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Field Compaction Characteristics of Ultra-Thin Porous Friction Course Based on Laboratory Simulation

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Abstract: As a preventive maintenance treatment, the ultra-thin porous friction course (UPFC) has been widely recognized and used in road maintenance because of its excellent performance and cost effectiveness. The Marshall compaction method (MCM) has been adopted to design UPFC mixtures worldwide, particularly in China. However, there are few studies concerning the field compaction properties of MCM-designed UPFCs. The laboratory test results of this study from simulating on-site compaction showed that all UPFC specimens with thicknesses of less than 20 mm barely achieved the target compaction thickness, and all UPFC specimens with different thicknesses failed to meet the air void (AV) requirements of UPFC mixes designed using the MCM. According to the results of a virtual compaction test, and using the discrete element method, the strong force chains were strengthened as the UPFC thickness decreased inside the specimen, making it difficult to evenly diffuse and transfer inside the specimen and resulting in insufficient compaction of the UPFC. Furthermore, it was demonstrated that the MCM-designed UPFC specimens showed significant differences in the AV distributions along the vertical and lateral directions from those of the UPFC specimens that simulated field compaction. The UPFCs designed using the MCM had a poor correlation with field compaction.

Keywords: air void distribution; discrete element method; field compaction characteristics; ultra-thin porous friction course; X-ray computed tomography; compaction method



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1. Introduction

Ultra-thin porous friction courses (UPFCs) are currently one of the most widely used maintenance preventive measures. As a typical open-grade friction course (OGFC) mixture, UPFC mainly contains fine aggregates and asphalt, which are applied to maintain the performance of road surfaces [1]. It has been demonstrated that UPFC technology is beneficial for the noise reduction and skidding resistance of road surfaces and enhances the traffic safety of drivers [2,3]. Owing to its excellent technical performance and cost effectiveness, it is currently widely used as a surface layer over highway pavements in Europe, the United States, Asia, and other regions and countries.

The full life-cycle cost of UPFCs has been comprehensively evaluated, demonstrating that they have significant economic and social benefits compared to other maintenance techniques [4–6]. To date, the materials, road performance, and engineering applications of UPFCs have been extensively studied. Son et al. developed a 4.75 mm ultra-thin SMA friction course and assessed the performance and engineering benefits of its wear process under laboratory and field conditions [7]. A high-toughness UPFC was proposed by Yu et al. according to the climatic characteristics of South China, and it has been used in more than 100 cases of road maintenance engineering owing to its excellent noise reduction, anti-skidding properties, and durability [8]. In addition, a low-carbon and sustainable

cold-mixed ultra-thin asphalt overlay was proposed [9]. Another study recommended a porous ultra-thin overlay (PUTO) technology [10], and its service performance was evaluated [11]. The compaction characteristics of UPFCs have also been the focus of researchers. It is well known that compared to ordinary asphalt layers, the thickness of a UPFC is only 1–2 cm, resulting in different compaction requirements, temperature, and other conditions in the process of construction [12]. Owing to its minimal thickness, heat is easily lost, leading to a rapid temperature drop rate during the paving process, which has an adverse effect on compaction [13]. Insufficient compaction leads to air void (AV) content in the UPFC over the design range, which impairs the moisture sensitivity, fatigue life, and road performance at different temperatures of the UPFC, making it prone to aggregate peeling, loosening, and other problems [14]. Luo et al. studied the field compaction parameters of a UPFC using laboratory compaction tests based on the energy equivalent principle [13]. Similarly, a study by Suresha et al. investigated the influence of Marshall compaction efforts on the compaction characteristics of UPFCs [15]. It was found that the target mineral gradation and the traffic level are key factors in selecting the suitable compaction efforts of a UPFC mix. Norhidayah et al. focused on the AV characteristics in PUTO using X-ray CT technology [16]. The aggregate size and compaction thickness of the UPFC mix affected the particle flow during the compaction process, thereby affecting the AV characteristics and determining the compaction effect. Similarly, Alvarez et al. investigated the influence of densification on the road performance of UPFC mixes [17]. Density control of the UPFC during construction is suggested to ensure a balance between mix durability and functionality. Furthermore, the internal AV structures were analyzed between laboratory samples and UPFC field cores and it was found that significant differences existed [18]. According to ground-penetrating radar data, Wang et al. studied the thickness and density in the field compaction process of UPFCs and proposed a corresponding prediction algorithm [19]. The current research on the compaction characteristics of UPFCs has made some progress, but further studies are still needed to describe the differences in the compaction characteristics between the field and indoor compaction of UPFCs more accurately to achieve better simulations of field cores with laboratory specimens.

One of the most used design methods for UPFCs is the Marshall compaction method (MCM), particularly in China. Many studies have proven that there is a poor correlation between field cores and MCM-designed asphalt mixtures with ordinary thickness [20–22]. Laboratory UPFC specimens molded via the MCM are 2.5 to 6 times thicker than the actual paving thickness of the UPFCs. The difference in thickness inevitably leads to different compaction characteristics of the UPFC, which have different effects on its volume parameters. If a MCM-designed UPFC cannot reflect the actual compaction condition, the performance evaluation of the UPFC will deviate significantly from that of the actual pavement. Therefore, it cannot contribute to accurate guidance for the application of thin-layer overlays [23,24]. Currently, no studies have used field compaction tests to verify MCM-designed UPFC mixes. There may also be a poor relationship between the MCM-designed UPFC specimens and the field core samples. Considering that the paving thickness of a UPFC is only 1–2 cm, more research on the correlation assessment of the compaction characteristics between on-site compaction and the MCM is required.

