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Abstract: Porous asphalt mixture can be used as a road surface paving material with the remarkable advantage to prevent water accumulation and ponding. However, the performance of porous asphalt mixture in low temperature environment has not been thoroughly investigated, and this forms the subject of research in the present study. The mineral aggregate gradation of porous asphalt mixture was designed based on Bailey method, and the low temperature performance of porous asphalt mixture was studied by means of the low temperature bending test. The factors affecting the low temperature performance of porous asphalt mixture were analyzed through the orthogonal experimental design method, and the effects of porosity, modifier content, aging condition, and test temperature on the low temperature performance of porous asphalt mixture were evaluated. The results showed that the modifier content was the most important factor affecting the low temperature performance of porous asphalt mixture, followed by the test temperature, while the porosity and the aging condition were the least. Among the three performance evaluation indicators, namely the flexural tensile strength, maximum bending strain, and bending stiffness modulus, the maximum bending strain had the highest sensitivity to the porosity. It can be seen from the single factor influence test of porosity that there existed an approximately linear relationship between the maximum bending strain and the porosity of porous asphalt mixture, and the maximum bending strain decreased with increasing porosity. Furthermore, in order to ensure the good working performance of porous asphalt mixture in low temperature environment, the porosity should also satisfy the required limits of the maximum bending strain.

**Keywords:** pavement; porous asphalt mixture; low temperature performance; orthogonal experimental design; porosity

### 1. Introduction

The existence of water film on road surface in rainy weather affects the effective contact between the tire of vehicle and the road surface. When the water film on road surface reaches a certain thickness, the braking distance of the vehicle will increase, and skid resistance of tires will decrease. These might cause drift of the vehicle and possibly endanger road-users' safety. Moreover, problems such as splashing water, water mist, and night glare caused by the discharge of water from road surface also adversely affect driving safety. The porous asphalt pavement is a surface layer paved with open-grade asphalt with interconnected gaps, and an impervious bonding layer is constructed underneath the surface layer [1]. In rainy weather, the rainwater infiltrates downwards through the porous surface layer, arrives at the surface of the impervious layer and then drains from the side



Citation: Wang, J.; Ng, P.-L.; Gong, Y.; Su, H.; Du, J. Experimental Study of Low Temperature Performance of Porous Asphalt Mixture. *Appl. Sci.* **2021**, *11*, 4029. https://doi.org/ 10.3390/app11094029

Academic Editor: Amir Tabakovic

Received: 27 March 2021 Accepted: 25 April 2021 Published: 28 April 2021

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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). along the edge of the pavement [2]. Moreover, due to the macro-texture of the surface, a higher skid resistance can be obtained for porous asphalt mixture when compared to other surface layer materials [3]. Therefore, the use of porous asphalt pavement is a method to effectively prevent the accumulation and ponding of water on road surface [4,5], which has been conceived and adopted in numerous countries including France, Germany, Spain, United Kingdom, New Zealand, Japan and the United States [6–12].

Porous asphalt is a composite material comprising of mineral materials, binders and additives. From pavement engineering viewpoint, the selection of raw materials is the key to determine the pavement properties of porous asphalt mixture [13,14]. In the process of mix proportioning, the identification of design objectives is of prime importance [15]. To determine the best combination of aggregate and binder so as to achieve good overall performance of the asphalt pavement, the mix proportion design of asphalt mixture must be engineered, which includes the identification of design objectives, the control of gradation and the determination of binder content [16,17]. Adjusting the design goals according to the application requirements is the prerequisite for ensuring the durability and economy of the pavement structure. Due to the diversity of design goals, there is no established universal specification for the mix proportion design, and different design methods for porous asphalt mixtures have been proposed for different design goals. Currently, many researchers have studied the mix proportion design of porous asphalt. Jiang [18] and Xing [19] studied the relationship between porosity and passing rates of series of sieve apertures through laboratory tests, and improved the mix proportions design method of porous asphalt. Zhang [20] applied the Bailey method to the mix proportion design of porous asphalt, and proposed the concept of "reserved porosity" to determine the target porosity. Luo et al. [21] proposed a new open-graded porous asphalt mixture that used epoxy asphalt as the binder to improve the pavement durability, and the results showed superior overall performance of the epoxy modified open-graded porous asphalt mix compared to conventional open-graded porous asphalt mixes. Qian and Lu [22] conducted an experimental study and performance evaluation of small particle porous epoxy asphalt mixture, and the mixture was designed with the aid of a binder drainage test and a raveling test. They found that the proposed porous epoxy asphalt mixture had good mechanical properties while retaining satisfactory frictional resistance and permeability. Xiao and Zhang [23] applied the Coarse Aggregate Void Filling (CAVF) method to the mix proportions design of porous asphalt, and proposed the method to determine the optimum compaction temperature of porous asphalt mixture.

