

## Research Article

# Prediction Model for Connected Voids Ratio of the Porous Asphalt Mixture

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The practice showed that the difficulty to precisely predict the water permeability of the asphalt mixture by porosity creates the problem of the discrepancy between the material design and its function. And in the porous asphalt mixture, it is the connected voids ratio that truly bears the function of water permeability. However, there are many factors influencing the connected voids, and their influence laws remain to be known. Having analyzed the effects of different technical parameter on connected voids, 135°C rotation viscosity parameter was chosen in this paper to study the influences of properties of the asphalt mixture on connected voids. The equivalent width among framework gaps was quantified. The relation between the equivalent width, passing ratio of key sieve, and connected voids was discussed, and hence the prediction model for connected voids was established. The research showed that asphalt mixture with high 135°C rotation viscosity of asphalt had smaller connected voids, but the viscosity had less influence on connected voids ratio of asphalt mixture with larger equivalent width among framework gaps. The larger the equivalent width among framework gaps, the bigger the connected voids ratio. The passing rate of 2.36 mm sieve increased; both voids ratio and connected voids ratio became smaller and the difference value between them increased. Since the limitations of the composite specimens limited the prediction range, when the passing rate of 2.36 mm gradation was too small, there was a huge difference between the prediction value and the actual value. This model can predict the connected voids ratio under the stage of gradation design, thus saving the experiment time, shortening the design period, and providing some guidance to the adjustment of the raw material choosing and gradation.

## 1. Introduction

Currently, most roads in cities are covered by impermeable material. Strength and durability are the main aspects that are focused, thus neglecting the effect on the environment. With the increase of the accident caused by “floating phenomenon,” the permeability of pavement gradually enters into the vision of the researchers and designers. It is now confirmed that porous asphalt mixture has good performance in permeability, antisliding, and noise reduction [1–4]. Therefore, adding asphalt rubber with good viscoelastic property into the porous asphalt mixture can not only improve the noise reduction effect but also dispose the waste tire, which would contribute to environment protection [5, 6].

As different cementing materials of the porous asphalt mixture have influence on the voids distribution characteristic, the permeability of pavement with the same air voids rate while using different cementing materials differs. Generally, the larger the air voids ratio of the porous asphalt mixture, the better water permeability the material has, but it is the connected voids that bear the function of permeability [4, 7]. Chen [8, 9] found that the water permeability in different directions of the specimen depends on the ratio of the connected voids in that direction, and there is obvious difference on the permeability in different directions. After the expansion and contraction of the porous asphalt mixture saturated with water in the freeze-thaw cycles are measured, it is found that after the freeze-thaw cycle, the expansion is greater than the contraction, and the bigger the voids ratio is,

the bigger the residual expansion rate and accumulated residual expansion rate are. Zhang et al. [10] added red mud as the filler into the porous asphalt mixture to study the performance of asphalt mixture. The research showed that the effect of the filler-bitumen ratio on the voids ratio is insignificant when red mud is used as filler, but as the filler-bitumen ratio increases, the mortar viscosity rises, and the mortar blocks the seepage path of the porous asphalt mixture, which would have negative effect on the connected voids ratio and the permeability. Besides, Suresha et al. [11] discovered that water permeability coefficient can partially influence the mechanic property of the material after they studied the relations among the volumetric parameter and water permeability coefficient under different gradation.

Many researchers studied the connection property of the asphalt mixture from the microscopic level. Masad et al. [12] achieved the recurrence of the space distribution through computed tomography (CT) and analyzed the relation between the permeability coefficient and connected voids. Xiao [13] obtained the internal framework structure of the specimen under different gradations by CT sectional image technology and distinguished the substance in the image by using improved Maximum Between-Cluster Variance method (OTSU) and then acquired the distribution and the characteristics of the aggregates, mortar, and voids. The result showed that there is relation between voids ratio and the connected voids ratio, and the larger the voids ratio is the larger the connected voids would be, and the difference value is 3%–6%. Jiang et al. [14] found that voids characteristic in the microscopic level is quite different under different gradation. Under the same condition of voids ratio, as the nominal size increases, the connected voids and the single voids area raise, the number of the gap in the same section decreases, and the anti-blockage capability improves.

The connected voids should be considered as an important parameter in the design stage, and the percolation model should be designed on the basis of voids connection characteristic. Guan [15] calculated the effective voids ratio without runoff on the road surface.

$$V' \geq \frac{3.07 \times 10^7 Q}{J \times F} + 8.32, \quad (1)$$

where  $V'$  (%) represents the interconnection voids,  $J$  (%) represents the synthesis gradient of the drainage pavement,  $F$  ( $\text{m}^2$ ) represents the drainage pavement area, and  $Q$  ( $\text{m}^3/\text{s}$ ) represents the net flow on the surface.

$$Q = q \times S \times Z, \quad (2)$$

where  $q$  ( $\text{m}^3/\text{s}/\text{km}^2$ ) represents designed the storm intensity,  $q = 16.71i$ ,  $i$  ( $\text{m}^3/\text{s}/\text{km}^2$ ) represents the average rainfall intensity of the design return period and the rainfall duration,  $S$  represents runoff coefficient, which is 0.7 of the drainage pavement, and  $Z$  ( $\text{km}^2$ ) represents catchment area.

The internal framework image of the porous asphalt mixture is analyzed by using COSMOS software, and the random permeability model was constructed based on

Monte Carlo method. As a result, the relationship between the effective porosity and the permeability was investigated. Al-Omari et al. [16] described the irregular path of the water flow, connected voids, and the voids surface area and established the functional equation to study the voids and the permeability.