The development of nondestructive technologies, especially image analysis and X-ray CT, has enabled road workers to thoroughly study the internal structure inside asphalt mixes over the past two decades. The relative properties can be obtained involving the distribution, orientation, contact, and AV distribution of the aggregates using X-ray CT technology [25]. The AV distributions of the specimens with different gradations molded by Superpave gyratory compaction (SGC) were obtained using X-ray CT to analyze the compaction characteristics [26,27]. In addition, relevant research on the meso-mechanical response of asphalt mixes during the compaction process has made significant progress owing to the continuous progress in the discrete element method (DEM). It has been demonstrated that the SGC test simulated via the DEM was consistent with the laboratory

test [28]. Moreover, the DEM was used to explore the effects of force chain evolution and aggregates in the compaction process [29]. There is no doubt that research progress on the application of CT technology and DEM in asphalt mixtures provides a powerful means and experience for exploring the current compaction characteristics of UPFCs.

Therefore, this study explores the field compaction mechanism of a UPFC designed using an MCM. Owing to the lack of field core samples, SGC and rolling-wheel compaction (RWC) methods were used to form laboratory specimens with the same thickness as the paving thickness of a UPFC, with the aim to simulate on-site compaction conditions. Accordingly, the compaction characteristics and mesoscopic force of the UPFC during the compaction process were studied. The research results are significant for improving the road performance of UPFCs.

2. Experimental Design

2.1. Experimental Objective

This study aimed to explore the field compaction properties of MCM-designed UPFC mixes based on laboratory simulations of the SGC and RWC methods. To achieve this objective, the AV characteristics and compaction mechanism of the UPFC were analyzed using X-ray CT and DEM according to the following tasks:

- To analyze the compaction characteristics of the MCM-designed UPFC mixes with different thicknesses, the SGC method was used to simulate field compaction.
- The compaction mechanism of the UPFCs with different thicknesses was analyzed using the DEM.
- To analyze the relationship between the AV characteristics of the MCM-designed laboratory specimens and the simulated field cores molded using the SGC and RWC methods, we evaluated the rationality of the UPFC mixes designed using the MCM.

2.2. Raw Materials and Mix Design

A kind of styrene–butadiene–styrene (SBS) high-viscosity asphalt was selected [30], with a dosage of 6% by weight of mineral aggregates. Limestone aggregates of 0–3 mm and basalt aggregates of 3–5 mm were adopted, and the ore powder was made of limestone. Basalt fiber accounted for 0.3% by weight of the mixture. The technical indexes of all materials met the requirements of the Chinese technical specifications for construction of highway asphalt pavements (JTG F40-2004) [31]. OGFC mixes with a maximum nominal particle size of 4.75 mm (OGFC-5) were adopted to prepare the UPFC, hereinafter referred to as OGFC-5 UPFC. Tables 1 and 2 present the OGFC-5 gradations and the mix designs, respectively.

Table 1. The mineral gradation of OGFC-5 mixtures.

Sieve size (mm)	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing rate (%)	100.0	92.1	16.1	11.7	9.8	7.9	7.2	5.0

Table 2. The results of OGFC-5 mix design.

Mix Design Method	Target Size of Specimen (mm)		OAC (%)	Target AV Ratio (%)	Measured AV Ratio (%)
	Diameter	Height			
Marshall	101.6	63.5	6.0	18.0	17.9

Note: OAC represents optimal asphalt content.

2.3. Methodology and Testing

2.3.1. Compaction Characteristics of OGFC-5 UPFC with Different Thicknesses

Khan et al. demonstrated that an internal rotation angle of 1.25° in the SGC method best reflected the compaction characteristics of the field cores [20]. In addition, the Stratagem Highway Researching Plan (SHRP) recommended an internal rotation angle of

1.16° and a compaction pressure of 600 kPa in the SGC method, which better represents the field compaction. Therefore, to simulate the compaction characteristics of the UPFC with the actual paving thickness, OGFC-5 specimens with different thicknesses were formed using the SGC method, and the compaction height changes in the OGFC-5 specimens under different compaction parameters were analyzed. Considering that the actual paving thickness of the OGFC-5 UPFC in a paving process is as thin as 1 cm, the target compaction heights were selected as 15, 20, 25, 40, and 63.5 mm, respectively. Table 3 lists the SGC parameters. Notably, the mixed masses of the SGC specimens under different test conditions were calculated according to the equivalent volumes of the Marshall specimens to ensure the same density of the mixtures.

Table 3. Compaction parameters.

Compaction Parameters	The Value of Compaction Parameters							
Target height (mm)	15	15	15	15	20	25	40	63.5
Target Radius (mm)	100	100	100	150	100	100	100	100
Vertical pressure (kPa)	600	600	800	600	600	600	600	600
Angle of internal gyration (°)	1.15	1.72	1.15	1.15	1.15	1.15	1.15	1.15
Specimen ID	S100/15	S100/15-1	S100/15-2	S150/15	S100/20	S100/25	S100/40	S100/63.5

2.3.2. Compaction Mechanism of OGFC-5 UPFC with Different Thicknesses

The DEM was used to simulate the SGC test to explore the compaction mechanism of the OGFC-5 mixture with different compaction thicknesses [32–34]. The displacement and force chain transmission of the DEM model were recorded at certain gyratory compaction times. Table 1 presents the OGFC-5 gradations used in the DEM simulations. To enhance the computing speed, the generated particles were greater than 2.36 mm. The Burgers model was used as the contact model, and its parameter values are listed in Table 4 [33,34]. As shown in Figure 1, the heights of the DEM model were 20, 40, and 63.5 mm, respectively. The model set an initial AV content of 35.0%, an angle of 1.15°, compaction pressure of 600 kPa, and a compaction time of 1 h between the loading wall and plane.