Although the porous asphalt has many advantages, there are also some drawbacks in its application. The low temperature cracking problem of asphalt pavement is reported to be prominent in some cold regions [24–27]. Survey results showed that more than one third of the damages of porous asphalt in cold regions were attributed to its inferior low temperature cracking resistance performance [28]. Asphalt mixture has the characteristics of stress relaxation. When the ambient temperature decreases slowly, the tensile stresses in asphalt mixture caused by temperature drop that accumulate gradually with time would be relieved by relaxation and would not reach the ultimate tensile stress level to cause cracking. On the other hand, the thermal contraction cracks of asphalt mixture often occur in extreme weather where the temperature descends rapidly, such as that caused by an acute cold current or cold wave. In such weather condition, the tensile stresses induced in asphalt mixture accumulate at a faster rate than the relaxation, so that cracks would appear when the ultimate tensile stress level is attained. It should be noted that for porous asphalt pavement in cold regions, in addition to the cracks caused by the ambient temperature reduction, the fluctuation of ambient temperature around the freezing point will cause the water trapped inside internal voids to undergo freeze and thaw and induce damages [29-31].

Porous asphalt pavement is more susceptible to freeze-thaw cycles in winter compared to ordinary dense gradation asphalt pavement [32]. Therefore, porous asphalt pavement used in cold regions should be designed to have excellent low temperature performance.

At present, research on porous asphalt has focused on various aspects including moisture susceptibility [2,22], fatigue resistance and healing effect [33], material optimization [34–36], filtration characteristics [37], rutting resistance [22,38], ravelling resistance [39], and noise reduction characteristics upon siltation [40]. However, research on low temperature performance of porous asphalt mixture is relatively in lack [41]. Fortier and Vinson [42] studied the relationship between low temperature cracking and aging performance of asphalt mixture and highlighted the importance of the appropriate use of modifier. Cheng et al. [43] found that the incorporation of ethylene bis stearic acid amide (EBS) and stearic acid amide (SA) could improve the low temperature deformability, reduce the failure stiffness modulus, and improve the low temperature crack resistance of warm-mixed porous asphalt mixture. Liu et al. [44] explored the feasibility of the application of porous asphalt mixture with steel slag for seasonal frozen regions, and ascertained the optimal replacement percentage of natural aggregate. In their test, steel slag coarse aggregate was used to replace basalt coarse aggregate at four levels (25%, 50%, 75%, 100%) by equal volume, and the results indicated that the low temperature cracking resistance of the mixture was significantly enhanced and acoustic emission energy was uniformly released by the incorporation of steel slag. Ma et al. [45] analyzed the effect of aging on the low temperature performance of porous asphalt mixture through the Thermal Stress Restrained Specimen Test (TSRST), and the results showed that the low temperature performance of porous asphalt mixture decreased after aging, while it was not much different from that of dense graded asphalt mixture. However, other factors such as porosity, modifier content, and test temperature also had effects on the low temperature performance of porous asphalt mixture. From literature review, the effects of these factors had not been adequately investigated, thus further research is needed.

In this paper, the low temperature performance of porous asphalt mixture is studied by means of the low temperature bending test. The mineral aggregate gradation of porous asphalt mixture is designed based on Bailey method [46,47], and the effects of porosity, modifier content, aging condition, and test temperature on the low temperature performance of porous asphalt mixture are assessed through orthogonal experimental design. The works have enabled the development of porous asphalt mixture with desirable engineering properties and resistance to low temperature.

The porous asphalt mixture developed in this research has been successfully applied to the viaduct bridge pavement of Liangdang County to Hui County section of G316 National Expressway in China. G316 National Expressway is a major highway from southeast part to northwest part of China, connecting Fuzhou City in Fujian Province and Lanzhou City in Gansu Province. The total length of the expressway is 2915 km. The section from Liangdang County to Hui County is located in Gansu Province in northern part of China and has a length of 53.4 km. Its major construction works took place from year 2016 to 2018. The porous asphalt surface layer has a thickness of 40 mm and has been testified to have good drainage performance as well as good overall performance in the cold environment of northern China.

#### 2. Low Temperature Performance Test

The commonly used low temperature performance test methods include indirect tensile test, thermal stress restrained specimen test [24], low temperature bending test, creep test, and shrinkage coefficient test. Gong [48] conducted a comprehensive comparative analysis of the commonly used low temperature performance test methods from the aspects of test accuracy and reliability, correlation between test objective and low temperature performance, test practicality and operability, and found that indirect tensile test and low temperature bending test were better test methods for evaluating low temperature performance of porous asphalt mixture. In this paper, low temperature bending test was used for studying the low temperature performance of porous asphalt mixture.

# 2.1. Raw Materials

The aggregate included S10, S12 and S16 diabase gravel produced in Heyuan, Guangdong Province of China. S10 and S12 were coarse aggregates with a maximum size of 13.2 mm and S16 was fine aggregates. The filler was limestone powder, and the asphalt used in the test was 70# matrix asphalt initially developed in a refinery laboratory in Nanjing City of China (the notion 70# refers to a needle penetration range of 70  $\pm$  10 at 25 °C in 5 s using a 100 g needle). The modifier was SINOTPS modifier manufactured by Shenzhen Oceanpower New Material Technology Company (Opmaterial) Ltd., China. It was a high-viscosity modifier and was a proprietary mixture of thermoplastic elastomer, thermoplastic resin, rubber-type polymers, and additives. Figure 1 depicts the SINOTPS modifier. The mean particle size of the SINOTPS modifier was 2.5 mm.



