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Study on the Void Structure Deterioration in the Rutting Zone of Porous Asphalt Pavement under Traffic Load based on the Discrete Element Method

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Abstract: In order to study the effect of traffic load on the void structure in the rutting zone of porous asphalt pavement, a virtual pavement model was constructed using the discrete element software PFC2D. The virtual rutting test on the two-dimensional discrete element model was conducted based on the static load equivalence principle to investigate the impact of different factors on the void structure deterioration in the pavement rutting zone. The results indicate that the greater the load, the greater the degree of compressive deformation in the void structure of the rutting zone. The void structure is rapidly compressed at the initial stage of load application, and after a prolonged load application, the pavement reaches a stable state that is essentially incompressible. The bonding capacity of asphalt is stronger at lower temperatures, and as the environmental temperature continues to rise approaching the asphalt's softening point, the deterioration degree of the void structure becomes severe. When the initial void ratio of the specimen is kept at a low level, the overall deterioration degree of the voids in the rutting zone is small. In contrast, specimens with higher void ratios experience greater void structure deterioration after loading, but the residual void ratio after the application of load still remains at a high level.

Keywords: Porous Asphalt Pavement; Discrete Element Method; Traffic Load; Rutting Zone; Void Structure Deterioration.

1. Introduction

The application of porous asphalt pavement can effectively address issues related to driving safety during rainy weather and traffic noise. Unlike dense-graded asphalt pavement, the surface layer of porous asphalt pavement is constructed with asphalt mixture with a void ratio of over 18%, allowing surface water to infiltrate and be transversally drained, thereby reducing driving spray and enhancing driving safety[1–4]. Meanwhile, the large void characteristics of porous asphalt pavement can effectively alleviate the local unstable airflow volume formed by the contact and separation of tires and the road surface during high-speed driving, thus favoring noise absorption [5–7]. However, researchers have found in recent years that under the compaction effect of vehicle loads during service [8], the voids of porous asphalt pavement degrade, resulting in a significant attenuation of its anti-skid and noise reduction functions. This has become a critical factor affecting the service life of porous asphalt pavement structure [9].

With the development of computer technology, numerical simulation methods have been widely applied. Simulation tests of porous asphalt mixtures based on the discrete element method can overcome the disadvantages of laboratory tests, accurately predict the voids deterioration of porous asphalt mixtures, and have the advantages of being time-efficient and cost-effective. You et al. [10] used two-dimensional and three-dimensional discrete element methods to explore the changes in the modulus of asphalt mixtures at different specific void levels. Ma et al. [11] explored the creep performance of asphalt mixtures at high temperatures through mesomechanical modeling and discrete element method virtual tests, focusing on the mechanisms and patterns of how microstructural parameters like void content, void size, and void distribution affect their performance.

This study constructed a virtual pavement model using the discrete element software PFC2D and conducted virtual rutting tests on the two-dimensional discrete element model based on the static load equivalence principle to study the impact of different factors on the void structure deterioration in the pavement rutting zone.

2. Virtual Pavement Model Construction

A two-dimensional virtual pavement model was generated using the mastic theory, considering porous asphalt pavement as composed of coarse aggregates, asphalt mastic, and voids. A program was written to randomly place irregularly shaped aggregate particles according to actual proportions. The uncovered cells were used to simulate asphalt mastic, and the void structure in the asphalt mixture was formed by randomly deleting some mastic cells, ultimately creating a two-dimensional virtual pavement model with a void ratio of 18% (as shown in Figure 1).

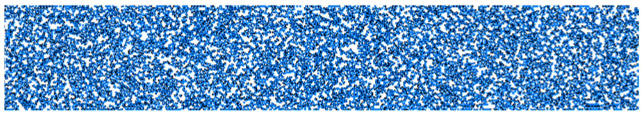


Fig 1. Two-dimensional virtual pavement model

Combining the mechanical behavior between particles in the discrete element model of porous asphalt pavement, the linear stiffness model was used to characterize the contact within and between aggregates, the parallel bond model was used to characterize the contact between asphalt mastic and adjacent aggregates, and the Burger's model was used to characterize the contact within the asphalt mastic. The elastic modulus of the aggregate was taken as 55.5 GPa, Poisson's ratio as 0.25, normal stiffness as 55.5 GPa·m, tangential stiffness as 18.5 GPa·m, and the friction coefficient as 0.5.