Table 4. The model parameters.

Model Parameters			Value
Kelvin model	Spring	shear stiffness (Pa·m)	5.1×10^7
		Normal stiffness (Pa·m)	5.1×10^7
	Dashpot	Normal stiffness (Pa·m·s)	3.6×10^6
		shear stiffness (Pa·m·s)	3.6×10^6
Maxwell model	Spring	shear stiffness (Pa·m)	4.3×10^9
		Normal stiffness (Pa·m)	4.3×10^9
	Dashpot	Normal stiffness (Pa·m·s)	1.8×10^9
		shear stiffness (Pa·m·s)	1.8×10^9

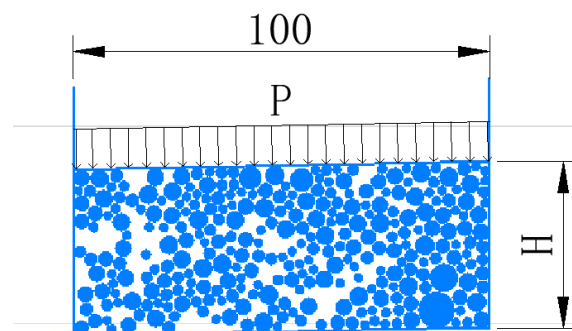


Figure 1. DEM model of SGC method.

2.3.3. AV Characterization of OGFC-5 UPFC Based on CT Scanning

The OGFC-5 mixture possesses an AV content of 18–25%. Internal AV characteristics (such as the AV content and size) are critical for noise reduction and drainage improvement. In view of this, 15 mm OGFC-5 specimens were formed using the SGC and RWC methods to simulate the field core samples of the UPFCs. Similar to the SGC specimen, the mix masses of the RWC specimen were calculated according to the equivalent volume of the Marshall specimens. The roller-forming equipment used was an Italian control pavement roller, as shown in Figure 2. A 400 mm × 300 mm × 15 mm (length, width, height, respectively) cuboid specimen was fabricated using a height control procedure, and core samples were drilled to obtain cylindrical specimens. The samples are listed in Table 5. According to the OFGC-5 UPFC mix design results using the MCM, 15 mm UPFC specimens formed via SGC and RWC that simulate the field compaction were not compacted to the target AV content and height, which indicated that the MCM-designed UPFC mixes did not conform to the field compaction.



Figure 2. Controls pavement roller.

Table 5. Summary of different test specimens.

Specimen ID	Molding Method	Target Specimen Size (Diameter × Height)	Measured Specimen Size (Diameter × Height)	Target AV Ratio (%)	Measured AV Ratio (%)
M100/63.5	Marshall	101.6 mm × 63.5 mm	101.6 mm × 63.0 mm	18	17.9
S100/15	SGC	100 mm × 15 mm	100 mm × 16.7 mm		27.2
S150/15	SGC	150 mm × 15 mm	150 mm × 16.8 mm		26.5
R100/15	RWC	100 mm × 15 mm	100 mm × 17.0 mm		27.4

In the experiment, the PrecisionIICT for industrial use produced by YXLON was used to scan the samples, and pictures were obtained every 0.1 mm along the height of the samples, as shown in Figure 3. These obtained pictures were automatically handled by a macro, and then Image-Pro Plus software (IPP 6.0.0.260) was applied to obtain the AV characteristics. According to the study conducted by Masad et al. [35], the average AV contents of the single and total images were determined using Equations (1) and (2), respectively. In addition, because the AV diameter largely depends on the packing degree of the granular skeleton inside the UPFC samples, the average AV diameter should be analyzed [36]. Therefore, the AV size decreased with increasing packing and particle contact. Equation (3) was adopted to calculate the average AV radius of the *i*-th image. Furthermore, the horizontal variability in the AV ratios and the mean AV diameter in the

cross sections of different radii (Figure 4) were investigated to obtain the horizontal AV distribution of the Marshall specimens and simulated field cores.

$$AV_i = \frac{A_{vi}}{A_i} \quad (1)$$

$$AV_s = \frac{\sum_{i=1}^n AV_i}{N} \quad (2)$$

$$d_i = 2\sqrt{\frac{A_{vi}}{\pi n}} \quad (3)$$

where A_i , A_{vi} , AV_i , d_i , and n are the cross-sectional area, AV area, AV ratio, AV mean diameter, and AV number of the i -th image, respectively. The AV_s and N correspond to the AV rate and total number of CT images of the test specimen, respectively.



Figure 3. CT scanning.

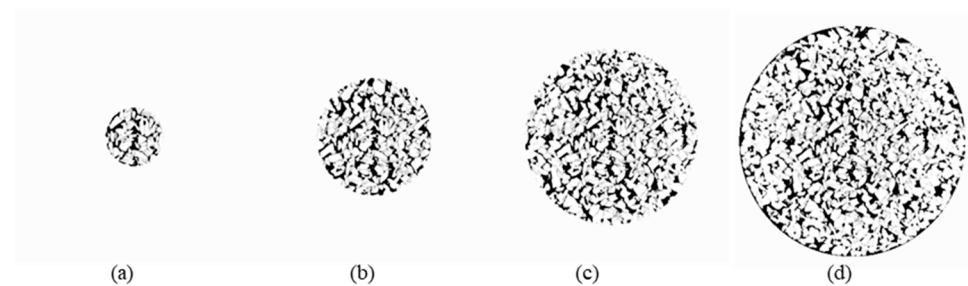


Figure 4. Different radius cross sections used in analysis on horizontal AV variability: (a) 1/4 radius; (b) 1/2 radius; (c) 3/4 radius; (d) full radius.