Figure 1. SINOTPS modifier.

The specifications and technical indicators of coarse aggregate are respectively summarized in Tables 1 and 2, and the specifications and technical indicators of fine aggregate are respectively tabulated in Tables 3 and 4. According to the test method described in Chinese Standard JTG E20-2011 [49], screening tests for aggregate and limestone powder were conducted. Figure 2 illustrates the test process, and the results are listed in Table 5. The technical requirements of limestone powder and the corresponding test results are given in Table 6.

Table 1. Specifications of coarse aggregate.

Designation	Percentage Passing through the Following Nominal Size Sieve Apertures (%)					ng
0	Range (mm)	19.0 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm
S10	10~15	100	90~100	0~15	0~5	—
S12	5~10	—	100	90~100	0~15	0~5



Figure 2. Aggregate and limestone powder screening.

<b>T</b> • <b>T</b>	<b>.</b>	Test I	Result
Test Item	Unit	5~10 mm	10~15 mm
Crushed value	%	6	.8
Los Angeles abrasion loss	%	9	.7
Apparent relative density	—	2.930	2.962
Water absorption	%	0.74	1.11
Soundness (mass loss with sodium sulfate)	%	5.2	
Needle flake granule content	%	10.2	8.5
Silt content (<0.075 mm particle content by water washing method)	%	0.5	0.9
Soft mineral content	%	1.3	0.7
Polished stone value	—	4	.5
Adhesion to asphalt	—	ļ	5

Table 2. Test results of technical indicators of coarse aggregate.

Note: Tests were carried out according to Chinese Standard JTG E20-2011 [49].

Table 3. Specifications of fine aggregate.

Designation	Nominal Size		Percentage Passing through the Following Sieve Apertures (%)						
Designation	Range (mm)	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
		mm	mm	mm	mm	mm	mm	mm	
S16	0~3	100	80~100	50~80	25~60	8~45	0~25	0~15	

Table 4. Technical indicator requirements and test results of fine aggregate.

Test Item	Unit	Test Result	Indicator Requirement
Apparent density Silt content (<0.075 mm	g/cm <sup>3</sup>	2.929	≥2.60
particle content by water washing method)	%	1.2	$\leq 3$

Table 5. Screening results of aggregates and filler material.

	Percentage Passing through the Following Sieve Apertures (%)						%)				
Materia	als	16 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
					mm						
Coarse	S10	100	91.3	35.9	0.8	0.4	0.4	0.4	0.4	0.4	0.4
aggregate	S12	100	100	99.1	3.3	0.6	0.6	0.5	0.5	0.5	0.5
Fine	C16	100	100	100	07.0	69.2	47 4	22 E	22.0	174	11.0
aggregate	510	100	100	100	97.0	00.3	47.4	55.5	22.9	17.4	11.9
Limestone p	owder	100	100	100	100	100	100	100	99.2	95.7	77.6

The properties of the matrix asphalt affect the properties of high-viscosity modified asphalt. The matrix asphalt used for preparing high-viscosity modified asphalt should meet the technical requirements of road petroleum asphalt in Chinese Standard JTG F40-2004 [50]. In this study, 70# matrix asphalt developed in Nanjing was adopted, and the test results of technical indicators per JTG E20-2011 [49] are shown in Table 7. It can be seen from the table that the matrix asphalt was classified per JTG F40-2004 [50] as a grade A asphalt, which is suitable for all grades of highways. Therefore, it is suitable to employ the matrix asphalt for preparing high viscosity modified asphalt.

Test Iter	n	Unit	Test Result	Indicator Requirement
Apparent de	ensity	g/cm <sup>3</sup>	2.699	≥2.50
Water con	tent	%	0.43	$\leq 1$
Particle size range	<0.6 mm	%	100	100
(by washing	<0.15 mm	%	95.7	90~100
method)	<0.075 mm	%	77.6	75~100
Appearar	nce	—	No agglomeration	No agglomeration
Hydrophilic coefficient		—	0.46	<1
Plasticity in	ndex	%	2.9	<4

Table 6. Technical indicator requirements and test results of limestone powder.

Table 7. Technical indicator requirements and test results of 70# matrix asphalt.

Test Item		Unit	Test Result	Indicator Requirement
Needle peneti	ration (25 °C, 5 s, 100 g)	0.1 mm	70.5	60~80
Softening point (ring and ball method)		°C	48.5	$\geq 46$
Ductility (10 °C)		cm	24.1	$\geq 20$
Density		g/cm <sup>3</sup>	1.031	Measured value
Rel	ative density	_	1.035	Measured value
Polling thin film	Quality change	%	-0.6	$\pm 0.8$
oven heated	Residual needle penetration ratio	%	69.1	≥61
(RTFOT)	Residual ductility (10 °C)	cm	7.8	$\geq 6$

Note: Tests were carried out according to Chinese Standard JTG E20-2011 [49].