3. Virtual Rutting Test

According to the Standard test methods of bitumen and bituminous mixtures for highway engineering (JTG E20-2011) [12], during the rutting test, the test wheel travels a distance of 230 mm in the central part of the specimen surface, with a reciprocating rolling speed of 42 times/min, a test wheel width of 50 mm, a test temperature of 60°C, a total applied load of 780 N, and a contact pressure of 0.7 MPa. Because the wheel rolling in a real test is continuous, with a certain periodicity and frequency, it is challenging to achieve this in virtual tests. Therefore, this section uses the static load equivalence principle for load conversion. By accumulating the time the tire passes over a certain point, the total load acting time on that point can be calculated.The formula for calculating the contact length between the test wheel and the rutting board surface in the direction of travel is as follows:

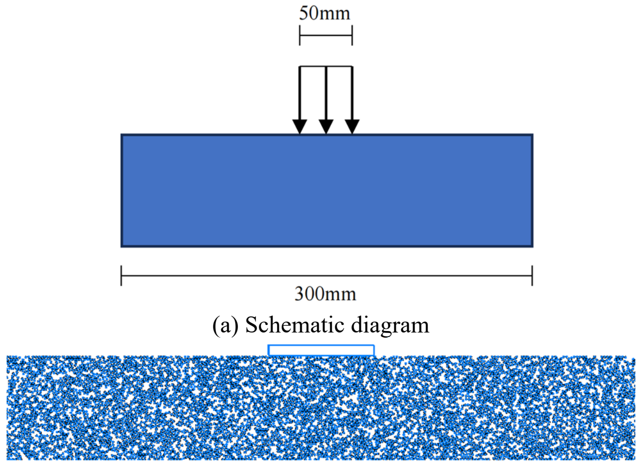
$$P = mg = pdl \tag{1}$$

Where P represents the total load; m represents the mass of the test wheel; g represents the acceleration due to gravity; p represents the contact pressure; d represents the width of the test wheel; l represents the contact length between the test wheel and the rutting board surface in the direction of travel. This yields the total duration of load acting on that point:

$$t = 3600 \times \frac{l}{230} = 3600 \times \frac{mg}{230pa} = 3600 \times \frac{78 \times 9.8}{230 \times 0.7 \times 50} = 342\text{s}, \tag{2}$$

Therefore, the total duration of load acting on a point of the rutting specimen is 342 seconds, with a uniformly distributed load of 0.7 MPa applied to the central part of the specimen surface, as shown in Figure 2.

To verify the feasibility of the two-dimensional discrete element model, the deformation results of the virtual rutting test model were compared with the results of the indoor test. Figure 3 shows the variation curves of the rutting deformation amount over time recorded in PFC2D and the rutting deformation amount over time in the indoor test. Both the experimental curve and the simulation curve in the figure indicate that at the initial stage of loading in the rutting test, the rutting deformation amount grows at a relatively fast rate. As the void structure compresses to a certain extent, the growth rate of rutting deformation slows down and gradually stabilizes. The simulation results are slightly greater than the indoor test results, likely because the coarse aggregate skeleton in the indoor rutting test specimens is more stable, while the particle shapes and sizes used in the virtual specimens may differ from the actual materials, resulting in relatively lower structural stability. Overall, however, the numerical variation patterns of both are essentially consistent, and the error is within an acceptable range, indicating that the two-dimensional discrete element model for porous asphalt pavement is feasible.