3. Results and Discussion

3.1. Compaction Properties of OGFC-5 UPFC with Different Thickness

According to the compaction parameters in Table 3, different OGFC-5 UPFC samples were prepared to monitor the compaction process. The simulated field compaction results for the OGFC-5 UPFC under different compaction parameters are presented in Table 6 and Figure 5. The curve of the specimen height with respect to the gyratory number is shown in Figure 5a. According to Equation (4), linear regression analysis was performed on the specimen height and gyratory number, as shown in Figure 5b. The results of the linear regression analysis are presented in Table 7.

$$\ln H(N) = a - k \ln(N) \quad (4)$$

where a and k correspond to the fitting parameters, and N and $H(N)$ represent the gyratory number and height at gyratory number of N , respectively. The parameters a and k reflect the initial density and difficulty of the compaction process, respectively. The larger the a and k values, the easier it is for the specimen to be compacted to the target height [37].

Table 6. The compaction results of different SGC compaction parameters.

Specimen ID	S100/15	S100/15-1	S100/15-2	S150/15	S100/20	S100/25	S100/40	S100/63.5
Gyratory number	200	200	200	200	200	128	80	32
Height	16.7	16.7	16.5	16.8	21.7	25.2	40.2	63.4
AV ratio	27.2%	27.3%	27.3%	26.5%	24.4%	18.6%	18.3%	19.1%

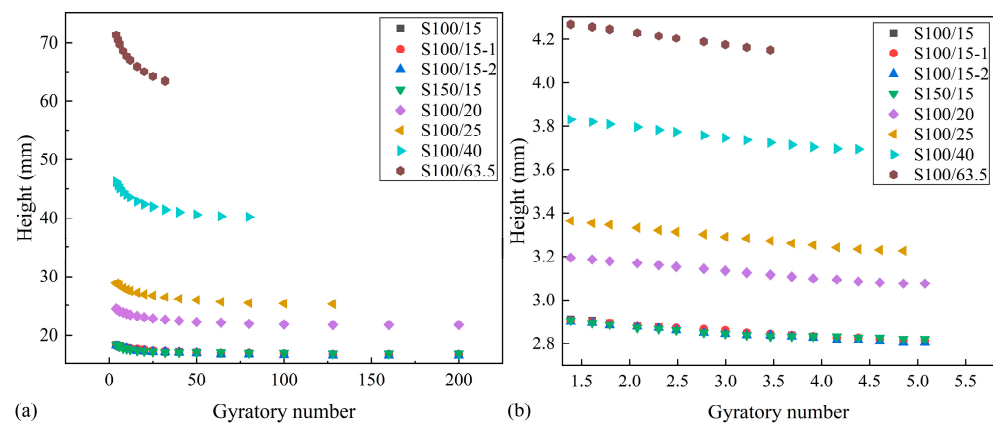


Figure 5. Compaction curves: (a) common coordinates; (b) semi-logarithmic coordinates.

Table 7. The results of linear-regression analysis.

Specimen ID	S100/15	S100/15-1	S100/15-2	S150/15	S100/20	S100/25	S100/40	S100/63.5
k	0.030	0.027	0.028	0.023	0.035	0.041	0.048	0.058
a	2.949	2.942	2.936	2.925	3.241	3.418	3.894	4.348
R^2	0.978	0.990	0.983	0.903	0.996	0.995	0.992	0.999

As shown in Table 6, 5 test specimens, S100/15, S100/15-1, S100/15-2, S150/15, and S100/20, were insufficiently compacted and did not achieve the target compaction thickness after 200 gyratory numbers. In addition, the AV contents of the five specimens were 27.2%, 27.3%, 27.3%, 26.5%, and 25.4%, respectively, which were much higher than the design AV requirement of 18% for UPFC mixes designed using the MCM.

According to Table 7, for the 15 mm UPFC specimen, the a and k values of all 15 mm $\times$ 100 mm (height and diameter, respectively) test samples showed little difference, and increasing the vertical pressure and the internal gyration angle had little effect on the compaction height. The S150/15 specimen had the smallest k value, indicating that the S150/15 specimen was the most difficult to compact to 15 mm. In this regard, the increased radius of the specimen made the compaction pressure more dispersed and increased the difficulty of compaction of the UPFC specimen. In addition, a decrease in the compaction thickness decreased the values of parameters a and k . The initial compaction density of the UPFC specimen decreased, which resulted in compaction difficulties. At the same time, Figure 5a exhibits that the smaller the compaction thickness, the more gyratory numbers were required. This could be because the pressure inside the specimen was non-uniform as the target compaction height decreased. The aggregates in one or several regions were stabilized and bore the main pressure, whereas the other unstabilized regions received less force, and it was difficult for the particles to move, rotate, and be sufficiently compacted.

3.2. Compaction Mechanism of OGFC-5 UPFC with Different Thickness

3.2.1. Displacement and Stress of Loading Wall

Figure 6 shows the displacement curve of the loading wall with respect to the loading time. Remarkably, there was an initial displacement at the time of formal loading because the wall needed to be preloaded before loading. Figure 6 shows the time it took for the SGC model displacement curves of different compaction thicknesses to reach the stable stage ranked 63.5 mm, 40, and 20 mm in descending order.