Currently, the high-viscosity modifiers commonly used in porous asphalt mixture include synthetic polymers such as SBS and proprietary systems such as SINOTPS. Gong [48] found that SINOTPS modifier had certain superiority. For instance, the ductility of SINOTPS modifier at low temperature was significantly better than that of SBS modifier. In view of the desirable performance of SINOTPS modifier, it was adopted in the present work. As confirmed by the experimental trial in this study, SINOTPS had good compatibility with asphalt and could melt to integrate with the asphalt quickly.

Gong [48] selected 70# asphalt as matrix asphalt, and tested the properties of modified asphalt with SINOTPS modifier content of 6%, 9%, 12%, and 15% respectively. By comparing the indicators of modified asphalt with different contents of SINOTPS modifier, it was found that at a modifier content of 12% or 15%, all the indicators of modified asphalt could meet the requirements of Chinese Standard JTG F40-2004 [50]. At 15% content of SINOTPS modifier, the viscosity of modified asphalt at 60 °C and 135 °C was much higher than that of modified asphalt with 12% content of SINOTPS. However, it should be noted that excessive viscosity of modified asphalt would adversely affect the field construction works. Considering the economic factors and aversion of negative effect on production and construction, the optimum content of SINOTPS in modified asphalt was set to be 12% in this study, and the technical indicators of the modified asphalt per JTG E20-2011 [49] are shown in Table 8.

T	est Item	Unit	Matrix asphalt/SINOTPS = 88/12
Needle pepetra	tion (25 °C 100 g 5 s)	0.1	49.5
Neeule pelletta	1011(25) C, $100$ g, $5$ S)	mm	49.0
Softening point	(ring and ball method)	°C	93.9
Duc	ility (5 °C)	cm	45.3
Elastic restitution		%	96.8
Dynamic viscosity (60 $^{\circ}$ C)		Pa∙s	69,618
Viscos	sity (135 °C)	Pa∙s	2.883
Viscou	is toughness	N∙m	23.47
To	ughness	N∙m	15.57
D 11: (1 : (1	Quality change	%	0.07
Rolling thin film oven heated	Residual needle	%	76.2
(RTFOT)	Residual ductility (5 °C)	cm	29.1

Table 8. Technical indicators of modified asphalt (12% SINOTPS).

Note: Tests were carried out according to Chinese Standard JTG E20-2011 [49].

### 2.2. Design of Mix Proportion

In the current experimental programme, the gradation design method based on Bailey method was adopted [51,52], and the gradation design process is illustrated in Figure 3. At the outset, to conduct the gradation design of porous asphalt mixture using Bailey method, the parameters including the 0.075 mm sieve passing percentage, design density, volume ratio of coarse aggregate, and reserved porosity need to be determined. The reasonable gradation obtained based on Bailey method is listed in Table 9. The bitumen/aggregate ratio was 5.36%, the porosity was 20.55%, and the Marshall stability was 4920 N. In the gradation design, two types of coarse aggregates (denoted as CA-1 and CA-2), one type of fine aggregate (denoted as FA) and one type of filler (denoted as MF) were used. The percentage by mass passing through 0.075 mm sieve aperture was 5% and the design density was 103% of the loose density. The volume ratio of coarse aggregate (CA-1:CA-2) was determined to be 55:45 according to the requirements in JTG F40-2004 [50]. The reserved porosity was determined to be 25% according to the requirement of the target porosity.



Figure 3. Gradation design of porous asphalt mixture based on Bailey method.

Table 9. Mine	eral aggregate	composition	of gradatior	ı scheme.
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Pitumon / A compacto Datio (0/)	Percentage of Mineral Aggregate (%)					
Ditumen/Aggregate Katio (%)	S10	S12	S16	Limestone powder		
5.36	46.68	37.02	12.83	3.47		

Because of porous asphalt is an open-graded mixture, its optimal bulk density, Marshall stability and flow are not directly comparable with dense graded asphalt. Therefore, it is not viable to determine the optimum asphalt content of porous asphalt mixture directly by using Marshall test method. Instead, the desirable range of asphalt content for porous asphalt mixture should be first determined by employing the binder drainage test and Cantabro test, and then the optimum asphalt content can be determined with respect to the functional requirements of porous pavement. The binder drainage test measures the mass of binder leakage from asphalt mixture through the perforated metal basket [53], and it determines the upper bound of bitumen/aggregate ratio. The Cantabro test measures the mass of disintegration from asphalt mixture under the effect of simulated traffic load in the Los Angeles machine [54], and it determines the lower bound of bitumen/aggregate ratio.

Reference is made to Table 9 of the mineral aggregate composition of porous asphalt mixture as the starting point. Assuming the initial bitumen/aggregate ratio as 5.36%, five different bitumen/aggregate ratios were taken in the proximity of the initial bitumen/aggregate ratio as tabulated in Table 10, where the bitumen/aggregate ratio ranged from 3.6% to 5.6% with equal increment of 0.5%. For each mix in the table, after Marshall test specimens were fabricated and demoulded as shown in Figures 4 and 5 respectively, binder drainage test was conducted to obtain the binder leakage loss rate and Cantabro test was conducted to obtain the cohesion loss rate. The test results are summarised in Table 10. The relationships between binder leakage loss rate, cohesion loss rate and bitumen/aggregate ratio are respectively plotted in Figure 6. From the inflection points of the two curves in Figure 6, the lower bound of bitumen/aggregate ratio determined by the Cantabro test was 4.15%, and the upper bound of bitumen/aggregate ratio determined by the binder drainage test was 5.05%.

