Mechanism of Aggregate Gradation Affecting Interconnected Porosity of Semi Flexible Asphalt Pavement

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Abstract. Semi-flexible pavement(SFP) can effectively refine rutting problem of asphalt pavements with the combining of rigidity and flexibility simultaneously. This study focuses on interconnected porosity rate(IPR), a key indicator to control engineering quality of semi-flexible pavement, and investigates mechanism of aggregates gradation (AG) affecting IPR. Based on the SFAC-20 AG range specified in Beijing local regulation DB11/T 1817, five different AG curves were selected. Among them, Gradation Curve I(GCI) locates at the median, Gradation Curve II(GCII) is close to the upper limit, Gradation Curve III(GCIII) is close to the lower limit, Gradation Curve IV(GCIV)has coarse materials near the upper limit and fine materials near the lower limit forming an inverted S-shape, and Gradation Curve V (GCV) has coarse materials near the lower limit and fine materials near the upper limit forming a regular S-shape. By the aid of the device independently developed for measuring IPR, aggregates characteristics value K_V and *IPR* of asphalt Marshall specimens of five different AG mixtures were compared. It was found that K_V of gradation aggregates directly affects *IPR* of asphalt mixture, and the two are linearly correlated. With the help of this research conclusion, it is possible to predict *IPR* of asphalt mixture for semi-flexible pavements , based solely on the K_V of gradation aggregates, without adding asphalt and forming asphalt Marshall specimens in advance.

Keywords: Semi flexible Pavement; Interconnected Porosity rate; Aggregate Gradation; Characteristic Value

1 Foreword

Semi-flexible pavement material is a specially designed asphalt concrete with a large IPR (20% to 35%)[1]. During construction, cement slurry is injected after laying asphalt mixture, and composite material's skeleton strength is formed by jointly interlocking action of coarse aggregates and cement slurry in interconnected porosity

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of asphalt mixture. SFP is believed to have high capacity and great potential to reduce permanent deformation under high temperature and heavy traffic loads.

SFP originated from application on Cognac airport runway in France in 1954, has subsequently been used in many countries since then. The IPR of asphalt mixture is the space for cement slurry infiltration. The size and connectivity of IPR are important factors affecting overall strength of SFP material. A. Setyawan[1] found that strength of SFP material is mainly influenced by strength of cement slurry through experiments, and the whole strength of SFP material is about 11% of the cement slurry strength used. Suhana Koting[2] found that when void ratio of asphalt mixture is less than 25%, it is difficult for cement slurry to completely fill in asphalt skeleton. And when void ratio is higher than 30%, SFP composite material will lose the necessary flexibility characteristics.Then void ratio is suggested to be designed between 25% and 30%. Tao Xu[3], through micro-morphological analysis and grouting experiments, proposed that IPR more affects asphalt infiltration rate, rather than the initial void ratio. And appropriately increasing coarse aggregates content of AG can improve filling effect of cement slurry in asphalt skeleton.

Interference method and volume method are commonly used techniques for designing AG of SFP materials. The interference method[4,5] utilizes a discontinuous gradation to ensure coarse aggregates interlocking each other, and achieve maximum compaction and stable skeleton gradation. The volume method[6-11], also known as Course Aggregate Void Filling Method, is another approach for designing AG of porous asphalt mixtures. Initially, aggregate skeleton gradation is designed based on experience or Taylor's formula, and void ratio of main skeleton is measured. Then, it is assumed that the volume of asphalt, along with the volume of fine aggregates and mineral powder, plus the designed target void volume, equals the void volume of main skeleton. This helps to determine the quantities of asphalt, fine aggregates, and mineral powder. Chong Huang[12] first clearly proposed concept and calculation method of IPR and found that when the designed void ratio of asphalt mixture is 25% to 33%, the IPR reaches 22-28%, with the mineral decisive size affecting the void ratio being 4.75mm. Xiangfeng Chen[13], referring to Japanese standards, used a single grain size of coarse aggregates ranging from 9.5 to 13.2 mm, and the maximum grain size of fine aggregates is 2.36 mm. The designed void ratio for SFP asphalt mixture is 20% to 28%, and the stability of the Marshall specimen decreases as the target void ratio increases. Jianguo Wei[10] studied the law of power index in Taylor's formula affecting skeleton void ratio, and found that the main skeleton void ratio is the smallest when power index is in the range of 0.5 to 0.6.