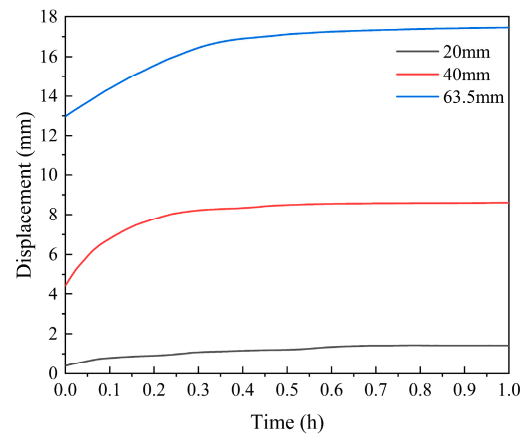


Figure 6. Displacement–time curves of loading wall.

The stress curve of the loading wall with respect to time is shown in Figure 7. The wall continued to move downward at a stress below 600 kPa, indicating that the model was still not fully compacted. The compaction tends to stabilize when the stress is maintained at approximately 600 kPa [38]. As shown in Figure 7, the stress of the 20 mm model was stable and fluctuated around 600 kPa at the earliest. Subsequently, the 40 mm and 63.5 mm models reached a stable stage.

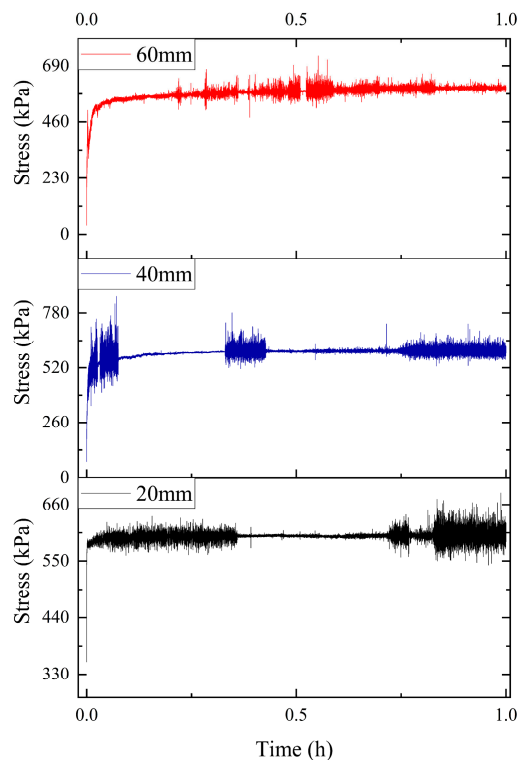


Figure 7. Stress–time curves of loading wall.

A conclusion drawn from Figures 6 and 7 is that the 20 mm UPFC model was the first to reach a steady state. On the one hand, this may be because the 20 mm model is the easiest to compact fully, and it enters the stable state first. However, this may be because the 20 mm model could not be fully compacted, leading to a stable state in advance. Therefore, further analysis of the displacement of the loading wall is required to determine its specific cause. Aggregate crushing can affect the degree of interlocking between aggregate particles and the filling effect of asphalt. However, it should be noted that the DEM model does not take into account the effects of aggregate fragmentation and morphology, which may lead to misjudgment of the compaction process, thereby affecting the stability and durability evaluation of the UPFCs. Crushed aggregates require different compaction energies to achieve optimal compactness. Meanwhile, aggregate crushing affects the volume change and compaction curve of UPFCs. Although the DEM model does not consider the aggregate fragmentation and morphology, which may lead to a certain deviation between the time–displacement curve and the actual compaction, the simulation results can basically explain the above-mentioned laboratory test results, that is, when the UPFC target compaction thickness is too small, no matter what compaction parameters are used, the UPFC sample cannot meet the compaction requirements.

The final displacements of all models with different heights were obtained, representing the compacted thickness of the model. The definition index D_H is the compacted thickness per unit height of the model, which reflects the difficulty of compaction at different heights. The D_H value was equal to the displacement of the loaded wall divided by the height of the model. The calculated D_H values are listed in Table 8. The D_H values ranked as D20, D40, and D63.5 in ascending order. This indicates that as the molding height decreased, the model became more difficult to compact. This result explains why a model displacement of 20 mm reached a stable state the earliest, which is consistent with the compaction data in Section 3.1.

Table 8. The D_H values.

UPFC Height/mm	20	40	63.5
Displacement of loading wall/mm	1.42	8.61	17.46
D_H	0.07	0.22	0.27

3.2.2. Micromechanical Response

Figure 8 presents the direction results of the normal contact force of the particles after loading for 1 h. The contact normal forces of the different models were distributed in all directions, and there were no distribution concentrations in any specific direction. Remarkably, the contact normal force of the 20 mm model exhibited a sudden increase in several directions. This phenomenon was also found in the 40 mm model, while the increment of the contact normal force was relatively small in comparison to that of the 20 mm model. As for the 63.5 mm model, the force values were relatively uniform in each interval. The maximum contact normal force values of the 20 mm and 40 mm models were 8 times and 2.67 times that of the 63.5 mm model, respectively. The smaller the molding height, the greater the force value observed.

The force chain and contact force were further studied to analyze the load transmission in the model. Figures 9 and 10 show the simulation results of the contact force and force chain, respectively. The colors of the particles in Figure 9 indicate the magnitude of the contact force. A phenomenon occurred where the contact forces of some particles were much stronger than that of other particles. The maximum force value increased with a decrease in model height, and the particle size showed a random trend in the force concentration region, indicating that the concentrated force region was independent of the particle size.