The permeability of the mixture was closely related to connected voids ratio, but the connected voids ratio of the mixture was influenced by multiple factors. Aggregates, asphalt, and gradation in large part determined connected voids ratio of the porous asphalt mixture. The current documents on the research of the connected voids were relatively inadequate, and this paper analyzed the main factors affecting the connected voids ratio and studied correlation between various factors and connected voids ratio and then established the prediction model for connected voids ratio.

The research results will contribute to the exquisite design of the porous asphalt mixture and to the improvement of the drainage, noise reduction, and the durability.

## 2. Materials and Methods

**2.1. Materials.** Natural granite was used throughout this research, which bore the characteristic of firmness, denseness, and durability, and thus can effectively play the role of the interlock denseness and help transfer the load through contact point. The properties of the aggregate used in this research are shown in Table 1.

As the property of the large voids characteristic of the porous asphalt mixture leaves the material more area exposed to the open air than that of the dense gradation, it is more susceptible to the environment. Normally, modified asphalt is employed to enhance the adhesion and the water damage resistance within the mixtures. Meanwhile, as the number of the private car is increasing, the disposal of the waste tire has been one of the significant environmental problems. It is confirmed that the powder from the waste tire could improve the property of road asphalt-70# [17, 18]. In this research, rubber powder of 40 mesh was used to modify the road asphalt-70#. The properties of the rubber powder are shown in Table 2.

Road asphalt-70#, asphalt rubber, and high-viscosity porous asphalt mixture specimens were used in this research to analyze the effect of the asphalt property on connected voids ratio of the mixtures. The rubber asphalt processing steps in this article are as follows: (1) The road asphalt-70# is heated to  $160^\circ\text{C}$  to present a fluid state. (2) The rubber powder should be weighed according to 15% of the asphalt quality, and the deviation should not be greater than 2%. The rubber powder should be slowly added to road asphalt-70# while mixing, and then the blending was continued for 45 min at a shear rate of 3000r/min. (3) After the stirring is completed, the mixture is kept at  $190^\circ\text{C}$  for about 60 min to obtain the rubber asphalt. Table 3 shows technical properties of the high-viscosity asphalt, asphalt rubber, and road asphalt-70#.

Xiao [13] improved the gradation based on the concept of frame framework stability and chose relative

TABLE 1: The performance of coarse aggregate.

Material name	Experiment items	Quality requirement	Results
Coarse aggregate	Crashed stone value (%)	≤26	18.25
	Los Angeles abrasion test value (%)	≤28	17.3
	Elongated and flaky particle content (%)	<15	10.5
	Water absorption (%)	≠2.0	Qualified
Fine aggregate	Bulk volume relative density (g/cm <sup>3</sup> )	—	2.569
	Apparent relative density (g/cm <sup>3</sup> )	≥2.6	2.655
	Apparent relative density (g/cm <sup>3</sup> )	≥2.5	2.643
	Sand equivalent (%)	≥60	65

TABLE 2: Physical and technical index of rubber powder.

Testing items	Calcium carbide content (%)	Fiber content (%)	Metal content (%)	Relative density (%)
Technical index	<3	<0.5	<0.01	1.2

TABLE 3: Technical index of modified asphalt.

Experiment item	Common asphalt	Asphalt rubber	High-viscosity asphalt
Softening point (°C)	48	66	81.8
15°C ductility(cm)	>100	12.4	>100
Penetration (0.1 mm)	66	42	43.1
Viscosity (135°C)	0.41	3.67	4.72

coarse gradation to design OGFC mixture. This paper adopted course aggregate voids filling (CAVF) method to design gradation, and the gradations are shown in Table 4. Table 5 provides the asphalt-aggregate ratio and voids ratio of mixture in this study, in which the optimum asphalt-aggregate ratio is determined by the same asphalt film.

Since there was difference in the asphalt density among different types of asphalt, the asphalt-aggregate ratio under the same gradation was a bit different.

There are Marshall specimens of different particle sizes in Figure 1. As seen in Figure 1, the surface morphology is determined by nominal maximum aggregate size, and the greater the particle size is, the coarser the gradation is and the greater the texture depth is.

**2.2. The Connected Voids.** The voids type of the porous asphalt mixture was divided into three types: connected voids, half-connected voids, and the closed voids, as is shown in Figure 2. The connected voids are effective voids which have at least two ports connected with external environment. These connected voids can not only drain off water but also absorb noise. And the half-connected voids have only one port connected with the external environment. Thus, they are incapable of draining. And the closed voids are isolated from the internal world, which leaves the mixture unable to absorb noise and drain.

Therefore, the greater the connected voids were, the better draining and noise absorption performance the mixture had. The air voids that were usually mentioned were

three types of voids. And this paper studied the influencing factors of the connected voids. The calculation equation of the connected voids ratio is as follows:

$$V' = \frac{V - V_C}{V} \times 100\%, \quad (3)$$

$$V_C = \frac{m - C}{\rho_w},$$

where  $V'$  (%) is connected voids ratio,  $V$  (cm<sup>3</sup>) is the volume of the specimen,  $V_c$  (cm<sup>3</sup>) is the volume of aggregate and the closed voids,  $m$  (g) is weight in the air of the specimen,  $C$  (g) is weight in water of the specimen, and  $\rho_w$  (g/cm<sup>3</sup>) is the density of 25°C water.