According to Road Engineering Association of Malaysia (REAM) [14], it is essential that porous asphalt skeleton achieved a certain percentage of air voids content (25-30%) in order to allow fluid grout ease penetration. The desired voids in asphalt mixture are essential for producing SRP as it will enhance ease filling voids by fluid grout via gravitational force without the aid of vibration. Vibrating compaction may damage structure of porous asphalt mixture due to high percentage of air voids.

In order to achieve appropriate IPR, many countries have developed their own AG curves for aggregate mix design when using SFP. Fig.1[14] shows three different AGs

(G1,G2, and G3) ranging from the most porous to the least porous respectively, which was referred by Nadiah from Malaysia.These three were chosen for the purpose of producing porous asphalt mixture in order to determine significant differences towards properties of SFP. Fig.2[15] provided more AG curves used by researches from many countries. Research from both domestic and international sources indicates that IPR is a key indicator for the injection of cement slurry and an important factor affecting the overall strength of semi-flexible pavements. At the same time, it is evident from the gradation curves of semi-flexible pavements in various countries that they all share a similar characteristic: there is a significant change in the gradation curve between 13.2 and 9.75 mm, where the percentage of aggregate passing drops sharply. The curve of the percentage passing for particles smaller than 9.75 mm is relatively flat. To further explore the special characteristics of such gradation curves and their intrinsic relationship with IPR of parent asphalt mixture, this study conducts a series of experiments and data analysis to investigate this issue.

2 Objective and methodology

This research aims to explore the correlation between AG and IPR. Five AG curves with different characteristics from SFAC-20 used in China were chosen and mixed with certain binder contents which are decided according to Schellenberg binder drainage test and Cantabro loss test. After molding Marshall specimens, AG and IPR of five different mixes were tested and calculated, and the correlation was established between these two parameters. And then, according to the established correlation, a fast and easy judging methodology was developed to identify *IPR* of different mixes within the SFAC gradation scope. This method make it easy to test *IPR* of asphalt mixture specimens, which just need sieve gradation aggregates and calculate K_V based on sieving results, without need of adding asphalt and preparing specimens.The flow chart of the methodology is shown in Fig. 3 for reference.

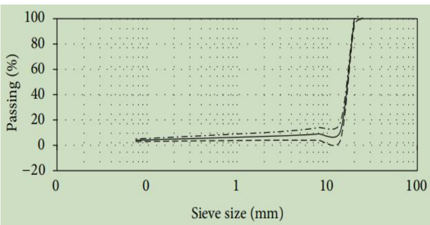

Fig. 1. Aggregate gradations for porous mix[14]

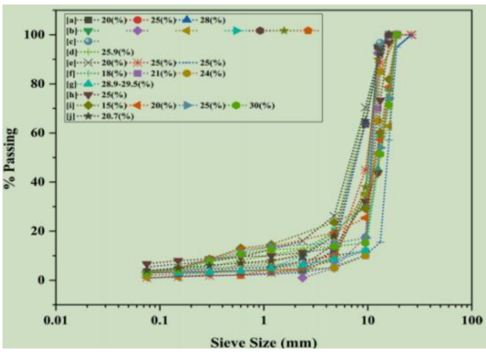

Fig. 2. Aggregate gradation for different air voids[15]