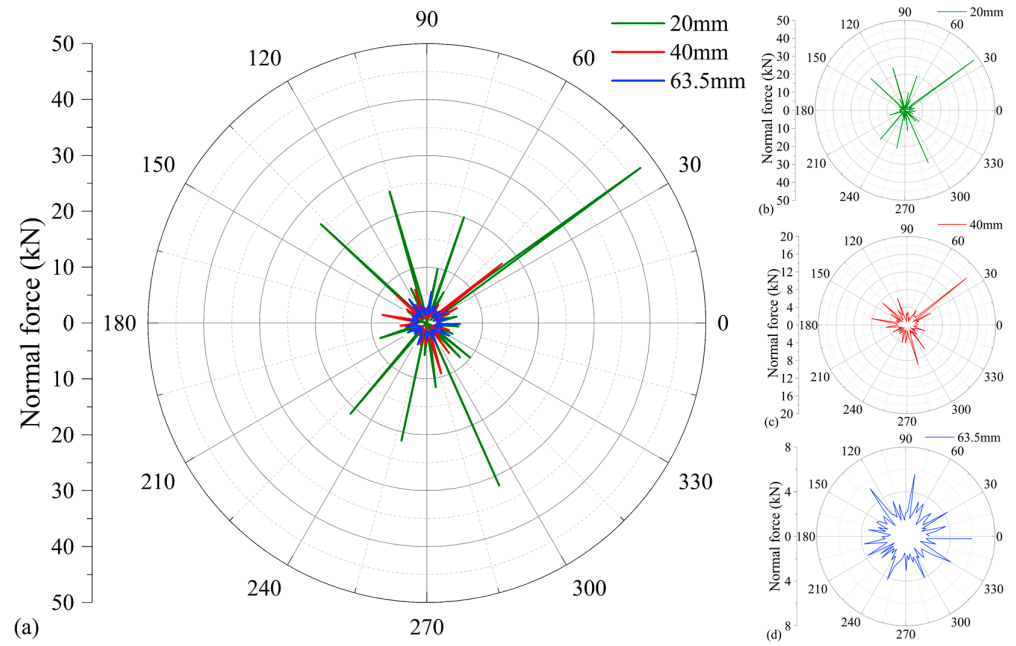


Figure 8. Direction distribution of contact normal force of different thickness UPFC model: (a) general drawing; (b) 20 mm; (c) 40 mm; (d) 60 mm.

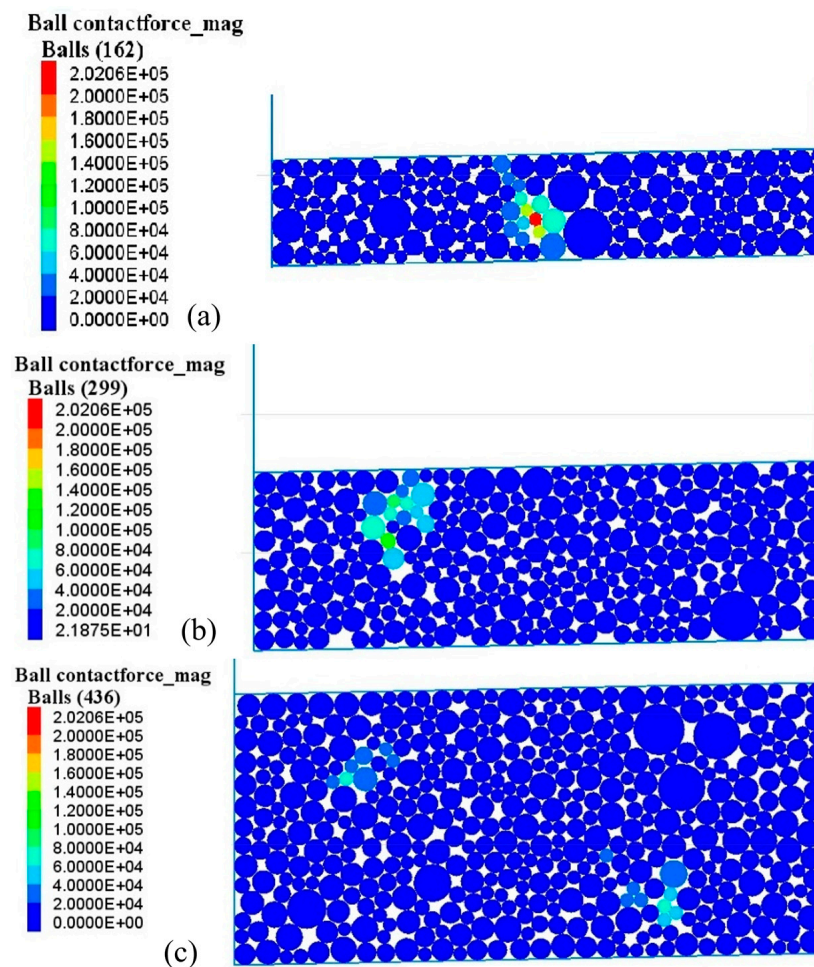


Figure 9. Contact force distribution of different thickness UPFC models: (a) 20 mm; (b) 40 mm; (c) 60 mm.