(a) Schematic diagram

(b) Model loading

Fig 2. Loading method

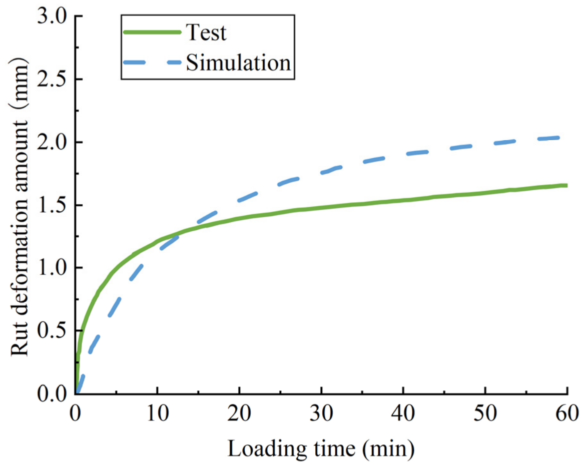


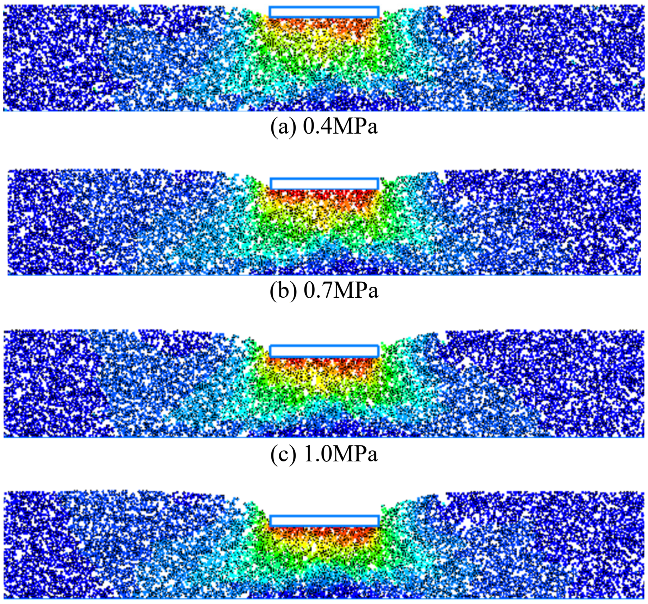
Fig 3. (Virtual) rutting test deformation curves

4. Void Structure Deterioration Patterns under Different Influencing Factors

The compression of void structure in the rutting zone of porous asphalt pavement caused by traffic load impedes surface infiltration. In this section, the deterioration patterns of void structure in the rutting zone of porous asphalt pavement will be studied under the influence of four factors: load magnitude, loading time, environmental temperature, and initial void ratio, using the constructed two-dimensional discrete element model.

4.1. Load Magnitude and Void Structure Deterioration Pattern

The magnitude of the load directly affects the pressure exerted by the tire on the pavement, which is the direct cause of pavement void structure deterioration. To investigate the effect of load magnitude on pavement rutting zone void structure deterioration, virtual rutting tests were conducted at four stress levels: 0.4 MPa, 0.7 MPa, 1.0 MPa, and 1.4 MPa, with a test temperature of 60°C. After the tests, the rutting test models with different load sizes were obtained, as shown in Figure 4, and the changes in void ratio before and after loading were calculated using discrete element software, as shown in Table 1.



(a) 0.4MPa

(b) 0.7MPa

(c) 1.0MPa

(d) 1.4MPa

Fig 4. Rutting test models after loading with different size loads

Table 1. Variation of void ratio at the rutting zone before and after load application

Load magnitude (MPa)	Rutting zone void ratio (%)		Change in void ratio (%)
	Before loading (%)	After loading (%)	
0.4	18	15.8	2.2
0.7	18	14.6	3.4
1.0	18	13.4	4.6
1.4	18	11.1	6.9

