Research Article

Combined Effect of Compaction Methods and Loading Conditions on the Deformation Behaviour of Unbound Granular Material

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Received 18 February 2020; Revised 29 June 2020; Accepted 1 July 2020; Published 22 July 2020

Academic Editor: Fan Gu

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Unbound granular material is an important construction material that is used for flexible pavement. As one of the most important indices used for describing the properties of unbound granular material, the deformation characteristic is significantly influenced by the compaction method used. However, the effects of the compaction method on the deformation behaviour are neglected in the existing studies. Hence, we investigate the deformation characteristics of unbound granular material produced by the vertical vibration compaction method (VVC) and the modified Proctor compaction method (MPC) via repeated triaxial load tests and reveal the effect of loading conditions and aggregate gradations. The results show that (a) the deformation of unbound granular material decreases as the stress level and confining pressure are increased; (b) the deformation resistance of unbound granular material produced by the VVC is superior to that produced by the MPC; (c) the difference of deformation resistance arising between using the VVC and MPC decreases as confining pressure increases and is not significant with changes in the stress level; (d) the extent of various factors on deformation characteristics from greatest to least is as follows: stress level > aggregate gradation > compaction method > confining pressure; and (e) increasing the content of coarse aggregates is conducive to enhancing the deformation resistance of unbound granular material, particularly for the VVC. Finally, a simple approach for modelling and predicting deformation is established.

1. Introduction

It is well known that flexible pavements with composite bases have desirable structural and functional capacities [1–3]. Unbound granular material (e.g., graded crushed stone) is an important construction material used in the base and subbase layers of flexible pavement; its advantages include the ability to provide structural support for asphalt concrete layers and an adequate response to traffic loads at a relatively low cost [4–6]. The fatigue cracking and rutting development of asphalt concrete layers are associated with the deformation characteristics of unbound granular material layers [7, 8]; these characteristics are predicted and controlled typically during pavement design [9, 10]. Hence, investigating the deformation characteristics of unbound

granular material for flexible pavement structures is beneficial [11, 12].

Rahman and Erlingsson [6, 13] investigated the effect of moisture on the resilient deformation behaviour of unbound granular material and established the corresponding prediction model. Alnedawi et al. [14–16] analyzed the effect of loading conditions (e.g., loading frequencies and vertical stress rest period) on the deformation behaviour of unbound granular material and built a prediction model of permanent deformation by utilizing a neural network. Osouli et al. [17] revealed the effect of aggregate fines on the deformation behaviour of unbound granular material. Gu et al. [9] characterized the permanent deformation properties of unbound granular material from the point of view of Pavement ME Design. Xiao et al.

[12] carried out a shakedown analysis of the deformation of unbound granular material, as based on moving wheel loads. Xu et al. [18] put forward the control standard for the deformation performance of unbound granular material. Lu et al. [19] studied the dynamic deformation of road high liquid limit subgrade soil. Saberian et al. [20] investigated the permanent deformation of unbound granular materials with crumb rubber and crushed glass. Zhang et al. [21–23] established a series of improved prediction models to evaluate the permanent deformation and resilient modulus for highway subgrade soils, and revealed the effect of compaction, matric suction, and traffic loads. These require a proper understanding of the deformation behaviour under various influencing factors such as loading conditions (e.g., loading stress, loading time, and confining pressure), aggregate gradation, and compaction density.

Among these factors, the compaction density, which has a direct relationship with the compaction method, is regarded as one of the most important indices of pavement properties of unbound granular material [13, 24–26]. In the Chinese specification “*Technical Guidelines for Construction of Highway Roadbases (JTG/T F20-2015)*” and “*Test Methods of Soils for Highway Engineering (JTG E40-2007)*,” there are two types of compaction methods available for producing experimental samples of unbound granular material: the vertical vibration compaction method (VVC) and the modified Proctor compaction method (MPCM). Both compaction methods are permitted during material design in China; these methods significantly influence the performance of unbound granular materials.

Existing studies [26–29] have proven that the compaction density and mechanical properties of unbound granular material produced by the VVC perform closely to what is observed in the field, which is superior to the MPCM because the VVC results in a similar compaction status to what is observed on construction sites. However, there is little analysis about the effect of compaction methods on the deformation behaviour of unbound granular material in the existing literature. Hence, it is necessary to investigate the deformation characteristics of unbound granular material produced by different compaction methods and reveal the effects of loading conditions (e.g., deviator stresses and confining pressures) and aggregate gradations; this is the purpose of this study.