<b>T</b> ( <b>1</b>	Bitumen/Aggregate Ratio (%)						
lest Item	3.6	4.1	4.6	5.1	5.6		
Binder leakage loss rate (%) Cohesion loss rate (%)	0.03 6.25	0.05 4.25	0.11 4.43	0.20 4.48	0.65 3.19		
	0.20	1.20	1.10	1.10	0.17		

Table 10. Test results of binder drainage test and Cantabro test.



Figure 4. Marshall test specimens.



Figure 5. Demoulding process of Marshall test specimens.



Figure 6. Relationships between binder leakage loss rate, cohesion loss rate and bitumen/aggregate ratio.

Porous asphalt mixture has the characteristic of high porosity. In order to ensure the durability of pavement structure, the thickness of porous asphalt film should be thicker than other types of asphalt mixtures. Therefore, the optimum asphalt content tends to have a larger value. Equation (1) can be used for computing the optimum bitumen/aggregate ratio [50].

$$OAC = 0.25OAC_{\min} + 0.75OAC_{\max}$$
 (1)

where *OAC* is the optimum bitumen/aggregate ratio (in %);  $OAC_{min}$  is the lower bound of bitumen/aggregate ratio determined from the Cantabro test (in %);  $OAC_{max}$  is the upper bound of bitumen/aggregate ratio determined from the binder drainage test (in %).

The optimum bitumen/aggregate ratio calculated from Equation (1) is 4.8%, and the optimum amount of asphalt is determined to be 4.58%. Upon obtaining the reasonable gradation and the optimum bitumen/aggregate ratio of porous asphalt mixture, these parameters need to be validated by examining whether the performance of the resulting porous asphalt mixture could meet the requirements stipulated in JTG F40-2004 [50]. The verification results are demonstrated in Table 11. It can be seen from the table that the properties of the porous asphalt mixture so obtained can fulfill the application requirements.

	Test Item	Unit	Test Result	Indicator Requirement
	Porosity	%	20.7	18~22
Marshall test	Marshall stability (double- sided compaction 50 times)	Ν	5480	≥5000
	Flow value	mm	2.38	2~4
Water permeability	Water permeability coefficient	mL/15 s	1602	>800
High temperature stability	Dynamic stability (60 °C, 0.7 MPa)	times/mm	5458	≥5000
Water	Residual stability of water immersion	%	94.0	≥85
immersion	Water immersion loss	%	2.49	$\leq 15$
stability	Freeze-thaw splitting strength ratio	%	91.4	$\geq 80$

Table 11. Performance verification of porous asphalt mixture.

# 2.3. Orthogonal Experimental Design

Orthogonal experimental design [55] is a commonly used scientific method for designing multi-factor experiments. It uses a set of standardized orthogonal tables to arrange experiments, and the technique has been widely adopted in the planning and design of experimental trials in production engineering and quality control [56]. In the implementation, the combinations of different experimental factors and levels are evenly matched and rationally divided. The experimental results are processed by statistical methods and as a result scientific conclusions can be obtained. The main advantage of orthogonal experimental design is to enable the selection of representative combinations of experimental factors instead of exhausting all possible combinations. Through the analysis of some representative experimental results, the influence degree of different factors on each evaluation indicator can be obtained, and the best combination of multiple factors can be obtained to achieve the experimentation purpose.

In this study, the choice of factors in the orthogonal experimental design was based on the environmental conditions and the representative mix designs. Four factors, namely the porosity (in %), modifier content (in %), aging, and test temperature (in °C), were included. For each factor, three levels were considered. The resulting matrix can cover a wide range of design scenarios of porous asphalt mixture in low temperature conditions.

(1) Orthogonal table design

The mineral aggregate gradation and optimum asphalt content of porous asphalt mixture obtained in Section 2.2 were used in the test. The types and properties of raw materials have been described in detail in Section 2.1. Based on the above discussions, the selected levels of modifier content and porosity are presented in Table 12, henceforth, a four-factor three-level orthogonal table as tabulated in Table 13 is set up.

Table 12. Values of levels of each factor.

	Factor				
Level Number	А	В	С	D	
	Porosity	Modifier content	Aging	Test temperature	
1	16.2%	9%	No aging	0 °C	
2	20.7%	12%	Short-term aging	−10 °C	
3	23.8%	15%	Long-term aging	−20 °C	

Group Number	Porosity (%)	Modifier Content (%)	Aging	Test Temperature (°C)
1	16.2	9	No aging	0
2	16.2	12	Short-term	-10
3	16.2	15	Long-term	-20
4	20.7	9	Short-term	-20
5	20.7	12	Long-term	0
6	20.7	15	No aging	-10
7	23.8	9	Long-term	-10
8	23.8	12	No aging	-20
9	23.8	15	Short-term	0

 Table 13. Orthogonal test table.