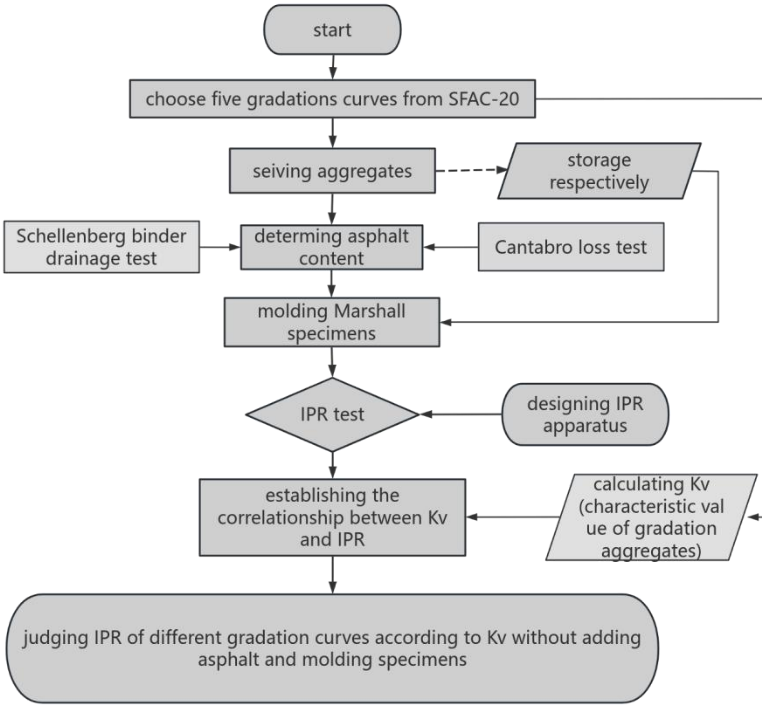

Fig. 3. Flow chat for methodology

3 Materials

Ordinary limestone aggregates and SBS asphalt, whose indicators meet the needs of SFP materials, were chosen for the study. Because only investigating the correlation between IPR and characteristic of different gradation mixes, the other conventional engineering indicators usually tested for these two materials, asphalt and aggregates, were omitted except from aggregates sieving tests.

4 Experiment

4.1 Choosing aggregate gradation curves

According to the local standard of Beijing "Design and Construction Technical Specifications for Injected Semi-Flexible Pavement"(DB11/T 1817-2021), SFAC-20 is taken as an example for this research . This study selects five specific gradation curves within this range to study the impact of mineral gradation on IPR, as shown in Fig. 4. It can be seen intuitively that GCI is at the median, GCII is close to the upper limit, GCIII is close to the lower limit, GCIV has coarse materials near the upper limit and fine materials near the lower limit forming an inverted S-shape, and GCV has coarse materials near the lower limit and fine materials near the upper limit forming a regular S-shape.

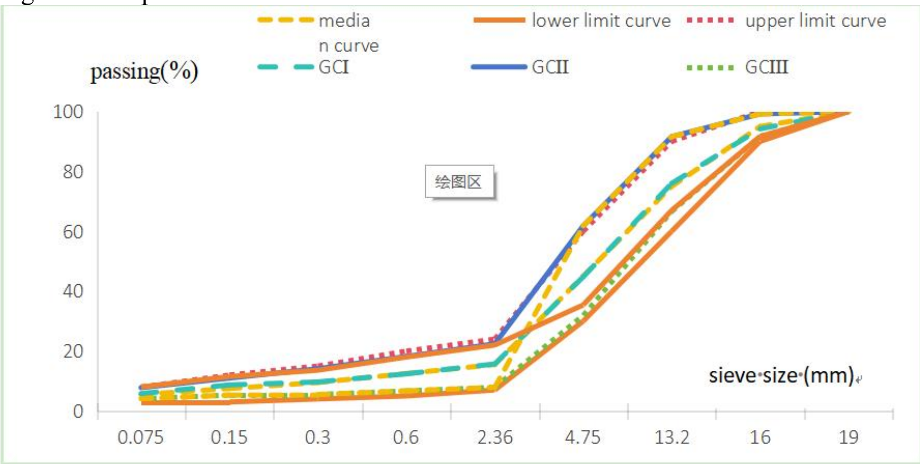

Fig. 4. Five AG curves at the range of SFAC-20 (from local standard of Beijing)

4.2 Sieving aggregates

To simplify experimental process and easily obtain the amount of gradation aggregates, aggregates are sieved according to the corresponding sieve size of SFAC-20, with sieve aperture sizes of 0.075mm, 0.15mm, 0.3mm, 0.6mm, 2.36mm, 4.75mm, 13.2mm, 16mm, 19mm, and 26.5mm. The sieved aggregates on each sieve were stored in piles separately for use.