2. Objectives

The objective of this study is to investigate the deformation characteristics of unbound granular material produced by different compaction methods. Specifically, the following two cases are considered:

- (a) The effect of various compaction methods on the deformation behaviour of unbound granular material
- (b) The sensitivity of loading conditions (e.g., deviator stresses and confining pressures) and aggregate gradations to the effect of compaction methods

This is achieved by running repeated triaxial load tests on unbound granular material produced by the VVC and MPCM for a range of loading conditions and aggregate gradations. All tests in accordance with Chinese specification “*Technical Guidelines for Construction of Highway Roadbases (JTG/T F20-2015)*” and “*Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTG E51-2009)*” are carried out on these unbound granular materials; the results are, then, compared. The method specified in the *JTG/T F20-2015* and *JTG E51-2009* is used to capture the axial strain with respect to different deviator stresses and confining pressures. A simple approach for modelling the deformation prediction is also established.

3. Materials and Methods

3.1. Materials. The unbound granular material is composed of four types of aggregates with different size ranges: 31.5–19 mm, 19–9.5 mm, 9.5–4.75 mm, and 0–4.75 mm. The aggregates are obtained from Shaanxi province of China, and their technical properties are shown in Table 1.

Two types of aggregate gradations are selected in this study, as shown in Table 2. The strong skeleton gradation is proposed in our previous research [30] via the optimization of the aggregate structure. The specification gradation is the midvalue of the standard aggregate gradation provided by the Chinese specification “*Technical Guidelines for Construction of Highway Roadbases (JTG/T F20-2015)*”.

3.2. Compaction Method. In this study, the VVC and MPCM are both adopted to produce the unbound granular material samples according to the Chinese specification “*Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTG E51-2009)*”. The processes of VVC and MPCM are as follows.

3.2.1. VVC

Step 1: the aggregates and water are mixed according to the target moisture content.

Step 2: the samples ($\Phi 152 \text{ mm} \times h 120 \text{ mm}$) are prepared using a vertical vibration compactor with an excitation force of 6800 N. The vibration duration and frequency are 70 s and 30 Hz, respectively.

Step 3: the dry density of the sample prepared in Step 2 is measured.

Step 4: Steps 1–3 are repeated, and the optimum moisture content and the maximal dry density are determined.

Step 5: the final cylindrical samples ($\Phi 100 \text{ mm} \times h 200 \text{ mm}$) are prepared using a vertical vibration compactor using the optimum moisture content. The vibration duration and frequency are 100 s and 30 Hz, respectively.

TABLE 1: Technical properties of aggregates.

Aggregate size (mm)	Bulk volume relative density (g/cm ³)	Water absorption (%)	Crushing value (%)	Los Angeles abrasion (%)	Content of needle-like (%)	Firmness (%)	Sand equivalent (%)	Liquid limit (%)	Plasticity index (%)
31.5~19	2.725	0.3	—	19.4	6.6	5.4	—	—	—
19~9.5	2.721	0.6	19.5	20.5	8.4	5.8	—	—	—
9.5~4.75	2.633	0.6	—	20.9	5.8	6.3	—	—	—
<4.75	2.645	0.7	—	—	—	6.2	71.5	17	2.8

TABLE 2: Aggregate gradation.

Diameter (mm)	Pass percent (%)	
	Strong skeleton gradation	Specification gradation
31.5	100	100
19	64	84
16	58	76
13.2	52	68.5
9.5	46	56.5
4.75	36	35
2.36	28	23.5
1.18	23	16
0.6	19	11
0.3	15	7.5
0.15	11	5
0.075	8	3.5

TABLE 3: Physical parameters of unbound granular materials.

Abbr.	Aggregate gradation	Compaction method	Maximum dry density (g/cm ³)	Optimum moisture content (%)
GM	Strong skeleton gradation	VVCM	2.425	3.8
GF	Specification gradation	VVCM	2.401	4.0
LX1	Strong skeleton gradation	MPCM	2.390	4.2
LX2	Specification gradation	MPCM	2.376	4.4

3.2.2. MPCM

Step 1: the aggregates and water are mixed according to the target moisture content.

Step 2: the samples ($\Phi 152 \text{ mm} \times h 120 \text{ mm}$) are prepared using a compaction hammer with a weight of 4.5 kg and the diameter of 5.0 cm. The samples are compacted in five layers, and each layer is compacted 98 times using the compaction hammer.