To simulate the aging of porous asphalt mixture from construction process to service stage, the aging of porous asphalt mixture was divided into short-term and long-term aging levels. Short-term aging refers to the aging of porous asphalt mixture caused by temperature during the paving construction process from mixing plant to pavement compaction. Long-term aging refers to the aging caused by external environmental factors including air, sunlight, precipitation, and traffic loads during the service of porous asphalt pavement. The simulation methods for aging in this test were as follows:

### I) Short-term aging

The fresh porous asphalt mixture was evenly spreaded in an enamel pan, with the mass per unit area in loose state of approximately 21 to  $22 \text{ kg/m}^2$ . It was placed in an oven and heated at 135 °C under forced ventilation for 4 h, then was taken out for test.

II) Long-term aging

The specimens were prepared from porous asphalt mixture after short-term aging according to the required time, size, and moulding method. The specimens were allowed to cool down for no less than 16 h and then were demoulded. Subsequently, the specimens were placed in the oven at 85 °C, and were continuously heated under forced ventilation for 120 h. Afterwards, the oven door was opened so that the specimens were natural cooled for no less than 16 h to room temperature. Lastly, the specimens were taken out for test.

- (2) Evaluation indicator
- I) Flexural tensile strength

The flexural tensile strength directly reflects the ability of porous asphalt mixture to resist bending failure under low temperature condition. The higher the flexural tensile strength of porous asphalt mixture, the better the low temperature performance of porous asphalt mixture.

II) Maximum bending strain

The bending strain reflects the deformation ability of porous asphalt mixture and is a main indicator for evaluating the low temperature performance. The larger the maximum bending strain, the higher the energy absorbing capacity of porous asphalt mixture before failure, and the better the low temperature crack resistance of porous asphalt mixture.

III) Bending stiffness modulus

The bending stiffness modulus is the ratio of flexural tensile strength to maximum bending strain. It reflects the flexibility of porous asphalt mixture under low temperature condition. A smaller bending stiffness modulus means a higher flexibility and is generally accompanied by a better low temperature crack resistance of the porous asphalt mixture.

## 3. Experimental Method and Results

# 3.1. Range of Evaluation Indicator Values

The rutting panel specimens were prepared and were cut into small prismatic trabecular specimens. The low temperature bending test was conducted at a loading rate of 50 mm/min and under the preset temperatures. The fabrication and loading process of prismatic specimens are depicted in Figures 7 and 8, respectively.



Figure 7. (a) Fabrication of prismatic specimen; (b) prismatic specimen prior to testing.



Figure 8. Bending test of specimen.

The flexural tensile strength, maximum bending strain, and bending stiffness modulus of specimens under the corresponding conditions were obtained as presented in Table 14. Based on the test results, to obtain the influence degree of various factors on the evaluation indicators, intuitive analysis was performed on the test data. By performing range analysis of the data listed in Table 14, the range analysis table as given in Table 15 can be obtained. In Table 15,  $k_i$  represents average response value of each evaluation indicator at each level of factors, where *i* means the factor level number, *i* = 1, 2, 3. According to the value of  $k_i$  at each factor level, the ranges of different evaluation indicators corresponding to the factor levels can be obtained, and the order of the primary and secondary factors can be judged according to the value of the range.

Group Number	Flexural Tensile Strength (MPa)	Maximum Bending Strain (με)	Bending Stiffness Modulus (MPa)
1	5.60	4996	1120
2	5.26	5388	976
3	5.15	5667	908
4	5.57	4832	1153
5	5.16	5491	939
6	5.05	6257	807
7	5.17	5220	991
8	5.56	5063	1098
9	5.22	5915	882

Table 14. Results of low temperature bending test.

Table 15. Range analysis of results of low temperature bending test.

		Factor Type			
Evaluation	Mean	А	В	С	D
Indicator	Value	Porosity	Modifier content	Aging	Test temperature
Flexural tensile strength (MPa)	$k_1$	5.33	5.45	5.40	5.20
	$k_2$	5.26	5.32	5.35	5.36
	$k_3$	5.32	5.14	5.16	5.46
	Range	0.07	0.31	0.24	0.26
Maximum bending strain (με)	$k_1$	5550.33	5016.00	5438.67	5621.67
	$k_2$	5526.67	5314.00	5378.33	5467.33
	$k_3$	5399.33	5946.33	5459.33	5187.33
	Range	176.33	930.33	81.00	434.33
Bending stiffness modulus (MPa)	$k_1$	1001.33	1088.00	1008.33	924.67
	$k_2$	966.33	1004.33	1003.67	980.33
	$k_3$	990.33	865.67	946.00	1053.00
	Range	35.00	222.33	62.33	128.33

#### 3.2. Influence Analysis of Factors

By analyzing the values of range in Table 15, the order of influence of factors on each of the evaluation indicators can be obtained. The order of influence of factors on the flexural tensile strength is as follows: modifier content > test temperature > aging > porosity. The order of influence of factors on the maximum bending strain is as follows: modifier content > test temperature > porosity > aging. The order of influence of factors on the bending stiffness modulus is as follows: modifier content > test temperature > aging > porosity.

The influence of three levels of each factor on evaluation indicators is graphically represented in Figure 9. In the figure, A to D indicate the factor type as shown in Table 15, and 1 to 3 is the level number of each factor.