4.3 Formulating aggregate mixtures

Calculating the amount of aggregates for each sieve size based on the passing percentage of each gradation curve. Then, according to the amount of aggregate mixture content required for preparation of Marshall specimens, determine the total amount of aggregates for each sieve size.

4.4 Defining asphalt content

Schellenberg asphalt drainage test. The Shellenberger asphalt drainage test is used to detect the amount of free asphalt that bleeds out of porous asphalt mixtures at high temperatures, with a qualified standard of less than 0.3%. The test is used to determine the maximum amount of asphalt for SFP. In this study, the asphalt mixes, corresponding to five different AG, were prepared using varying binder contents from 2.9 to 3.3%(2.9, 3.1, 3.3) by weight of the mix. Three mixes were prepared for each binder content for all the asphalt mixes. The asphalt content range was decided by engineering experience. Mathematically drainage rate is calculated as the percentage of binder by weight of the asphalt mixture which kept in an oven at 185℃ for 4 h. This was the first test to act as the selection criteria for asphalt content. The asphalt content 3.2% satisfying the criteria of less than 0.3% drainage rate was selected for further tests to be conducted.

Cantabro loss test. The Cantabro loss value is used to determine the minimum amount of asphalt required.When the asphalt content is too low, it will result in insufficient binding of the mixture and lead to the loss of aggregate from the road surface under the action of traffic loads. According to Shellenberger Asphalt drainage rate test result 3.2%, asphalt contents from 2.8 to 3.2%(2.8, 3.0, 3.2) by weight of the mix were decided. Modeling Marshall specimens and making them being rotated and impacted a specified number of times in the Los Angeles abrasion testing machine, and the percentage of the mass of the material that is lost from the specimen is measured. An abrasion loss of less than 20% is considered to be a qualified amount of asphalt.

Determining asphalt content. According to the Shellenberger Asphalt drainage Test and the Cantabro loss Test, asphalt contents for five different gradation mixtures from GCI to GCV finally were determined as 2.9%, 2.9%, 2.85%, 2.9%, 2.85% separately. To reduce impact of asphalt content on IPR, It is recommended to use a smaller value that simultaneously satisfies Shellenberger asphalt drainage value and Cantabro loss value, with the Cantabro loss controlled around 18% - 20%.

4.5 IPR test

This study independently developed a device for measuring IPR of asphalt mixture specimens, the main components of which are a cylindrical container with a diameter of D_1 and a fine graduated glass tube with a diameter of D_2 forming a communicator, shown as Fig.5. When using it, put enough water at room temperature into the container, and after the water level is still, read the height of the communicator through the fine graduate scale tube as h_1. Then, gently place a Marshall specimen into the container, ensuring that the specimen is fully immersed, and after the water level is still, read the water level height of the communicator at this time as h_2. According to Archimedes' principle, when an object sinks into the water, the volume of water it displaces is the volume of the object itself. By using the formula(1) , the volume V_1 of the solid part and the closed porosity part of the specimen can be calculated.

$$V_1 = \frac{\pi \, (D_1^2 + D_2^2) \times (h_2 - h_1)}{4} \quad (1)$$

Finally, IPR can be calculated by the formula (2).

$$IPR = \frac{V - V_1}{V} \times 100\% \quad (2)$$

Among it ,

$$V = \frac{\pi D^2}{4} \times H \quad (3)$$

D——diameter of Marshall specimens(mm);

H——height of Marshall specimens(mm).

The equipment is simple and easy to operate, reducing errors in test process. It is very convenient to calculating V_1 using formula and determining *IPR* based on the volume V of standard specimen.The IPR test results of Marshall specimens of asphalt mixtures made from five different gradation mixtures are shown in the last column of Table 1.