Step 3: the dry density of the sample prepared in Step 2 is measured.

Step 4: Steps 1–3 are repeated, and the optimum moisture content and the maximal dry density are determined.

Step 5: the final cylindrical samples are compacted to a size of $\Phi 100 \text{ mm} \times h 200 \text{ mm}$ using a compression testing machine using the optimum moisture content.

The maximum dry density and the optimum moisture content of different unbound granular materials are shown in Table 3. GM and LX1 stand for the samples with the strong skeleton gradation compacted by the VVCM and MPCM, respectively. GF and LX2 stand for the samples with the specification gradation compacted by the VVCM and MPCM, respectively. The strong skeleton gradation and the specification gradation can be found in Table 2.

In addition, a sampling inspection shows that the errors of the dry density and the moisture content of the final formed samples are both less than 5%, compared to the maximum dry density and the optimal moisture content. Hence, we consider that the samples that are finally formed

are corresponding to the maximum dry density and the optimal moisture content under the molding method.

3.3. Test Method. The repeated triaxial load test is generally considered to be the most appropriate tool for characterizing the deformation properties of unbound granular material [31]. The test apparatus MTS810 is used in this study, as shown in Figure 1.

The repeated triaxial load tests are implemented according to the Chinese specification “*Test Methods of Soils for Highway Engineering (JTG E40-2007)*”. The samples are totally saturated and sealed with a 0.5 mm thick rubber membrane. It should be explained that the thickness of the rubber membrane is not assigned in the Chinese specification. According to the suggestion of ASTM D4767, the membrane thickness does not exceed 1% of the sample diameter. In this study, no membrane correction is applied because the maximum permissible thickness of the membrane is 1 mm (1% of 100 mm). After inspecting the membrane for punctures and making it leakproof, all pipelines and valves are completely sealed and shut down to isolate the void space of the sample from outside the system during the entire experimental process.

The repeated load triaxial tests are employed under a stress-controlled mode at a loading frequency of 1 Hz. The controlled stress, namely, the deviator stress σ_d , is applied in the axial direction and is constant during the experimental process. The confining pressure stress σ_c (equal to the minor principal stress σ_3) is applied by pressurizing the cell water surrounding the cylindrical sample of unbound granular material. Hence, the axial stress σ_a (equal to the

FIGURE 1: Repeated triaxial load test apparatus.

maximum principal stress σ_1) acting on the sample is equal to the sum of the deviator stress σ_d and the confining press σ_c .

In this study, three types of confining stress (50, 100, and 150 kPa) are selected because the horizontal stress of the pavement structure under loads of moving vehicles ranged, in general, from 50 kPa to 150 kPa [32]. The deviator stress is described via the “stress level” index, which is calculated through equation (1), of which five types (0.1, 0.3, 0.5, 0.7, and 0.9) are selected. Accordingly, the relationship of σ_a , σ_d and σ_c can be expressed as equation (2). The detailed testing conditions for each aggregate gradation and compaction method are shown in Table 4. There are a total of 60 groups of experiments in this study.

$$S = \frac{\sigma_d}{\sigma_s}, \quad (1)$$

$$\sigma_a = \sigma_c + S\sigma_s, \quad (2)$$

where S is the stress level, σ_d is the deviator stress, and σ_s is the ultimate strength of the tested sample measured via the static triaxial test according to the Chinese specification “*Test Methods of Soils for Highway Engineering (JTG E40-2007)*”.

4. Results and Discussion

The loading number and the axial strain measured in the repeated triaxial load tests are the most important indices that characterize the deformation behaviour of unbound granular material [25, 26]. Brown et al. [33, 34] and Rahman and Erlingsson [6] found that the axial strain of unbound granular material tended to be stable when the loading number reached 10000 times. Hence, the failure criterion of samples in this study was selected as follows:

- (i) The loading number exceeds 10000 times, and the sample has not failed, as shown in Figure 2(a)

- (ii) The loading number does not reach 10000 times, but the sample has failed, as shown in Figure 2(b)

Accordingly, the deformation resistance can be evaluated through

- (i) The permanent strain when the loading number reaches 10000 times and the sample has not failed
- (ii) The ultimate loading number when the sample has failed

4.1. Effect of Compaction Methods. The relationship between the loading number and the axial strain of unbound granular material is plotted in Figure 3. The definitions of abbr. GM, GF, LX1, and LX2 can be found in Table 3.

