Development and Evaluation of Porous Pavement Surface Mixtures with Bio-based Epoxy Asphalt Binder

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16. Abstract

Porous asphalt mixture, as one type of pavement surface materials, is designed intentionally to leave a large interconnected air void system in the mixture. It can be placed on pavement to reduce hydroplaning-related traffic accidents, mitigate heat-island effect, and reduce traffic noise. However, due to its thermoplastic and high porosity nature, porous asphalt mixture generally has low durability in the field. This study aims to improve the durability, strength, and sustainability of porous asphalt mixture by formulating bio-based epoxy asphalt binder (BEAB) and improving its mixture design. In the study, a BEAB formula was firstly developed through a uniform experimental design. Then, the performance of porous asphalt mixture containing BEAB was tested and evaluated along with traditional porous asphalt mixture. Finally, a simple ranking approach was introduced to improve the current mixture design approach. Based on laboratory test results and analysis, the optimum BEAB formula was identified as 7% epoxidized soybean oil (ESBO), 5% maleic anhydride (MA), and 88% base asphalt (PG 67-22). Compared to the base asphalt, the formulated BEAB may improve the strength, durability, and environmental sustainability of porous asphalt mixture without reducing its permeability and cracking resistance. In practice, to achieve balanced pavement performance for water permeability, mixture durability, strength, and cracking resistance, a 4.75-mm nominal maximum aggregate size (NMAS) open gradation with an optimum BEAB content is recommended. The developed BEAB-based porous asphalt mixture would promote the applications of porous asphalt pavement ("green pavement") and open-graded friction course (OGFC) in more community health related scenarios.

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Abstract— **Porous asphalt mixture, as one type of pavement surface materials, is designed intentionally to leave a large interconnected air void system in the mixture. It can be placed on pavement to reduce hydroplaning-related traffic accidents, mitigate heat-island effect, and reduce traffic noise. However, due to its high porosity nature, porous asphalt mixture generally has low durability in the field. This study aims to improve the durability, strength, and sustainability of porous asphalt mixture by formulating bio-based epoxy asphalt binder (BEAB) and improving its mixture design. In the study, a BEAB formula was firstly developed through a uniform experimental design. Then, the performance of porous asphalt mixture containing BEAB was tested and evaluated along with traditional porous asphalt mixture. Finally, a simple ranking approach was introduced to improve the current mixture design approach. Based on laboratory test results and analysis, the optimum BEAB formula was identified as 7% epoxidized soybean oil (ESBO), 5% maleic anhydride (MA), and 88% base asphalt (PG 67-22). Compared to the base asphalt, the formulated BEAB may improve the strength, durability, and environmental sustainability of porous asphalt mixture without reducing its permeability and cracking resistance. In practice, to achieve balanced pavement performance for water permeability, mixture durability, strength, and cracking resistance, a 4.75-mm nominal maximum aggregate size (NMAS) open gradation with an optimum BEAB content is recommended. The developed BEAB-based porous asphalt mixture would promote the application of porous asphalt pavement ("green pavement") and open-graded friction course (OGFC) in more community health related scenarios.**

Index Terms—Porous asphalt mixture, open-graded friction course (OGFC), green pavement, bio-based epoxy asphalt, durability, environmental sustainability, epoxidized soybean oil

I. INTRODUCTION

POROUS asphalt mixture (commonly known as the open-graded friction course [OGFC] mixture in the U.S.) contains aggregates with an open gradation, which is designed intentionally to leave a large interconnected air void system in the mixture. To reduce hydroplaning-related accidents on roads during heavy rain, porous asphalt mixture is often placed at the surface of asphalt pavements. In addition, porous asphalt mixture has several other beneficial functions related to environment and community health, such as mitigating heat-island effect in urban areas and reducing traffic noise generated at the tire/pavement interface.

Due to its high porosity nature, however, porous asphalt mixture typically has low durability in the field. There is a need to improve the strength and durability of porous asphalt mixture so that it may better serve the public for its safety, environment, and health related benefits. Porous asphalt mixture relies mainly on the asphalt binder to provide structural integrity and cracking resistance. To ensure the durability of porous asphalt mixture, an asphalt binder with low temperature susceptibility and high strength is desired.

Epoxy resin, as one unique type of asphalt modifier, has attracted interest in research institutes and public agencies due to its thermosetting property that can significantly improve the strength of asphalt binder. Epoxy asphalt is an asphalt binder modified with epoxy resin and its curing agent(s). After curing, epoxy resin can form a highly cross-linked, three-dimensional network in epoxy asphalt [1]. Different from other commonly used polymer modified asphalt binders whose physical properties change significantly with temperature, epoxy asphalt is thermosetting [2]. In addition, epoxy asphalt has good resistance to aging and chemical attack [1, 3]. Based on previous studies [4, 5], porous asphalt mixtures containing epoxy asphalt have been proved to have superior performance in laboratory evaluation and field pavement applications.