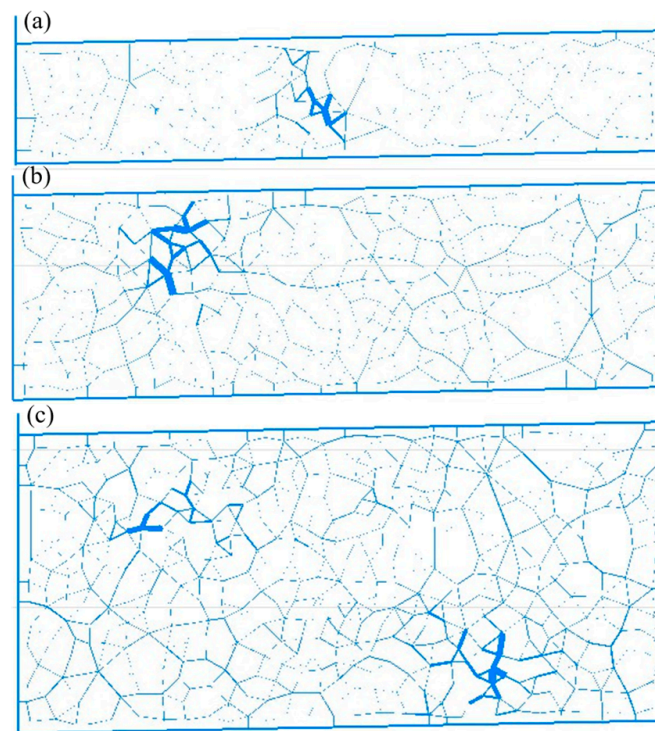


Figure 10. Force chain distribution of different thickness UPFC models: (a) 20 mm; (b) 40 mm; (c) 60 mm.

A schematic of the force chain clearly reflects the load transmission in the model. The thickness of the force chain in Figure 10 indicates the magnitude of the contact force. It can be found that the 63.5 mm model had more uniform thickness in the force chain, while the 20 mm model had less force in other areas owing to the existence of a strong chain area. With a decrease in height, the force chain became more significant, resulting in a load that is more difficult to fully diffuse and transfer inside the model [39]. Particles in the weak force chain region could not move and rotate sufficiently, making the model more difficult to compact. In conclusion, the target height of the UPFC specimen designed by the MCM method was 63.5 mm, which varied from the actual UPFC paving thickness, making it difficult to achieve the specified on-site compaction degree. Therefore, it is possible to consider reducing the target height of the UPFC to make the MCM design more in line with construction.

3.3. AV Characterization of OGFC-5 UPFC Based on CT Scanning

3.3.1. Vertical Distribution

The vertical distributions of the AV content and coefficient of variation (COV) are shown in Figure 11. The vertical distribution of the AV diameter is shown in Figure 12. As shown in Figures 11a and 12, the curves of the AV content and AV diameter are in a “bathtub” shape along the vertical direction. The AV content was homogeneous and stable in the middle part, whereas those in the bottom and top parts were much larger than the average AV content. In addition, except for the Marshall specimen, the AV content of the other simulated field cores exceeded the design range. The overall AV content and diameter of the MCM-designed UPFC samples was smaller than those of the simulated field cores. The results show that the MCM-designed UPFC did not correspond well with the field construction situation. Obviously, in order to achieve the AV content of the Marshall-designed UPFC during the on-site construction process, it is necessary to increase the compaction tonnage, which will inevitably lead to an increase in the aggregate crushing. Crushed aggregates further embed and fill voids, resulting in a decrease in porosity. However, this will have an adverse impact on the performance of the UPFC.

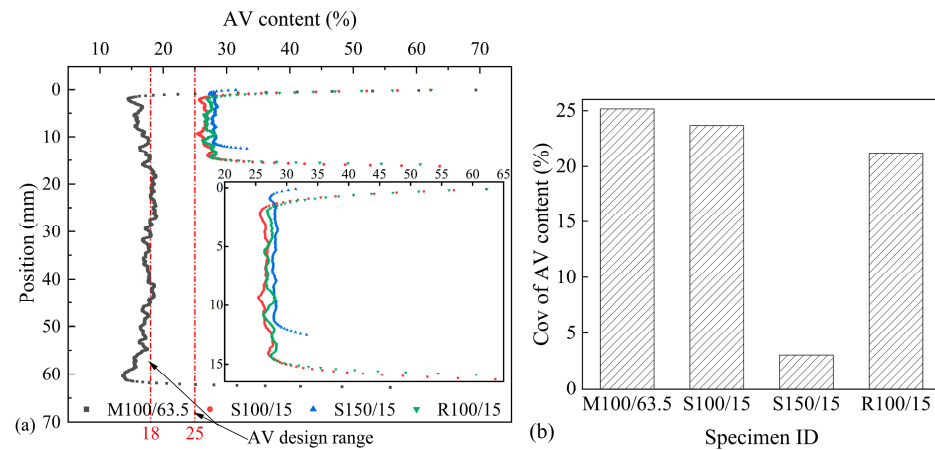


Figure 11. The vertical distribution: (a) mean AV content; (b) vertical variability.

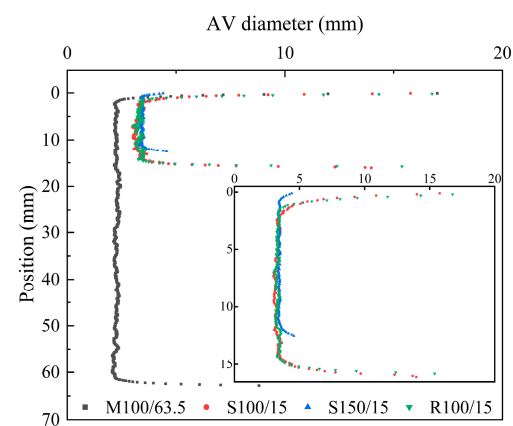


Figure 12. The vertical distribution of AV diameter.