As shown in Figure 3, the axial strain at the same loading number and the ultimate axial strain of the unbound

TABLE 4: Testing conditions.

Confining press σ_c (kPa)	Deviator stress σ_d (kPa)	Axial stress σ_a (kPa)	Ultimate strength σ_s (kPa)	Stress level S
50	85	135	853	0.1
100	128	228	1281	0.1
150	170	320	1698	0.1
50	256	306	853	0.3
100	384	484	1281	0.3
150	509	659	1698	0.3
50	427	477	853	0.5
100	641	741	1281	0.5
150	849	999	1698	0.5
50	597	647	853	0.7
100	897	997	1281	0.7
150	1189	1339	1698	0.7
50	768	818	853	0.9
100	1153	1253	1281	0.9
150	1528	1678	1698	0.9

FIGURE 2: Failed sample.

FIGURE 3: Continued.

FIGURE 3: Continued.

FIGURE 3: Relationship between the axial strain and loading number under different compaction methods. (a) $(s) = 0.1, \sigma_3 = 50 \text{ kPa}$, (b) $(s) = 0.1, \sigma_3 = 100 \text{ kPa}$, (c) $(s) = 0.1, \sigma_3 = 150 \text{ kPa}$, (d) $(s) = 0.3, \sigma_3 = 50 \text{ kPa}$, (e) $(s) = 0.3, \sigma_3 = 100 \text{ kPa}$, (f) $(s) = 0.3, \sigma_3 = 150 \text{ kPa}$, (g) $(s) = 0.5, \sigma_3 = 50 \text{ kPa}$, (h) $(s) = 0.5, \sigma_3 = 100 \text{ kPa}$, (i) $(s) = 0.5, \sigma_3 = 150 \text{ kPa}$, (j) $(s) = 0.7, \sigma_3 = 50 \text{ kPa}$, (k) $(s) = 0.7, \sigma_3 = 100 \text{ kPa}$, (l) $(s) = 0.7, \sigma_3 = 150 \text{ kPa}$, (m) $(s) = 0.9, \sigma_3 = 50 \text{ kPa}$, (n) $(s) = 0.9, \sigma_3 = 100 \text{ kPa}$, and (o) $s = 0.9, \sigma_3 = 150 \text{ kPa}$.

granular material produced by the VVCM under the same loading conditions are lower than those produced by the MPCM. For high stress levels, the ultimate loading number in the case of using the VVCM is higher than that in the case of using the MPCM. This implies that the VVCM results in an improved degree of deformation resistance for unbound granular material samples; the VVCM provides a higher degree of compaction energy that results in a denser aggregate structure for unbound granular material, when compared to the MPCM. However, the difference of axial strain (or the loading number for high stress levels) between the VVCM and MPCM is weaker than that between the two aggregate gradations. The ultimate axial strain of unbound granular material using the strong skeleton gradation is, on average, 20.11% lower than that using the specification gradation, whereas the difference of ultimate axial strain (or the ultimate loading number for high stress levels) between different compaction methods is, on average, 9.67%.

Moreover, the difference in deformation resistance arising from using the VVCM and MPCM decreases as confining pressure increases, particularly for the strong skeleton gradation. For instance, when the stress level ranges from 0.1 to 0.5, the differences of ultimate axial strain in the case of using the strong skeleton gradation are, on average, 18.75%, 11.11%, and 8.72% at the confining pressure of 50 kPa, 100 kPa, and 150 kPa, respectively, while those for the case of using the specification gradation are 14.16%, 13.91%, and 13.23%, respectively. When the stress level exceeds 0.7, a similar phenomenon also can be found, as in Figures 4(j)–4(l). This is because a higher confining pressure can enhance the degree of compaction of the aggregate structure, which partly compensates for the difference of compaction energy between the VVCM and MPCM. On the other hand, as previously mentioned, the most significant difference between the strong skeleton gradation and the specification gradation is that the former has a more coarse aggregate content. It also can be speculated that the sensitivity of the VVCM to the deformation characteristics increases as the coarse aggregate content is increased. In addition, the stress level has less influence on the difference between deformation resistances that were observed while using different compaction methods.

