially and then decreases as the rock content increases, and the structure of SRM varies in sequence: suspended dense and skeletal dense. Therefore, the variation in resilient modulus of SRM is influenced by both the density and structure.

Figure 12. Modulus and CBR of SRM with different rock content.

4.2. Effect of the Maximum Particle Size

Figure 13 shows the results of maximum dry density and optimum moisture content of SRM with different maximum particle size produced by the VCM. It can be concluded that the maximum dry density gradually increases with the maximum particle size increasing; on the contrary, the optimum water content gradually decreases. The reason for this phenomenon is that, as the particle size increases, the specific surface area of the mixture decreases relatively, and the water requirement for lubricating the particles also decreases. Meanwhile, the number of rock particles in SRM decreases, meaning that a framework dense structure is easily formed, and the density is increased.

Figure 13. Optimum moisture content and maximum dry density of SRM with different maximum particle size.

Figure 14 shows the results of resilient modulus and CBR of SRM with different maximum particle size produced by the VCM. The same as the density, the resilient modulus and CBR also increase with the increasing of the maximum particle size.

Figure 14. Modulus of SRM with different maximum particles.

5. Field Application

A comparison of mechanical properties between the laboratory-prepared SRM and field SRM subgrade was conducted, in order to recommend a more reasonable laboratory compacting method for SRM. The on-site subgrade constructed with SRM was compacted 6–8 times by the vibratory roller. The road for the field measurement was located in the Wuyi section of Wucheng-Wuyi Highway, G235 National Road, Jinhua City, Zhejiang Province, has a total length of 4.472 km, and a design standard of a two-way six-lane first-class highway. The subgrade was constructed with SRM. The resilient modulus and CBR of the subgrade in the field were tested. The required equipment in the test mainly included the loading equipment, jack, dynamometer, rigid bearing plate, and pavement deflectometer. The field test of the CBR is shown in Figures 15 and 16.

Figure 15. Construction field.

Figure 16. CBR Test in Field.

The measurement results in the field and the laboratory results are shown in Tables 6 and 7. From the results, it can be known that SRM prepared by the VCM have higher densities and mechanical strengths than SRM prepared by the SPCM, which makes the mechanical properties of SRM prepared by the VCM more consistent with the field SRM subgrade. The ratio of the average CBR and resilient modulus of specimens prepared by the SPCM and the field SRM subgrade from two sites is only 56.2% and 74.2%, respectively. The ratio of the average CBR and resilient modulus of specimens prepared by the VCM and the field SRM subgrade two sites is 86.9% and 89.1%, respectively. The above results indicate that the VCM has a higher accuracy than the SPCM in evaluating the CBR and resilient modulus of the field SRM subgrade. This phenomenon is explained by the fact that the VCM not only improves the density but also drives the particles to arrange more closely, and further makes the friction between the particles larger. However, the fragmentation of SRM compacted by the SPCM is more critical than that of SRM compacted by the VCM, which negatively influences the mechanical properties of SRM.

Table 7. Correlation of resilient modulus.

Measuring Point	Resilient Modulus of Laboratory Test Piece (MPa)		Resilient Modulus of on-Site Subgrade (MPa)	Correlation (%)	
	SPCM	VCM		SPCM	VCM
Point 1	59.27	71.12	80.32	73.8	88.5
Point 2	61.21	73.44	82.01	74.6	89.6

6. Conclusions

(1) The vibration frequency, exciting force, and static surface pressure of vibration compactor for SRM is recommended as 25 Hz, 5.3 kN, and 154.0~163.2 kPa, respectively.

(2) The maximum dry density, optimum moisture content, CBR, and resilient modulus of SRM prepared by the VCM are 1.021 ± 0.005 , 0.84 ± 0.01 , 1.46 ± 0.02 , and 1.16 ± 0.03 times those of SRM prepared by the SPCM, respectively. The fragmentation on SRM caused by the VCM is smaller than the SPCM.

(3) Through the laboratory test, the differences in the compaction characteristics, CBR and resilient modulus of SRM and its influencing factors are revealed. The results show that the most obvious influence on the compaction and mechanical properties of SRM

prepared by the VCM is the soil–rock ratio, followed by the maximum particle size, and gradation basically has no effect.

(4) The CBR and resilient modulus of laboratory-prepared SRM by the VCM have higher correlation with the field measurement than the SPCM. The VCM can evaluate the mechanical properties of the field SRM more precisely than can the SPCM.

(5) To ensure the accuracy of the test, the mold diameter must be no less than four times the maximum particle size of the material. The mold diameter is 150 mm in VCM, so it is suitable only for SRM with particle sizes less than 40 mm. In future, the authors intend to use numerical simulation methods to investigate the effect of 40–100 mm particles on the compaction characteristics and mechanical properties of SRM.

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