As seen in Table 1, as the load magnitude increases, the disturbance to the pavement structure also increases, and the void deterioration in the rutting zone shows an accelerated growth trend. That is, increasing the load results in greater compression and deformation of the void structure in the rutting zone, affecting the functionality of the porous asphalt pavement. In practical engineering, the design and maintenance of porous asphalt pavement must fully consider the expected traffic loads and avoid overloading as much as possible. The effect of different loads on the void ratio in the rutting zone is shown in Figure 5. By fitting the load magnitude and the void ratio in the rutting zone after loading, the fitted formula is:

$$VV = -3.9373e^{P/1.54191} + 20.87393 \quad R^2 = 0.99756 \tag{3}$$

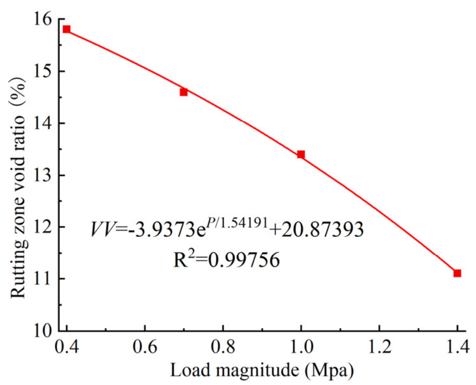
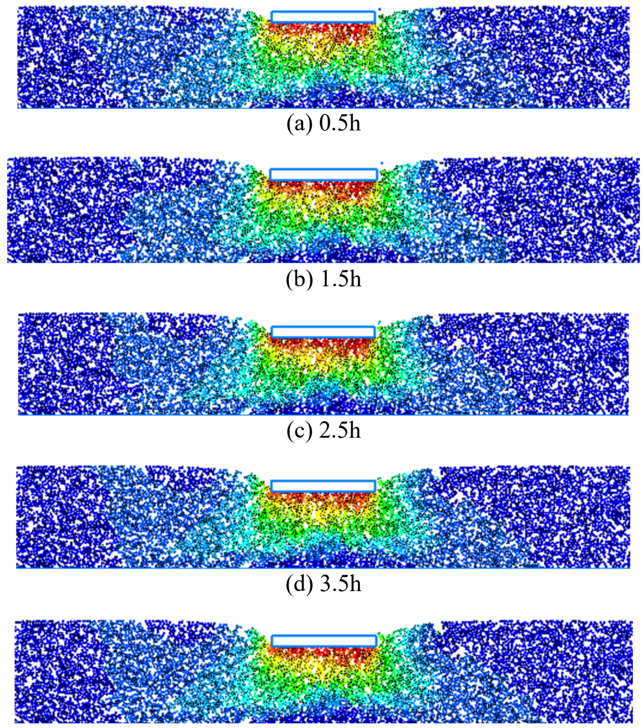


Fig 5. Effect of different loads on the void structure at the rutting zone

Where VV represents the the rutting zone void ratio; P represents the load magnitude.

4.2. Loading Time and Void Structure Deterioration Pattern

Loading time refers to the duration of the pressure exerted by the tire on the pavement. Prolonged loading time leads to increased fatigue damage to the pavement materials, causing deformation and stress concentration in the pavement materials, which accelerates the deterioration of the void structure. To study the effect of loading time on the deterioration of the pavement rutting zone void structure, virtual rutting tests were conducted with five different loading times: 0.5h, 1.5h, 2.5h, 3.5h, and 4.5h. The test temperature was consistently 60℃, and the load magnitude was uniformly 0.7MPa. The rutting test models for different loading times are shown in Figure 6, and the changes in void ratio before and after loading, calculated using the discrete element software, are shown in Table 2.



(a) 0.5h

(b) 1.5h

(c) 2.5h

(d) 3.5h

(e) 4.5h

Fig 6. Rutting test models after different loading times

Table 2. Variation of void ratio at the rutting zone before and after load application

Loading time (h)	Rutting zone void ratio (%)		Change in void ratio (%)
	Before loading (%)	After loading (%)	
0.5	18	15.7	2.3
1.5	18	14.5	3.5
2.5	18	14.2	3.8
3.5	18	13.9	4.1
4.5	18	13.8	4.2