The measuring steps of the connected voids of the specimen are as follows: (1) measuring the height of the specimen and the weight in the air of the specimen, (2) submerging the specimen into water for 1 hour and obtaining the weight in water of the specimen, and (3) calculating the connected voids by this equation of the specimen.

**2.3. Equivalent Width among Framework Gaps.** The content of various gradation of aggregation influenced the internal framework of the mixture, and the gaps among the aggregate influenced volume parameter of the mixture, so it was necessary to calculate the equivalent width among framework gaps. In the two-dimensional plan in Figure 3, the distance between the filled circle and the external boundary  $L_1$  is  $L_1 = S_{\text{circle}}/l_{\text{circle}}$ , where  $S_{\text{circle}}$  represents ring area and  $l_{\text{circle}}$  represents the perimeter of the filled circle.

TABLE 4: Mixture gradation.

Gradation types	Mass percent of aggregate passing through the following sieve pores (mm) (%)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
OGFC-5	—	—	100	90	21.1	20	15.5	11.9	9.1	7
OGFC-10	—	100	84.7	22.8	15.6	12.6	9.4	6.5	5.1	4.6
OGFC-13(1)	100	87	63.7	28.3	22.1	14	10.2	7.2	5.2	4.7
OGFC-13(2)	100	87	63.7	22	19.3	14	10.2	7.2	5.2	4.7
OGFC-13(3)	100	87	63.7	22	16.5	14	9.2	6.3	4.5	4.0
OGFC-13(4)	100	87	63.7	13.2	12.3	8.4	7.0	6.3	5.0	4.0

TABLE 5: Asphalt-aggregate ratio and the voids ratio of different mixture.

Index of the mixture Asphalt types	Asphalt-aggregate ratio (%)			Voids ratio (%)		
	Asphalt mixture-70#	Asphalt rubber mixture	High-viscosity asphalt mixture	Asphalt mixture-70#	Asphalt rubber mixture	High-viscosity asphalt mixture
OGFC-5	6.25	6.3	6.35	17.7	17.5	17.9
OGFC-10	5.65	5.7	5.75	18.1	17.8	18.0
OGFC-13(1)	—	5.9	—	—	14.6	—
OGFC-13(2)	5.75	5.8	5.85	18.23	17.2	18.66
OGFC-13(3)	—	5.7	—	—	19.5	—
OGFC-13(4)	—	5.6	—	—	22.9	—



FIGURE 1: Marshall specimens.

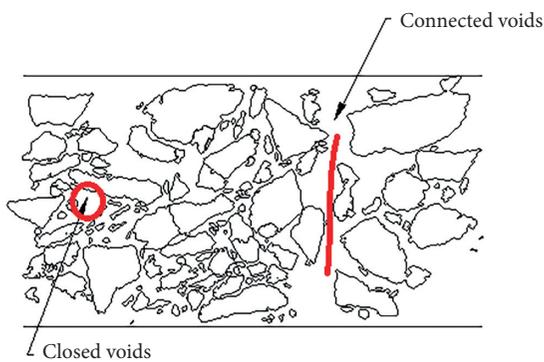


FIGURE 2: Porous asphalt mixture voids diagram.

Employing this calculation method to the two-dimensional plan of the asphalt mixture, Figure 3(b) is the binary image of the two-dimensional plan of the porous

asphalt mixture. The black area is the nonaggregate area, and the white part is the aggregate area. After calculating the perimeter and the area of the whole coarse aggregate ( $>2.36$  mm), the average distance of the coarse  $L_3$  is  $L_3 = \text{area}_{\text{not-coarse-aggregate}} / l_{\text{aggregate}}$ , where  $\text{area}_{\text{not-coarse-aggregate}}$  is the nonaggregate area and  $l_{\text{aggregate}}$  is the perimeter of the coarse aggregate. Generalizing this calculating method to the calculation of distance of the three-dimensional plan, the coarse aggregate gap width was calculated using the following equation:

$$D = \frac{\text{VCA}_{\text{DRC}} \times V}{S_{\text{AC}}}, \quad (4)$$

where  $\text{VCA}_{\text{DRC}}$  (%) is the voids in coarse aggregate calculated by rodded test,  $S_{\text{AC}}$  ( $\text{cm}^2$ ) is superficial area of coarse aggregate calculated by Chinese specification T-0309-2005 [19], and  $V$  ( $\text{cm}^3$ ) is the total volume (aggregate volume and VCA volume).

**2.4. The Calculation of the Voids in Mineral Aggregate (VMA) Based on the Voids Filling Method.** The content of the coarse aggregate was larger than that of the fine aggregate in porous asphalt mixture, and the fine aggregate had no interference on the contact within the coarse aggregate; thus, the voids in coarse aggregate (VCA) calculated by rodded test were similar to the mixtures. Voids in mineral aggregate (VMA) were calculated by the voids filling method under the condition of no molding of the specimen, and the volume of the fine aggregate was deducted from  $\text{VCA}_{\text{DRC}}$ . The equation is as follows:

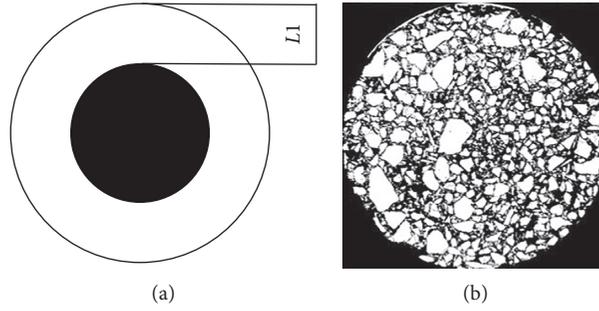


FIGURE 3: Gap width calculation schematic diagram.