4.2. Effect of Stress Levels. The relationship between the axial strain and loading number is plotted in Figure 4.

As shown in Figure 4, when the stress level ranges from 0.1 to 0.5, the axial strain accumulates approximately linearly in the initial stages and, then, gradually tends to be stable. Although the samples are all not failed until the loading number exceeds 10000 times, the ultimate axial strain increases as the stress level is increased. When the stress level ranges from 0.7 to 0.9, the samples fail rapidly after the loading number reaches 1000 times. The ultimate loading number also decreases as stress levels increase. This implies that the deformation resistance of unbound granular material decreases as the stress level increases. Moreover, the abovementioned law does not change significantly in accordance with the compaction method, aggregate gradation,

or confining pressure. This indicates that the effect of the stress level on deformation characteristics is more significant than other factors.

4.3. Effect of Confining Pressures. The relationship between axial strain and loading numbers is plotted in Figure 5.

As shown in Figure 5, it can be found that the ultimate axial strain increases as the confining pressure is increased. This trend is obviously growing as the stress level increases. For instance, at a stress level of 0.1, the ultimate axial strain in the case of 150 MPa confining pressure is, on average, 12.6% higher than that in the case of 50 MPa confining pressure, while at a stress level of 0.9, the difference between the two confining pressures is, on average, 31.0%. This implies that the effect of traffic loads on the deformation resistance of unbound granular material is highly sensitive. In addition, the difference among the three confining pressures in the case of using the strong skeleton gradation is more significant than what is observed where the specification gradation is used; this is mainly reflected in the difference of ultimate axial strain at high confining pressure. It indicates that increasing the content of coarse aggregates is conducive to enhancing the deformation resistance of unbound granular material at high levels of confining pressure.

4.4. Prediction Equation of the Deformation Behaviour for the VVCM. The prediction equation of the deformation behaviour provides the basis for further study on the design standards of unbound granular material [35].

Puppala et al. [36] proposed a deformation model based on the mean normal bulk stress, as shown in the following equation:

$$\varepsilon_a = a_1 \left(\frac{\sigma_m}{p_a} \right)^{a_2} N^{a_3}, \quad (3)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, σ_m is the mean normal bulk stress, p_a is the atmospheric pressure, and a_1 , a_2 , and a_3 are the coefficients.

Korkiala-Tanttu [37] developed the K-T model to predict the deformation behaviour, as shown in the following equation:

$$\varepsilon_a = CN^b \frac{R}{1-R}, \quad (4)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, C is the permanent strain in the first loading cycle, b is the shear ratio parameter, and R is the shear failure ratio.

Chow [38] built the UIUC model to evaluate the deformation characteristics using the deviatoric stress and shear strength ratio, as shown in the following equation:

$$\varepsilon_a = a_1 N^{a_2} \sigma_d^{a_3} \left(\frac{\tau_f}{\tau_{\max}} \right), \quad (5)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, σ_d is the dynamic deviator stress,

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 4: Continued.

(g)

(h)

(i)

(j)

(k)

(l)

FIGURE 4: Relations between the axial strain and loading number under different stress levels. (a) $\sigma_3 = 50$ kPa, GM, (b) $\sigma_3 = 50$ kPa, GF, (c) $\sigma_3 = 50$ kPa, LX1, (d) $\sigma_3 = 50$ kPa, LX2, (e) $\sigma_3 = 100$ kPa, GM, (f) $\sigma_3 = 100$ kPa, GF, (g) $\sigma_3 = 100$ kPa, LX1, (h) $\sigma_3 = 100$ kPa, LX2, (i) $\sigma_3 = 150$ kPa, GM, (j) $\sigma_3 = 150$ kPa, GF, (k) $\sigma_3 = 150$ kPa, LX1, and (l) $\sigma_3 = 150$ kPa, LX2.

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 5: Continued.

(g)

(h)

(i)

(j)

(k)

(l)

FIGURE 5: Continued.

FIGURE 5: Continued.

FIGURE 5: Relations between the axial strain and loading number under different confining pressures. (a) $(s) = 0.1$, GM, (b) $(s) = 0.1$, GF, (c) $(s) = 0.1$, LX1, (d) $(s) = 0.1$, LX2, (e) $(s) = 0.3$, GM, (f) $(s) = 0.3$, GF, (g) $(s) = 0.3$, LX1, (h) $(s) = 0.3$, LX2, (i) $(s) = 0.5$, GM, (j) $(s) = 0.5$, GF, (k) $(s) = 0.5$, LX1, (l) $(s) = 0.5$, LX2, (m) $(s) = 0.7$, GM, (n) $(s) = 0.7$, GF, (o) $(s) = 0.7$, LX1, (p) $(s) = 0.7$, LX2, (q) $(s) = 0.9$, GM, (r) $(s) = 0.9$, GF, (s) $(s) = 0.9$, LX1, and (t) $(s) = 0.9$, LX2.