From Table 2, it can be seen that as the loading time increases, the void ratio in the rutting zone initially decreases at a relatively fast rate, then slows down and tends to stabilize. This indicates that at the initial stage of loading, the tire exerts a significant compressive force on the voids in the rutting zone, causing the void structure to compress rapidly. After prolonged loading, the pavement reaches a stable state where it is essentially incompressible, with the void structure tends to stabilize, and the void ratio is maintained at about 13%. The effect of different loading times on the void ratio in the rutting zone is shown in Figure 7. The loading time and the post-loading void ratio in the rutting zone were fitted, and the fitted formula is:

$$VV = 2.17505e^{-t/0.29411} + 2.24517e^{-t/1.88591} + 13.57985$$

$$R^2 = 0.99933 \quad (4)$$

Where VV represents the the rutting zone void ratio; t represents the loading time.

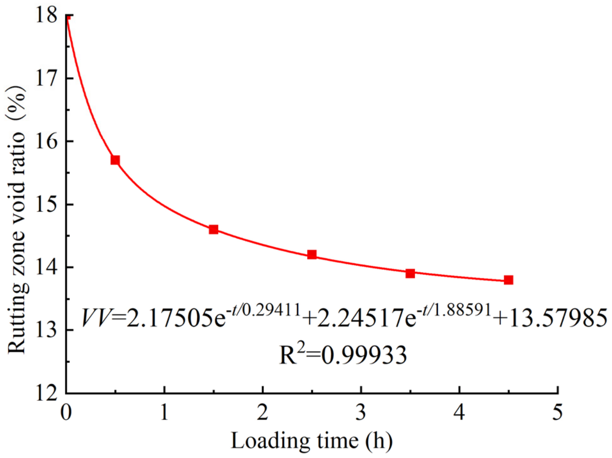
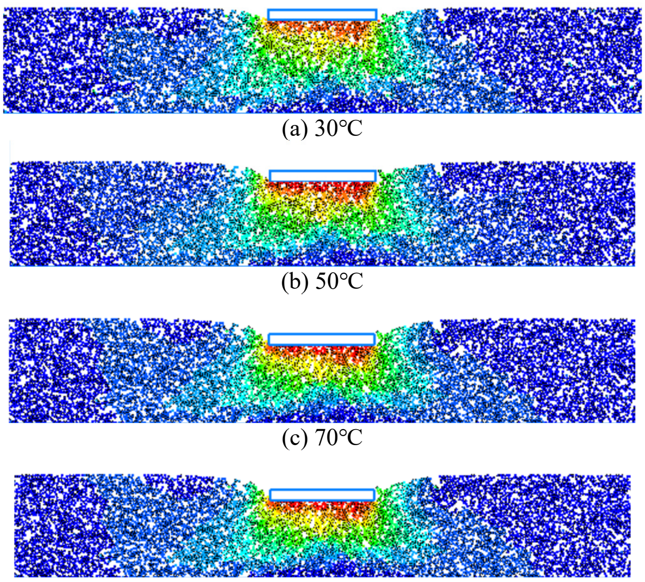


Fig 7. Effect of different loading duration on the void ratio at the rutting zone

4.3. Environmental Temperature and Void Structure Deterioration Pattern



(a) 30℃

(b) 50℃

(c) 70℃

(d) 90℃

Fig 8. Rutting test models with different environmental temperatures

Environmental temperature significantly affects the structural stability of asphalt mixtures. High temperatures accelerate the aging and deterioration of asphalt, causing it to lose its original bonding capability and elasticity, resulting in reduced structural stability of the pavement. As the temperature rises, especially near the softening point, the shear strength of the asphalt mixture decreases and its stability diminishes to investigate the effect of environmental temperature on the deterioration of pavement rutting zone void structure, virtual rutting tests were conducted at seven different temperatures: 30°C, 40°C, 50°C, 60°C, 70°C, 80°C, and 90°C. The test duration was 60 minutes, and the load magnitude was 0.7MPa. After the tests, the rutting models for different temperatures were obtained. The conditions of the rutting models at 30°C, 50°C, 70°C, and 90°C are shown in Figure 8. The changes in void ratio before and after loading, calculated using the discrete element software, are shown in Table 3.