$$\text{VMA} = \text{VCA}_{\text{DRC}} - \frac{(1 - \text{VCA}_{\text{DRC}}) \times \rho_c \times P_{2.36 \text{ mm}} - P_{0.075 \text{ mm}} / 1 - P_{2.36 \text{ mm}}}{\rho_f} - \frac{(1 - \text{VCA}_{\text{DRC}}) \times \rho_c \times P_{0.075 \text{ mm}} / 1 - P_{2.36 \text{ mm}}}{\rho_m} \quad (5)$$

The asphalt wrapping the surface of the coarse aggregate of the mixture had played the role of lubricating effect, enhancing compactability. A research [20] showed that a

0.5% increase in asphalt-aggregate ratio will lead to a 0.1%~2% of VMA, so the equation needs to be modified. The equation is as follows:

$$\text{VMA} = \text{VCA}_{\text{DRC}} - \frac{(1 - \text{VCA}_{\text{DRC}}) \times \rho_c \times P_{2.36 \text{ mm}} - P_{0.075 \text{ mm}} / 1 - P_{2.36 \text{ mm}}}{\rho_f} - \frac{(1 - \text{VCA}_{\text{DRC}}) \times \rho_c \times P_{0.075 \text{ mm}} / 1 - P_{2.36 \text{ mm}}}{\rho_m} - \frac{P_a}{0.5\%} \times 0.15\%, \quad (6)$$

where  $\rho_c$  ( $\text{g}/\text{cm}^3$ ) is the synthesis of density of the coarse aggregate,  $\rho_f$  ( $\text{g}/\text{cm}^3$ ) is the density of the fine aggregate,  $\rho_m$  ( $\text{g}/\text{cm}^3$ ) is the synthesis of density of the filler,  $P_{2.36 \text{ mm}}$  (%) is the passing ratio of 2.36 mm sieve,  $P_{0.075 \text{ mm}}$  (%) is the passing ratio of 0.075 mm sieve, and  $P_a$  (%) is the asphalt-aggregate ratio.

### 3. The Analysis of the Model Parameters and the Correlation

**3.1. The Parameters of the Prediction Model for the Connected Voids Ratio.** Water permeability coefficient could directly characterize the drainage capacity of the mixture. Though the calculation method of water permeability and experiment instrument and calculation method vary in different countries, causing the difference of the voids ratio, connected voids ratio, and water permeability, the general principle and tendency are consistent, which is that the water permeability increases as the voids ratio increases.

The properties of asphalt do not affect the voids ratios of the mixture, but whether the property differences of the asphalt would affect the water permeability of the mixture remains to be known. The greater the asphalt-aggregate ratio of the mixture is, the lower the voids ratio is. Liu held

that [21] under the same condition of material, gradation, and molding method, there is a linear correlation between the asphalt-aggregate ratio and the voids ratios of the mixture, and the asphalt-aggregate ratio directly influences the voids ratio and hence the water permeability. The gradation is an important part of the mixture which influences the framework within the mixture and influences the pavement performance. Generally, the change of  $P_{2.36 \text{ mm}}$  can effectively control the voids ratio of the mixture. As the nominal size and the content of the coarse aggregate increase, the voids width within the mixture increase. The VMA represents the content of gaps other than aggregates. The value of the VMA could directly influence the voids ratio. Guan [22] studied the VMA of the porous asphalt mixture and discovered that VMA is influenced by gradation, the asphalt content as well as other factors, and it is mainly influenced by gradation and established the prediction model for VMA. And results showed that the prediction value is precise, and the regression coefficient is  $R^2 = 0.9861$ . As a result, the connected voids ratio prediction model adopted asphalt quality coefficient, passing ratio of key sieve, asphalt-aggregate ratio, nominal aggregate size, the gap width of the aggregate, and VMA.

### 3.2. The Effect of Asphalt Quality on the Connected Voids.

The mechanical properties and volume parameters of asphalt mixtures are different in practical engineering because of the different density and performance of asphalt. Xu et al. [23] used three kinds of asphalt mixtures with the same gradation and different asphalt (PG70, PG76, and high-viscosity asphalt) to conduct water permeability tests. The results showed that the quality of asphalt could not affect the water permeability of the mixtures. But the three kinds of asphalt used in the research were all high-quality asphalt. The performance of asphalt might exceed the limit of affecting water permeability; in other words, the quality of asphalt outside the threshold has little effect on the water permeability of the mixtures. Therefore, the asphalt with different quality was selected to analyze the relationship between the air voids ratio and the asphalt quality in this study.

**3.2.1. Correlation Analysis of Asphalt Technical Index and Connected Voids.** It is greatly important for later research to choose an asphalt technical index that remarkably influences the connected voids. After analyzing the relations among various asphalt technical indexes, this paper chose and in the meantime considered the experiment temperature and the experiment phenomenon. Firstly, the asphalt technical indexes were normalized and the relation between asphalt technical index and connected voids is illustrated in Figure 4. Since the experiment of the ductility was conducted under different condition, this parameter mainly reflected the extension of the asphalt and had little influence on connected voids and thus will not be considered in this experiment.