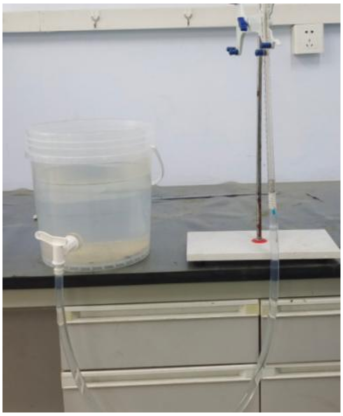

Fig. 5. Photo of IPR apparatus.

Table 1. IPR of five gradation asphalt mixture

Types of AG	Specimen number	Height of specimen (mm)	Volume of specimen (mm^3)	water level before placing specimen (h_1)	Water level after placing specimen (h_2)	Calculating volume of displaced water by specimen (mm^3)	Calculating *IRP*(%)	
I	1	89.83	1639	3.3	5.17	1320	19.4	19.25
	2	90.1	1644	3.1	4.98	1330	19.1	
II	1	104.2	1900	3.3	5.51	1560	17.9	17.75
	2	104.4	1905	3.1	5.32	1570	17.6	
III	1	98.19	1791	3.1	4.9	1270	29.1	28.65
	2	90.03	1642	3.2	4.87	1180	28.2	
IV	1	93.22	1701	6.4	8.13	1240	27.1	26.65
	2	90.68	1654	6.2	7.95	1220	26.2	
V	1	95.42	1741	4.8	6.74	1370	21.3	21.4
	2	97.03	1770	5.6	7.57	1390	21.5	

5 Results analysis

Characteristic value *Kv* of each gradation type is calculated, which is the ratio of the volume of small particle part to the volume of large particle part in the mixture, amplified by 10,000 times. The specific calculation process is shown in Table 2.

In this methodology, sieve size d_i represents particle size, the cube of sieve size d_i^3 represents the particle volume V_E, the residue percentage on each size a_i represents the amount of particles on each sieve, and the product of particle volume V_E and quantity a_i represents the total volume of particles on each sieve.

Summing the total volume of particles for each sieve with a particle size greater than or equal to 4.75 mm, and also summing the total volume of particles for each sieve with a particle size less than or equal to 2.36 mm. Calculating the ratio of the total volume of the small particle size fraction to that of the large particle size fraction, and then multiplying this ratio by 10,000. The resulting value is AG characteristic value K_V.

Table 2. Calculating AG characteristic value *Kv*

di(mm)	26.5	19	16	13.2	4.75	2.36	0.6	0.3	0.15	0.075
ai(%)	0	5.8	18.2	31.2	29.1	3.3	2.7	1	2.9	3.1
V_E	0	39782.2	74547.2	71759.0016	3118.701563	43.3760448	0.5832	0.027	0.0097875	0.001307813
$\sum V_E$			189207.1032					43.99734011		
Kv					(43.99734011/189207.1032) *10000=5.14					

Note: *di*--seive size(mm); a_i--sieve residue percentage; V_E--equivalent volume, V_E=di^3×ai; $\sum V_E$--Total equivalent volume.

Correlation between *IPR* and *Kv*. Measuring and calculating K_V*s* and *IPRs* of five AG asphalt mixtures separately, and then a regression analysis between K_V*s* and *IPR*s is performed, as shown in Fig.6. The correlationship formulae between the two is: $IPR = -2.4867K_V + 28.494$, with a regression coefficient square is 0.87.The larger the K_V value is, the smaller the connected porosity rate is. Using this predictive method, the size of *IPR* can be preliminarily determined at the stage of mineral mixture, without waiting until the asphalt is added and the specimen is formed for measurement.