Table 3. Variation of void ratio at the rutting zone before and after load application

Environmental temperature (°C)	Rutting zone void ratio (%)		Change in void ratio (%)
	Before loading (%)	After loading (%)	
30	18	16.6	1.4
40	18	16.1	1.9
50	18	15.4	2.6
60	18	14.5	3.5
70	18	13.4	4.6
80	18	12.1	5.9
90	18	10.8	7.2

From Table 3, it can be seen that when the environmental temperature is below 60°C, the degree of void ratio reduction in the rutting zone is relatively small, indicating that at lower temperatures, asphalt has strong adhesive properties and the mixture has high stability. As the environmental temperature continues to rise, approaching the softening point of asphalt (93°C), the degree of void structure deterioration becomes severe. This indicates that at this point, the viscosity of the asphalt has drastically decreased, increasing the mixture's fluidity, making it prone to deformation and displacement, which exacerbates the void deterioration. The impact of different environmental temperatures on the void ratio in the rutting zone is shown in Figure 9. The environmental temperature and the post-loading void ratio in the rutting zone were fitted, and the fitted formula is:

$$VV = -1.88272e^{T/57.04884} + 19.85522 \quad R^2 = 0.99847 \quad (5)$$

Where VV represents the the rutting zone void ratio; T represents the environmental temperature.

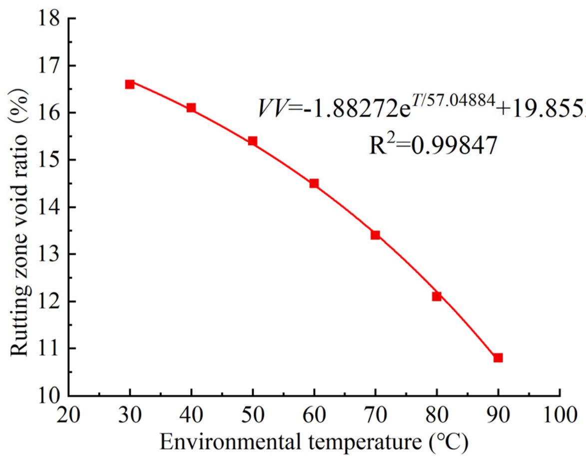
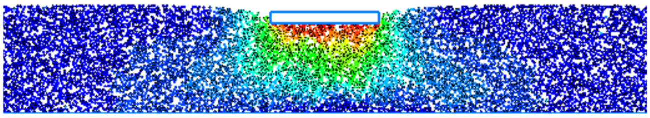


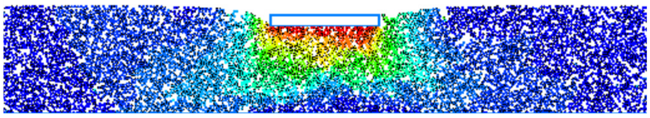
Fig 9. Effect of different environmental temperatures on the void ratio at the rutting zone

4.4. Initial Void Ratio and Void Structure Deterioration Pattern

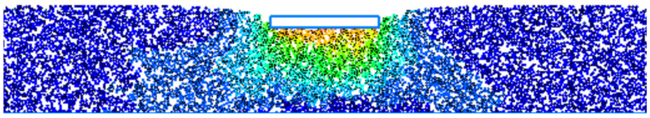
Voids, as an essential component of porous asphalt pavements, play a crucial role in their performance. Selecting an appropriate void ratio is vital; void ratios that are too large or too small cannot form a stable skeleton structure to resist the compaction effects of vehicle loads. To study the effect of initial void ratio on the deterioration of pavement rutting zone void structure, virtual rutting tests were conducted with initial void ratios of 16%, 18%, 20%, 23%, and 25%. The test temperature was uniformly 60°C, and the load magnitude was 0.7MPa. After the tests, the rutting test models for different initial void ratios were obtained, as shown in Figure 10. The changes in void ratio before and after loading, calculated using the discrete element software, are shown in Table 4.