The penetration experiment reflected the degree of the hardness under room temperature, which had little influence on connected voids. The softening point was the temperature at which different asphalts had the same viscosity, and because of the differences among the viscosity-temperature curve, the differences could not reflect the disparity of the viscosity under high temperatures. Therefore, the softening point cannot reflect the state of the mixture forming asphalt under high temperature. In the end, the 135°C rotation viscosity was chosen to analyze the relation between the types of the asphalt and the connected voids: (1) In the actual process of the construction, the mixture would remain in a state of heat dissipation from discharging to paving to rolling, and the temperature would apparently fall to 130°C–160°C when rolling; hence, it was suitable to choose 135°C rotation viscosity as the model parameter. (2) It was found that the mortar combined with high-viscosity asphalt and the fine aggregate under high temperature can easily form granule when using vacuum method to calculate theoretical density of different mixtures, and this granule usually contained air which cannot be dissipated easily and prevented from forming connected voids. The value of high-viscosity asphalt mixture vacuum method was below the real value and the air contained in the mucilage was difficult to diffuse, and these were the reasons for not using vacuum method for modifying asphalt mixture [24].

**3.2.2. The Relation between Asphalt Viscosity and the Connection Voids.** This experiment studied the differences of the

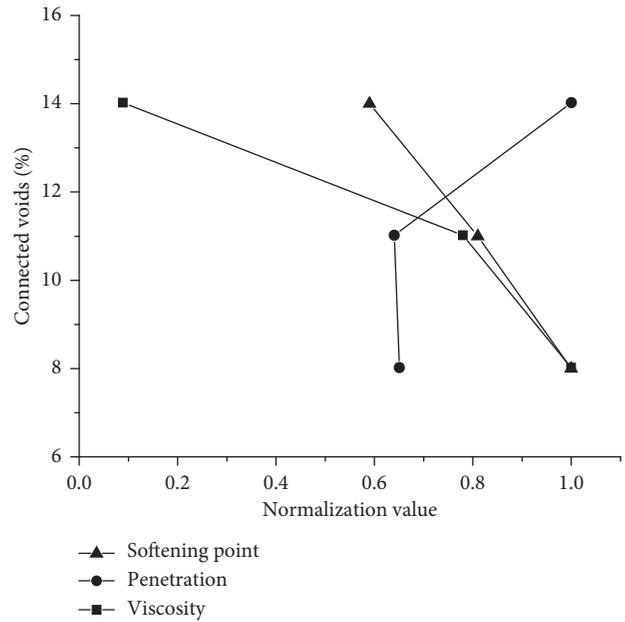


FIGURE 4: The relation between asphalt index and connected voids.

connected voids of different asphalt mixture by forming OGFC-5, OGFC-10, and OGFC-13(2) specimens, and the result is shown in Figure 5.

Figure 5 shows that when the voids ratio of the three kinds of mixtures are similar, the connected voids ratio decreases as the 135°C asphalt rotary viscosity rises. The OGFC-5 is especially influenced by the rotation viscosity, and the connected voids ratio of road asphalt mixture-70# is approximately 14% and the connected voids ratio of rubber asphalt OGFC-5 is 11%, while the connected voids ratio of high-viscosity asphalt OGFC-5 is only 8%. The connected voids of OGFC-10 and OGFC-13(2) have the same changing trend, and the connected voids ratio of the high-viscosity asphalt is the least and the connected voids ratio of the common asphalt mixture is the largest, but the asphalt properties have little effect on the connected voids ratios of the OGFC-10 and OGFC-13. It could be concluded from Figure 5 that there was a linear correlation between the asphalt viscosity and the connected voids ratio. Therefore, in the prediction model for connected voids ratio, the influence of rotation viscosity and connected voids was linear, and the influence had slight changes under different equivalent width among framework gaps.

Under high temperature, the cementing material combined by the asphalt with high viscosity and the fine aggregates can easily form granule and the air would be trapped within the granule, which would form closed voids. This is why the vacuum method was not adopted to calculate the theoretical density for the modified asphalt mixture. Asphalt with high viscosity had stronger tension and smaller liquidity and thus had better sealing effect on voids. The viscosity of the asphalt near the aggregate surface (structure asphalt) is relatively large because of the interaction between asphalt and mineral powder [25]. The permeation of free asphalt was because of low viscosity. However, free asphalt viscosity of high-viscosity asphalt is greater than that of road asphalt-70#, which reduces interaction of free asphalt. The gap between the mineral

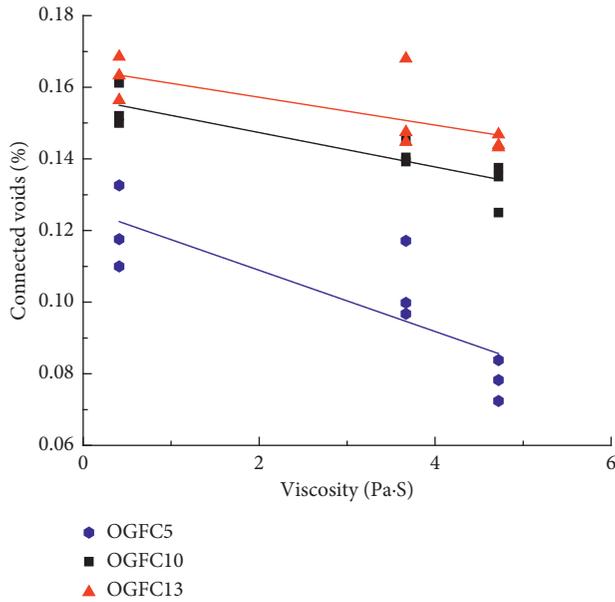


FIGURE 5: Relation between viscosity and connected voids ratio.

powder of high-viscosity asphalt mixture is larger than that of asphalt mixture-70#, and the closed void ratio in mortar granule of high-viscosity asphalt mixture is larger than that in asphalt mixture-70#. In addition, there is an existing research [26] which showed that the viscosity of rubber asphalt is related to the tire used by rubber powder. Whether the rubber powder from different sources affects the connected voids ratio of the porous asphalt mixture remains to be studied.