TABLE 5: Prediction equations.

Aggregate gradation	Compaction method	Prediction equation	R^2
Strong skeleton gradation	VVCM	$\varepsilon_a = 2.79S^{0.765}\sigma_c^{0.255}(1 - (1/(0.21N + 1)))$	0.982
Specification gradation	VVCM	$\varepsilon_a = 5.77S^{0.648}\sigma_c^{0.117}(1 - (1/(0.38N + 1)))$	0.966
Strong skeleton gradation	MPCM	$\varepsilon_a = 4.69S^{0.675}\sigma_c^{0.151}(1 - (1/(0.35N + 1)))$	0.953
Specification gradation	MPCM	$\varepsilon_a = 3.63S^{0.642}\sigma_c^{0.249}(1 - (1/(0.40N + 1)))$	0.951

τ_f is the maximum shear stress in the normal state, $\tau_{\max}$ is the maximum shear stress, and a_1 , a_2 , and a_3 are the coefficients.

Lu et al. [19] put forward the deformation equation with the deviatoric stress and static failure stress, as shown in the following equation:

$$\varepsilon_a = a_1 \left(\frac{\sigma_d}{\sigma_f} \right) N^{a_2}, \quad (6)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, σ_d is the dynamic deviator stress, σ_f is the static failure stress, and a_1 and a_2 are the coefficients.

Zhang et al. [23] developed an improved deformation model considering the origin octahedral shear stress, as shown in the following equation:

$$\varepsilon_a = a_1 N^{a_2} \left(\frac{\theta_0}{p_a} \right)^{a_3} \left(\frac{\tau_{\text{oct}}}{p_a} \right)^{a_4} \left(\frac{\theta_w}{\theta_s} \right)^{a_5}, \quad (7)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, θ_0 is the initial bulk stress, p_a is the atmospheric pressure, τ_{oct} is the octahedral shear stress,

θ_w is the volume moisture content, θ_s is the saturated volume moisture content, and a_1 – a_5 are the coefficients.

In this study, the prediction equation is established according to the relationship of the axial deformation, loading number, confining stress, and stress level, which can be expressed as the following equation:

$$\varepsilon_a = a_1 S^{a_2} \sigma_c^{a_3} \left(1 - \frac{1}{a_4 N + 1} \right), \quad (8)$$

where N is the loading number, ε_a is the axial strain after N times of repeated loading, σ_c is the confining stress, S is the stress level, and a_1 , a_2 , a_3 , and a_4 are the coefficients.

The prediction equations for different aggregates and compaction methods are listed in Table 5.

It can be found that the correlation coefficients all have high levels ($R^2 \geq 0.95$), thus demonstrating the reliability of the deformation equations. Compared to the existing models, as previously mentioned, the prediction equations proposed in this study consider the relationship of the deformation, loading number, confining stress, and stress level and reflect the effect of the compaction method and aggregate gradation. It will be helpful to enrich the prediction tool of deformation behaviour of unbound granular materials.

5. Conclusions

The objective of this study is to investigate the deformation behaviour of unbound granular material produced by different compaction methods and to reveal the effects of loading conditions and aggregate gradations.

- (i) The deformation of unbound granular material decreases as the stress level and confining pressure are increased.
- (ii) The deformation resistance of unbound granular material produced by the VVCM is superior to the MPCM.
- (iii) The difference in deformation resistance resulting from using the VVCM and MPCM decreases as confining pressure is increased, particularly for the strong skeleton gradation. The effect of the stress level is not significant.
- (iv) The extent that different factors affect the deformation resistance of unbound granular materials is as follows: stress level > aggregate gradation > compaction method > confining pressure.
- (v) Increasing the content of coarse aggregates is conducive to enhancing the deformation resistance of unbound granular material, particularly for the VVCM.
- (vi) A simple approach for modelling the deformation prediction of unbound granular material is established.

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

This study was sponsored in part by the National Natural Science Foundation of China under grant no. 51808326, to which the authors are very grateful. In addition, the authors would like to thank Editage (<http://www.editage.com>) for English language editing.

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