(1) Porosity

It can be seen from Figure 9 that the porosity has effect on the three low temperature performance evaluation indicators, but the effect is limited to within 4% over the range of porosity studied. When the porosity increased from 16.2% to 20.7%, the flexural tensile strength, maximum bending strain, and bending stiffness modulus of porous asphalt mixture decreased by 1.3%, 0.4%, and 3.5%, respectively. When the porosity further increased from 20.7% to 23.8%, the flexural tensile strength and bending stiffness modulus increased by 1.1% and 2.5% respectively, while the maximum bending strain decreased by 2.3%. Theoretically, an increase in porosity of asphalt mixture will reduce the flexural tensile strength. On the other hand, when the porosity is higher, the connected porosity also increases. The existence of interconnected pores could relieve the expansion pressure generated by the freezing action, and this could partially offset the adverse effect of porosity

on flexural tensile strength at low temperature. Through the analysis of orthogonal test results, it is found that among the three evaluation indicators, the maximum bending strain has the highest sensitivity to porosity. Therefore, it is advisable to design a single factor influence test to study the influence of porosity on the maximum bending strain, as described later in this paper.



**Figure 9.** Influence of different levels of each factor on evaluation indicators. (**a**) Curves of flexural tensile strength; (**b**) Curves of maximum bending strain; (**c**) Curves of bending stiffness modulus.

### (2) Modifier content

The modifier content is the most important factor affecting the low temperature performance of porous asphalt mixture. As can be seen from Figure 9, by increasing the modifier content from 9% to 15%, the flexural tensile strength decreased by 5.7%, the maximum bending strain increased by 18.5%, and the bending stiffness modulus decreased by 20.4%. The results demonstrate that SINOTPS modifier can significantly improve the deformation capacity and energy absorption capability of porous asphalt mixture, so that the porous asphalt mixture exhibits better low temperature performance.

## (3) Aging

Aging has relatively little effect on the low temperature performance of porous asphalt mixture. The factors of porosity and aging are together the least and the second-least influential among the four factors. From Figure 9, it can be seen that the flexural tensile strength, maximum bending strain, and bending stiffness modulus of porous asphalt mixture with short-term aging are respectively 0.9%, 1.1%, and 0.5% lower compared to those of porous asphalt mixture with no aging. The flexural tensile strength and bending stiffness modulus of porous asphalt mixture with long-term aging are respectively 4.4% and 6.2% lower whereas the maximum bending strain is 0.4% higher, compared to those of porous asphalt mixture with no aging. The modest decrease in low temperature performance of porous asphalt mixture through aging was in line with the findings by Ma et al. [45]. The slight effect of aging should be due to the effectiveness of the high viscosity SINOTPS modifier in improving the antiaging performance of porous asphalt mixture.

#### (4) Test temperature

The influence of test temperature on low temperature bending test results is less significant than that of modifier content. At this juncture, it is noteworthy that the brittle point is a threshold temperature of asphalt mixture at which its behaviour is transitioned from plastic to brittle. In low temperature bending test, in order to prevent possible sudden brittle fracture from affecting the accuracy of the results, the test temperature is generally set at higher than the brittle point temperature. For porous asphalt, the brittle point is lower than that of ordinary dense graded asphalt [57], and the test temperature can generally be set at -10 °C to -20 °C. Consequently, in order to investigate the effect of temperature changes on the low temperature performance of porous asphalt mixture, three levels of test temperature, namely 0 °C, -10 °C, and -20 °C, were adopted in the test.

From Figure 9, it can be seen that when the test temperature was decreased from 0 °C to -20 °C, the flexural tensile strength increased by 5.0%, the maximum bending strain decreased by 7.7%, and the bending stiffness modulus increased by 13.9%. The results indicated that in this temperature range, the porous asphalt mixture still exhibited plastic deformation, and the brittle point temperature was not reached [58]. The maximum bending strain decreased with the test temperature, indicating that the lower the test temperature, the less capable the porous asphalt mixture in resisting deformation. At the same time, the bending stiffness modulus of porous asphalt mixture increased with decreasing test temperature, indicating a reduction in the low temperature crack resistance of porous asphalt mixture.

#### 3.3. Influence of Porosity on Maximum Bending Strain

The porosity is amongst the most concerned indicator in the design of porous asphalt mixture. To further analyze the influence of porosity on the low temperature performance of porous asphalt mixture, the single factor influence test of porosity was conducted. The test selected the maximum bending strain as the evaluation indicator.

The experiment adopted the same mineral aggregate gradation and raw materials as those in the orthogonal test, the modifier content was 12%, and the bitumen/aggregate ratio was 4.8%. The mixing and moulding process of porous asphalt mixture was consistent with that in the orthogonal test, and the porous asphalt mixture was not subjected to aging. According to the results analysis of orthogonal test, as the porosity increased from 16.2% to 23.8%, the maximum bending strain decreased by 3.3% only. To attain higher statistical confidence, in the single factor influence test of porosity, on the basis of the orthogonal test results, another two groups of specimens with porosity of 18.4% and 26.3% were added. The five groups of specimens were subjected to low temperature bending test at -10 °C. With reference to the test results, the relationship between the maximum bending strain  $\varepsilon_B$  (in  $\mu \varepsilon$ ) and the porosity  $n_0$  (in %) was obtained, as depicted in Figure 10.