**3.3. The Effect of Equivalent Width among Framework Gaps on the Connected Voids.** The differences of the nominal diameter and gradation of the porous asphalt mixture resulted in the differences of equivalent width among framework gaps and hence the differences of the connected voids ratio. This paper studied the connected voids ratio of the asphalt rubber mixture of OGFC-5, OGFC-10, and OGFC-13(2) with the same voids ratio and concluded that the larger the nominal diameter was, the bigger the equivalent width would be and the larger the connected voids ratio would be. The experiment result is shown in Figure 6. Mixture equivalent width was predicted by equation (6). The equivalent width of OGFC-5, OGFC-10, and OGFC-13(2) is illustrated in Table 6, and it can be seen that OGFC-5 has the smallest equivalent width and the equivalent width of OGFC-10 was larger than OGFC-5 and smaller than OGFC-13. Framework voids consist of voids and asphalt, and equivalent width would influence the characteristic of the voids of the mixture.

From Figure 6, it can be seen that when the voids ratio is approximate of all gradations of porous asphalt mixtures, the connected voids ratios increase as equivalent width rises. A slight increase in the equivalent width can be seen between OGFC-10 and OGFC-13, and there is not much difference between them in terms of connected voids ratio. While the equivalent width sees a remarkable increase from OGFC-5 to OGFC-10, the growth of the connected voids is most

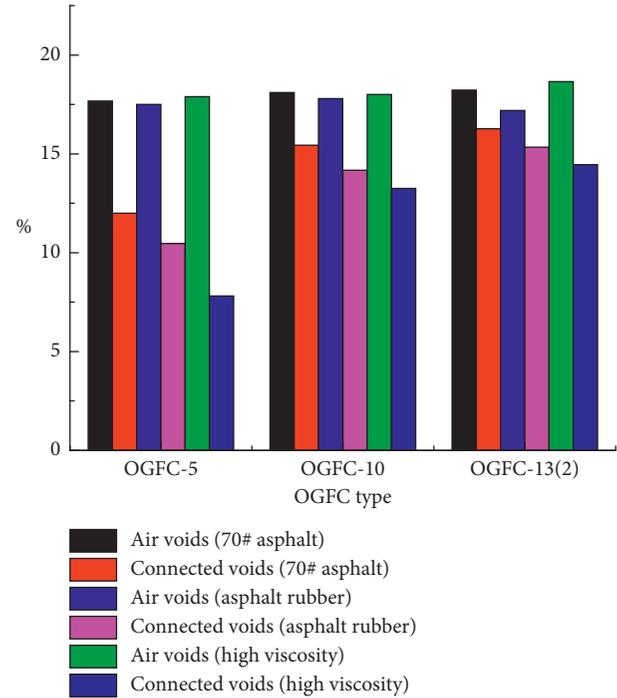


FIGURE 6: Voids ratio and connected voids ratio of different nominal maximum aggregate sizes.

TABLE 6: The framework voids width of the mixture.

Gradation	OGFC-13	OGFC-10	OGFC-5
VCA <sub>DRC</sub> (%)	42.7	39.7	42.0
D (cm)	0.0074	0.0070	0.0048

conspicuous between the high-viscosity asphalt mixture of OGFC-5 and OGFC-10 about 5.5%, and the growth of the rubber asphalt mixture and road asphalt mixture-70# is, respectively, 3.7% and 1.1%. The result showed that coarse aggregates with larger nominal size had larger equivalent width which the asphalt cannot enclose. The framework of the specimen OGFC-5 is made of aggregates from 2.36 mm to 4.75 mm, and the equivalent width of the specimen is smaller than the equivalent width of the OGFC-10 and OGFC-13. The equivalent width of OGFC-5 is easily filled up and forms closed voids.

**3.4. The Influence of the Passing Rate of the Key Sieve on the Connected Voids.** Tang [27] made a regression analysis on the experiment data of the mixture with a variety of gradations to select variables for voids ratio, and the results showed that  $P_{2.36\text{ mm}}$  plays a decisive role on the mixtures voids ratio; thus, this paper chose 2.36 mm sieve as the dividing sieve to define fine aggregate and coarse aggregate. As the voids ratio of the OGFC-13 asphalt mixture increased, the connected voids ratio increased. When the  $P_{2.36\text{ mm}}$  was increased, the content of the fine and the coarse aggregates changed, and the proportion of the fine aggregate increased, so the mortar volume increased. At this time, the

mortar would wrap and adhere to the surface of the coarse aggregate and fill in the framework voids. Therefore, the voids ratio would decrease with the increase of  $P_{2.36\text{mm}}$ . The relationship between  $P_{2.36\text{mm}}$  and voids ratio and connected voids ratio is, respectively, shown in Figure 7.

The  $P_{2.36\text{mm}}$  had good correlation with both voids ratio and connected voids ratio. The relation between the passing rate of the key sieve and the voids ratio can be expressed as follows:

$$\begin{aligned} V_V &= -0.840 \times P_{2.36\text{mm}} + 0.0878, & R^2 &= 0.892, \\ V' &= -0.886 \times P_{2.36\text{mm}} + 0.103, & R^2 &= 0.892, \end{aligned} \quad (7)$$

where  $V_V$  (%) is the voids ratio.