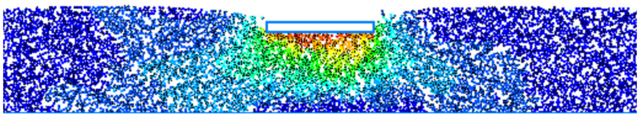
(a) VV =16%



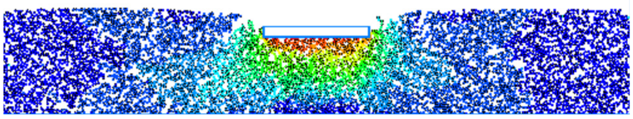
(b) VV =18%



(c) VV =20%



(d) VV =23%



(e) VV =25%

Fig 10. Rutting test models with different initial void ratios

Table 4. Variation of void ratio at the rutting zone before and after load application

Initial void ratio (%)	Rutting zone void ratio (%)		Change in void ratio (%)
	Before loading (%)	After loading (%)	
16	16	12.5	3.5
18	18	14.6	3.4
20	20	16.8	3.2
23	23	16.6	6.4
25	25	15.9	9.1

From Table 4, it can be seen that when the initial void ratio of the specimens is maintained at a low level (16%-20%), the overall degree of void deterioration in the rutting zone is relatively small, with the least void ratio change occurring at 20%. When the initial void ratio continues to increase, the coarse aggregates in the mixture excessively accumulate, causing the internal structure to become loose, leading to a higher overall degree of void deterioration in the rutting zone. The impact of different initial void ratios on the void ratio in the rutting zone is shown in Figure 11. It can be seen that although the specimens with higher void ratios experience greater void structure degradation after loading, the residual void ratio remains at a high level. Therefore, to ensure good permeability of porous asphalt pavement during operation, it is recommended to use porous asphalt mixtures with an initial void ratio of 20%-23%.

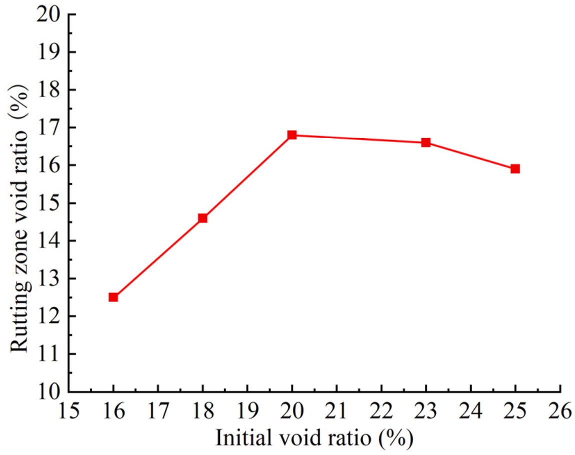


Fig 11. Effect of different initial void ratios on the void ratio at the rutting zone

5. Conclusion

Based on the discrete element method, a two-dimensional discrete element model of the porous asphalt pavement was constructed to simulate the rutting test. The results obtained are basically consistent with indoor tests, verifying the reliability of the modeling method and mesoscopic parameters. Through the constructed two-dimensional discrete element model, the deterioration patterns of the void structure in the rutting zone under different load magnitudes, loading times, environmental temperatures, and initial void ratios were studied. The results show that the greater the load, the greater the degree of compression deformation of the void structure in the rutting zone; The void structure is rapidly compressed at the initial stage of load application, and the pavement reaches a basically incompressible stable state after long-term load action; The asphalt has a strong bonding ability at low temperatures, and when the environmental temperature continues to rise until it approaches the softening point of the asphalt, the degree of void structure deterioration becomes severe; When the initial void ratio of the specimen is kept at a low level, the overall decay degree of the voids in the rutting zone is small, and the void ratio change is minimal at 20%, While the specimens with higher void ratios have a greater degree of void structure deterioration after load application, the residual void ratio remains at a relatively high level.

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