As shown in Figure 11b, the COV of the Marshall specimen was the largest among all test samples. This is because the SGC and RWC methods exert a kneading effect during the compaction process, such that the aggregates can be fully moved and arranged, thereby producing a relatively homogeneous internal structure. However, because the Marshall compaction method relies mainly on vertical impact, the homogeneity of the internal structure of the sample was relatively poor. The COV of the S150/15 specimen was the smallest, indicating that increasing the compaction area improved vertical uniformity [18,40]. In addition, the COV values of the 15 mm specimens were all smaller than those of the 63.5 mm specimen, indicating that a small compaction thickness was conducive to uniform compaction. The reason that the 15 mm UPFC specimen could not reach the target height was not compaction. According to Figures 10 and 12, a concentrated force region existed, resulting in insufficient movement and packing between the aggregates when the compaction thickness of the UPFC was small. Thus, the AV size between the aggregates was large, and the thin UPFC specimen could not be compacted to the target thickness.

3.3.2. Horizontal Distribution

The horizontal distributions of the AV content and COV are presented in Figure 13. The AV content of the 63.5 mm Marshall specimen was the most uniform and stable in the horizontal direction, while that of the other 15 mm simulated field cores exhibited a wave shape along the horizontal distribution. In addition, Figure 13b shows that the COV of all the specimens showed a wavy trend along the radial direction. Remarkably, the S150/15 specimen had the smallest COV, which conforms to the conclusion drawn from Figure 11b. Overall, the horizontal distributions of the AV between the MCM-designed UPFC and the simulated field cores were quite different. It was also proven that the MCM-designed UPFC mixes did not accurately reflect the field construction of the UPFC.

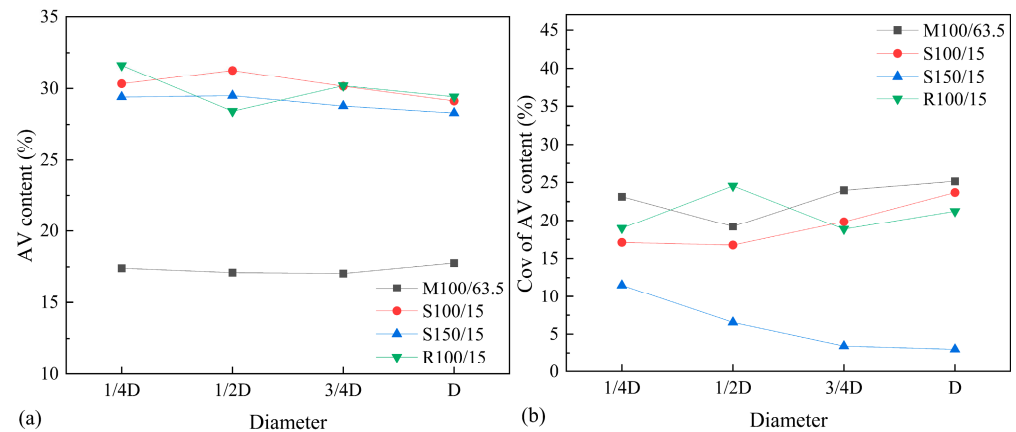


Figure 13. The horizontal distribution: (a) mean AV content; (b) horizontal variability.

4. Conclusions

The compaction characteristics of an OGFC-5 UPFC specimen designed using the MCM and simulated field cores were studied at multiple scales using laboratory compaction tests, DEM, and X-ray CT techniques. On the basis of the results, some conclusions were drawn, as follows:

- (1) The compaction-test data demonstrate that the simulated field specimens with thicknesses of 15 and 20 mm barely achieved the target compaction thicknesses. All the UPFC specimens of different thicknesses failed to meet the AV requirements of the UPFC mixes designed via the MCM.
- (2) As the compaction thickness decreased, the values of parameters a and k also decreased. The initial compaction density of the UPFC specimen decreased, which resulted in compaction difficulties.
- (3) According to the results of the SGC test based on the DEM, the smaller the height of the virtual specimen, the earlier its displacement and stress reached a stable state. Moreover, as the model decreased in height, the D_H value; that is, the compacted thickness per unit height of the model, decreased, and the model was more difficult to compact.
- (4) DEM models with different thicknesses exhibited several force concentration regions. Compared to that of the 63.5 mm model, the maximum contact normal force of the 20 mm and 40 mm models increased by 266% and 800%, respectively. The decrease in the UPFC thickness strengthened the strong force chain in quantity and strength inside the specimen, resulting in difficulty in evenly diffusing and transferring pressure inside the specimen.
- (5) Based on the results of the UPFC specimens obtained using CT scanning, a small compaction thickness was conducive to uniform compaction. The AV distributions of the Marshall specimens were quite different in the vertical and horizontal directions from those of the UPFC specimens that simulated the field compaction. The MCM-designed UPFCs showed poor consistency with the field compaction.
- (6) According to the investigation results, the MCM-designed UPFC is not in compliance with on-site construction. In order to better align with actual construction and ensure the performance of the UPFC, potential paths to improve UPFC designs from the perspective of mixture design include reducing the height of the MCM design specimens and changing the UPFC design methods.

These research results provide feasible references for achieving more durable UPFCs. However, this study did not take into account the influence of some factors, such as mineral gradation and aggregate characteristics, and it lacked on-site experimental validation. Future research will focus on the above aspects, particularly regarding the effects of aggregate morphology and crushing on the compaction behavior of UPFCs.

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