It can be seen that the slope of the equation is different, which means that as the voids ratio decreases the differential value between voids ratio and the connected voids ratio increases. And with the increase of the mortar, it is easier for the mortar and the aggregates to form closed voids. Therefore, when  $P_{2.36\text{mm}}$  rises, the closed voids would expand and the differential value between the voids ratio and connected voids ratio would increase.

**3.5. The Correlation between the VMA and the Connected Voids Ratio.** The parameter VMA can partly restrict the voids ratio. Guan et al. [22] found that the bigger the content of the aggregate of the mixture gradation is, the bigger the VMA is, and under certain gradation the compressed mixture is denser when more asphalt was contained in the mixture, and the VMA is relatively small. There was correlation between voids ratio and the VMA, and it is shown in Figure 8. Therefore, when predicting the voids ratio and the connected voids ratio, VMA should not be omitted.

It can be seen from Figure 8 that VMA is partly correlated to the voids ratio and connected voids ratio, and their relationship can be expressed as

$$\begin{aligned} V_V &= 1.118 \times \text{VMA} - 0.125, & R^2 &= 0.89, \\ V' &= 1.165 \times \text{VMA} - 0.169, & R^2 &= 0.845. \end{aligned} \quad (8)$$

The voids ratio was the residual volume after the VMA filling the asphalt, and connected voids ratio is obtained by excluding the closed voids from the voids. Thus, VMA had relatively good correlation with both voids ratio and connected voids ratio.

## 4. The Establishment of the Prediction Model

**4.1. The Prediction Model.** In the prediction model, the dependent variable was connected voids ratio  $V'$  and independent variable is  $P_{2.36\text{mm}}$ , VMA,  $G$  (equivalent width among framework gaps), and  $N$  (135°C rotation viscosity). The regression model was established, and the general expression is as follows:

$$V' = \beta_1 \text{VMA} - \beta_2 P_{2.36} - \beta_3 P_a - \beta_4 G - \beta_5 N - \beta_6, \quad (9)$$

where  $G$  (cm) is equivalent width among framework gaps and  $N$  (Pa·s) is asphalt rotation viscosity.

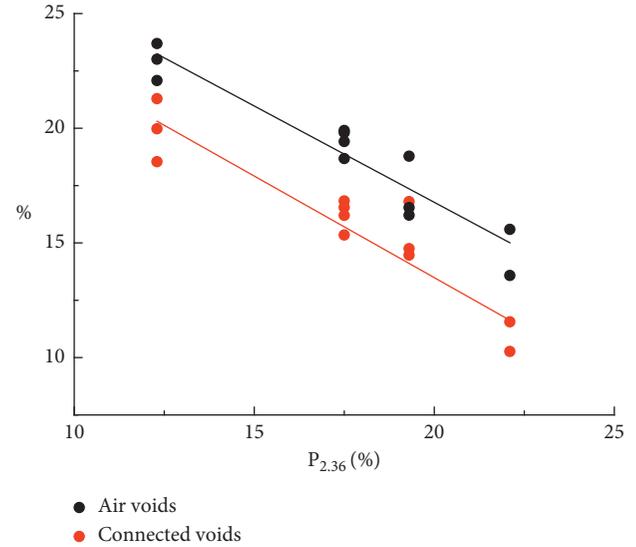


FIGURE 7: The relationship between passing rate of 2.36 mm screen hole and voids percent and connected voids percent, respectively.

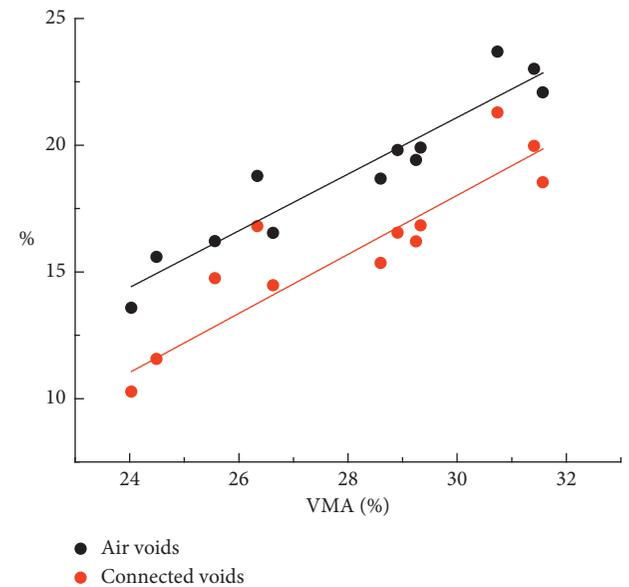


FIGURE 8: The correlation between VMA and voids fraction and connected voids fraction.

TABLE 7: Model goodness-of-fit test.

Model	$R$	$R^2$	Adjustment $R^2$	Standard error
1	0.955	0.912	0.887	0.01276

The prediction model for the connected voids ratio is as follows:

$$\begin{aligned} V' &= 0.871 \text{VMA} - 0.184 P_{2.36} + 2.483 P_a + 0.041 G \\ &\quad - 0.011 N - 0.291. \end{aligned} \quad (10)$$

**4.2. The Verification of the Prediction Model.** The voids ratio of the porous asphalt mixture and the connected voids ratio

TABLE 8: Variance analysis.