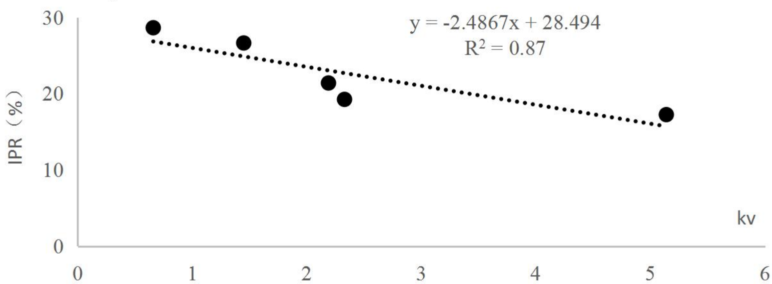

Fig. 6. Correlation between *IPR* and *Kv*

6 Conclusions

Based on extensively reviewing of literature related to IPR of semi flexible pavements, this paper focuses on the characteristics of gradation aggregates and investigates the relationship between the characteristics value of gradation aggregates and IPR. The results confirm that there is a strong correlation between K_V of the gradation aggregate and *IPR*. It is possible to calculate the K_V value solely based on the results of the aggregate screening test, and then preliminarily determine the size of *IPR* of SFP material through the established $K_V \sim IPR$ relationship curve.It is important to realize that the methodology proposed in this paper has been streamlined the process for determining IPR. In the new evaluation system, there is no need to determine asphalt content through Schlumberger draingage test and Cantabro loss test, nor is there a need to mix asphalt mixture and prepare Marshall specimens.

Referrence

1. Setyawan A. Design and properties of hot mixture porous asphalt for semi-flexible pavement applications. https://core.ac.uk/download/pdf/12345925.pdf, last accessed 2024/06/30.
2. Koting S, Karim M R, Mahmud H B, et al. Mechanical propeties of cement-bitumen composites for semi-flexible pavement surfacing[J]. Baltic Journal of Road & Bridge Engineering, 2014, 9(2): 191-199.
3. Tao Xu, Shuguang Hou, Kai Huang. Aggregate Gradation Influence on Grouting Results and Mix Design of Asphalt Mixture Skeleton for Semi-Flexible Pavement. Journal of testing and evaluation. Mar 2017, 45(2): 591-600. https://doi.org/10.1520/JTE201501901.
4. Kan Li. Research on the Applicability of Semi-Flexible Materials as Anti-Rutting Functional Layer for Asphalt Pavements[D]. South China University of Technology, 2016.10.
5. Zenghuang Yu. Research on the Pavement Structure and Road Performance of Semi-Flexible Asphalt Mixture[D]. Hunan University, 2007.04.
6. Yingying Dong.: Research on design parameters and construction techniques of high performance semi-flexible pavement[D]. Chongqing: Chongqing Jiaotong University, 2008.03.
7. Yang Zhang. Research on design and shrinkage characteristics of semi-flexible pavement materials. Southeast University[D]. 2018,03
8. Dalin Pan, Xiaoning Zhang. Design methods for asphalt mixture of semi-flexible pavement matrix [J]. Highway Engineering, 2000,25(1):22-23
9. Lei Cheng. Research on the performance and design methods of mixture for semi-flexible pavement [D]. Chang'an University, 2002
10. Jianguo Wei, Xudong Zha, Jianlong Zheng, et al. Relative proportion of asphalt coarse aggregate [J]. Journal of Chang'an University (Natural Science Edition).2008, 28(2):13-17.
11. Lingling Hu, Zuguo Liu, Dake Zhang, et al. Design method for asphalt mixture of semi-flexible composite pavement matrix.
12. Chong Huang. Research on volume stability and crack resistance of semi-flexible pavement materials[D]. Wuhan University of Technology, 2010.
13. Xiangfeng Chen. Study on the mix design of high-performance liquid cement grouting

materials and performance for semi-flexible pavement [D]. Xi'an:Chang'an University, 2010: 65-67.
14. Nadiah Md. Husain, Mohamed Rehan Karim, Hilmi B. Mahmud, and Suhana Koting. Effects of Aggregate Gradation on the Physical Properties of Semi flexible pavement. Hindawi Publishing Corporation Advances in Materials Science and Engineering. Homepage, http://dx.doi.org/10.1155/2014/529305, last accessed 2024/06/01.
15. Mohammad Shahid Raza, Shashi Kant Sharma. A review of mechanical and durability properties and microstructure of semi- fexible pavement.Innovative Infrastructure Solutions. Homepage, https://doi.org/10.1007/s41062-024-01393-w, last accessed 2024/06/01.