Figure 10. Relationship between maximum bending strain and porosity.

It is evident from Figure 10 that there exists an approximately linear correlation between the maximum bending strain and the porosity of porous asphalt mixture, and the maximum bending strain decreases as the porosity increases. The relationship between the maximum bending strain and the porosity is expressed in Equation (2) with coefficient of determination  $R^2 = 0.986$ .

$$\varepsilon_B = 7527.7 - 100.9n_0 \quad (16.2 \le n_0 \le 26.3)$$
 (2)

when designing the mix proportion of porous asphalt mixture, in order to ensure good working performance of porous asphalt mixture in low temperature environment, the porosity should also conform to the required limits of the maximum bending strain in relevant technical standards. In the cold regions of northern China, when applying porous asphalt pavement, the maximum bending strain of porous asphalt mixture should not be less than 5000  $\mu\epsilon$  in accordance with JTG F40-2004 [50]. From Equation (2), it is noted that when the porosity is controlled within 25%, thus the limit requirement on maximum bending strain is satisfied.

Finally, the possible use of recycled asphalt pavement to enhance the sustainability of highway infrastructure has attracted vast research interest in recent years [59–61]. Recycled asphalt mixtures, which are prepared by blending reclaimed asphalt pavement, virgin bitumen, and mineral additives, offer various advantages including resources recycling, cost saving, and reduced environmental impact [62]. Further research on the utilization of reclaimed asphalt in porous asphalt pavements and their low temperature performance is recommended.

### 4. Conclusions

In this paper, the low temperature performance of porous asphalt mixture has been studied through the low temperature bending test. The following major conclusions can be drawn:

(1) Through orthogonal experimental design, four main factors affecting the low temperature performance of porous asphalt mixture have been analyzed. The results revealed that the descending order of influence of factors on flexural tensile strength of porous asphalt mixture was: modifier content, test temperature, aging condition, and porosity. The descending order of influence of factors on maximum bending strain was: modifier content, test temperature, porosity, and aging condition; and the descending order of influence of factors modulus was: modifier content, test temperature, aging condition, and porosity.

(2) The modifier content was the most important factor affecting the low temperature performance of porous asphalt mixture, followed by test temperature. By increasing the modifier content from 9% to 15%, the flexural tensile strength decreased by 5.7%,

the maximum bending strain increased by 18.5%, and the bending stiffness modulus decreased by 20.4%. The results demonstrated that SINOTPS modifier could significantly improve the deformation capacity and energy absorption capability of porous asphalt mixture. By decreasing the test temperature from 0 °C to -20 °C, the flexural tensile strength increased by 5.0%, the maximum bending strain decreased by 7.7%, and the bending stiffness modulus increased by 13.9%. The results indicated that the lower the test temperature, the less capable the porous asphalt mixture in resisting deformation, and the poorer the low temperature crack resistance of porous asphalt mixture.

(3) The factors of porosity and aging were the least and the second-least influential among the four factors. The porosity affected the three low temperature performance evaluation indicators, but the effect was limited to within 4% when the porosity increased from 16.2% to 23.8%. Compared with porous asphalt mixture with no aging, the flexural tensile strength and bending stiffness modulus of porous asphalt mixture with long-term aging were respectively 4.4% and 6.2% lower, whereas the maximum bending strain was 0.4% higher. The slight effect of aging should be due to the effectiveness of the SINOTPS modifier in improving the anti-aging performance of porous asphalt mixture.

(4) The orthogonal test results revealed that the maximum bending strain had the highest sensitivity to porosity among the three performance evaluation indicators, namely the flexural tensile strength, maximum bending strain, and bending stiffness modulus. The effect of porosity on low temperature performance of porous asphalt mixture has been further examined through the single factor influence test. The results showed that there existed an approximately linear correlation between the maximum bending strain and the porosity of porous asphalt mixture, and the maximum bending strain decreased with increasing porosity. Furthermore, when designing the mix proportions of porous asphalt mixture, to ensure good working performance of porous asphalt mixture in low temperature environment, the porosity should also satisfy the limit requirements of the maximum bending strain in relevant technical standards. Further research on the low temperature performance of the porous asphalt mixture containing recycled asphalt materials is recommended.

Author Contributions: Conceptualization, J.W. and Y.G.; methodology, Y.G.; formal analysis, J.W. and Y.G.; investigation, J.W., P.-L.N. and Y.G.; resources, P.-L.N. and Y.G.; data curation, Y.G.; visualization, H.S.; validation, H.S. and J.D.; writing—original draft preparation, J.W., P.-L.N. and Y.G.; writing—review and editing, J.W., P.-L.N. and H.S.; project administration, J.D.; supervision, J.D.; funding acquisition, P.-L.N. and J.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China under the National Project for Research and Development of Major Scientific Instruments (Grant No. 51727813) and the European Regional Development Fund (Project No. 01.2.2-LMT-K-718-03-0010) under grant agreement with the Research Council of Lithuania (LMTLT).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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