Model	Sum of squares	Degree of freedom	Mean square	F
Regression	0.30	5	0.006	37.099
Residual error	0.03	18	0.00	—
Summary	0.33	23	—	—

TABLE 9: Verification gradation.

Gradation types	The quality percentage of passing the screen hole (square screen hole, mm) (%)										Asphalt-aggregate ratio (%)
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Gradation 1	100	95	70	15	13	13	9	7	5	4	4.4
Gradation 2	100	88.9	70.5	18.9	15.2	11.5	8.5	6.4	5	4.6	5.5
Gradation 3	100	86.3	63.7	23.7	20.3	13.9	10.5	7.4	5.2	4.7	6
Gradation 4	100	95	74	23	15	12	9	6.5	5	4.5	5
Gradation 5	100	92	64.3	11.4	4.8	4.3	3.8	3.3	2.8	2.3	3.5

TABLE 10: Predictive valuation test.

Gradation number	Actual value (%)	Prediction value (%)	Deviation rate (%)
1	17.20	18.13	-5.39
2	17.20	16.94	1.51
3	12.40	13.44	-8.37
4	17.60	19.37	-10.06
5	20.80	24.76	-19.04

were influenced by many factors. Therefore, firstly, the fitting degree of the prediction model is checked and the model is further verified through formed specimen.

**4.2.1. The Analysis of the Fitting Degree.** The verification of the fitting degree and variance analysis are shown in Tables 7 and 8.

Model regression coefficient  $R^2 = 0.912$  meant that, in the variation of dependent variable of the connected voids ratio, the percentage of connected voids ratio which can be predicted by the multiregression equation of VMA,  $P_{2.36\text{ mm}}$ , Pa, G, and N is 91.20%. The predicted standard error was 0.01276, which was the average error of the dependent variable. The statistics of the significance test F was 37.099 and according to the molecular freedom degree 5 and the denominator freedom degree 18, and the result is shown in Table 8:  $F: Fa = 0.05 (5,18) = 2.77$ . Since 37.099 is bigger than 2.77, it was concluded that VMA,  $P_{2.36\text{ mm}}$ , Pa, G, and N were closely connected with the connected voids ratio.

**4.2.2. The Verification of the Prediction Model.** This paper chose 1–3 gradation in Table 9 to form Marshall specimens with high-viscosity asphalt, and the asphalt-aggregate ratios were 4.4%, 5.5%, and 6%, respectively, and the gradations 4 and 5 adopted road asphalt-70# to form Marshall specimens, and the asphalt-aggregation ratio was 5% and 3.5%, respectively. The connected voids ratio of various specimens was tested, and the actual value and the prediction value were compared. The calculation of VMA was based on equation (7).

According to Table 10, it can be concluded that except gradation 5, the deviation rate between actual value and the prediction value fell under 10%, and this meant that the prediction model was of high accuracy.

The reason that disparity between actual value and prediction value of gradation 5 was relatively large was that the data specimen did not choose gradation under 12% when the model parameter  $P_{2.36\text{ mm}}$  was determined. The limitation of the fitting specimen restrained the prediction range of the model.

## 5. Conclusion

This paper established the prediction model for connected voids ratio by analyzing various factors that affected the connected voids ratio of the asphalt mixture. The main conclusions of this paper are stated as follows.

The differences of the gradations and the qualities of the asphalt caused the differences of the connected voids ratio in specimens. The result showed that the connected voids ratio decreased the specimen with the same voids ratio as the 135°C rotation viscosity increased, and the asphalt rotation viscosity had remarkable effect on the connected voids ratio of OGFC-5. The voids ratio of asphalt mixture-70#, asphalt rubber mixture, and high-viscosity asphalt mixture of OGFC-5 was around 17%, and the connected voids ratios were 14%, 11%, and 8%. Asphalt rotation viscosity had less influence on the connected voids ratios of OGFC-10 and OGFC-13.

The connected voids ratio as well as the equivalent width increased as the maximum nominal size of the mixture rose. When the increase amplitude of the equivalent width among

framework gaps gradually decreased, the connected voids increase amplitude gradually fell as well. From OGFC-5 to OGFC-10, the increase amplitude of the connected voids ratio was most conspicuous and the connected voids ratio from OGFC-10 to OGFC-13 was less obvious.

VMA had good correlation with voids ratio and connected voids ratio. VMA,  $P_{2.36\text{mm}}$ ,  $P_a$ ,  $G$ , and  $N$  were selected as model parameters to establish the connected voids ratio prediction model. The model was validated by laboratory experiments, and the result showed that the model with reasonable parameters had a high degree of applicability. Despite the omission of the specimen of  $P_{2.36\text{mm}}$  under 12%, the prediction model remained to be modified.

This paper illustrated that the properties of the raw materials had in part influence on the connected voids ratio of porous asphalt, and the design of the drainage pavement should consider both the mechanical properties and the functional properties to choose the materials. It is worth noting that the prediction model for connected voids ratio was based on the volume parameter of Marshall specimen, and there was difference in the actual drainage pavement volume parameter; thus later research should compare the difference and modify the model. This prediction model aims to predict the connected voids ratio in the design stage to reduce the workload of experiment and shorten the period of mix proportion. Thus, the prediction model for connected voids ratio is of great importance to improve the efficiency of construction.

## 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 regarding its publication.

## Authors' Contributions

Xiang Li was responsible for methodology, investigation, data curation, and writing and preparation of the original draft. Zhaoyi He was responsible for resources, project administration, and writing, reviewing, and editing of the paper.

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