However, due to its high cost and proprietary nature, the epoxy asphalt has not been widely used in roadway pavements [2]. In addition, epoxy resins and most of their common curing agents (e.g., aliphatic, aromatic amines, and anhydrides) are petroleum based, some of which are toxic [6].

In recent years, significant concerns on environmental issues, sustainability of infrastructure, depletion of nonrenewable resources for pavement construction, and climate change, have led to substituting petroleum-based materials with their bio-based counterparts [6-9]. To our knowledge, the application of bio-based epoxy asphalt binder in porous asphalt mixtures has not been attempted. In addition, current designs of porous asphalt mixture are mainly targeted towards high permeability, while giving less consideration to other functional requirements such as durability and environmental benefits [10].

This study aims to improve the strength, durability, and environmental sustainability of porous asphalt mixtures by developing bio-based epoxy asphalt and improving the current mixture design approach. The remainder of the report is structured as follows. A comprehensive review of the literature regarding the formula and performance of bio-based epoxy resin is summarized in Section II. The raw materials and test materials involved in the study are described in Section III. The test methods for evaluating the performance of bio-based epoxy asphalt and porous asphalt mixtures are described in Section IV. Section V provides a detailed experimental design for the study. The test results and analysis are presented in Section VI. Finally, the major findings and potential impacts are summarized in Section VII.

II. LITERATURE REVIEW

To identify the raw materials and formula of bio-based epoxy resin (BER), a comprehensive review on BER-related literature published in recent years in chemical engineering was summarized as follows.

Since traditional thermo-stable petrochemical polymers are difficult to be recycled, currently there is a considerable amount of research work on epoxidized vegetable oils (EVOs), such as soybean oil, linseed oil, castor oil, and sunflower oil as a base for ecological and thermoset polymers [11]. Among all the EVOs, epoxidized soybean oil (ESBO) and epoxidized linseed oil (ELO) are two popular types due to their stability in the market and the large degree of unsaturation able to be epoxidized in their structures [12]. ESBO is a bio-based product from the epoxidation of soybean oil with hydrogen peroxide and either acetic or formic acid, which is non-toxic and of higher chemical reactivity [13]. Compared to other EVOs, due to the low cost of soybean oil (about $600/ton), the ESBO implies its great potential in industrial process [14]. The curing agents for ESBO can be classified into three groups, including amine hardeners, anhydride (e.g., maleic anhydride [MA], glutaric anhydride [GA]) and acid hardeners (e.g., adipic acid [AA]), and initiators for chain-growth polymerization [15]. The reaction of MA with a double bond of ESBO is a common method to introduce an anhydride group into a triglyceride. In addition to the MA, AA and GA are two other common curing agents for ESBO [16].

The process of curing involves changing the properties of the given resin by creating cross-linking. To obtain the optimum properties for bio-based epoxy resin, several researchers conducted laboratory testing and found that the greater the number of cross-links produced in the reaction between the resin and curing agent, the better the mechanical properties of the resulting epoxy resin [17, 18]. Thus, it is vital to identify the optimum curing agent ratio for the bio-based epoxy resin.

In 2002, Gerbase et al. evaluated the dynamic mechanical and thermal behavior of soybean oil related epoxy resins. They found that the mechanical properties of cured epoxy resins are very sensitive to the chemical and structural natures of curing agents, the type and concentration of cured initiators, cured reaction conditions, and epoxy conversion, which is closely related to the molar ratio of anhydride to epoxy. They also found that the degree of cross-linking was generally improved when more anhydride (e.g., MA) was used in the original formulation [19].

In 2012, Espana et al. aimed to improve the mechanical, thermal, and thermo-mechanical properties of bio-based epoxy resin by evaluating the ratio of ESBO and MA. They found that optimum results were obtained when equivalent epoxide weight was equal to anhydride equivalent weight [11]. In 2018, we tried adding ESBO and MA into asphalt and found increase strength of asphalt mixtures [20].

In 2015, Ding evaluated the effects of different curing conditions on the mechanical properties of BER. He found a large improvement in all the mechanical properties of the BER created with ELO, AA, and 4-Dimethylaminopyridine (DMAP). He also found that utilization of accelerators (e.g., DMAP) can significantly increase the rate of curing reaction. Among various accelerators, DMAP gave the highest curing rate [16].

Thus, based on the literature review and our prior work, several possible asphalt modification materials (i.e., ESBO, MA, AA, GA, and DMAP) were selected for comparison and optimization of bio-based epoxy asphalt binder. The next step is to identify the effect of curing agents on the properties of bio-based epoxy asphalt binder (BEAB) and to optimize the formula of BEAB.

III. MATERIALS

1. Raw Materials

1) Epoxidized Soybean Oil (ESBO)

The ESBO sample was obtained from the Chemical Company. Based on its product specifications, the freeze and fire points of the ESBO are 0°C and 315°C, respectively. The state of ESBO before and after heating is shown in Fig. 1. As we can see in Fig. 1, the state of ESBO changed from semi-solid to liquid after heating.

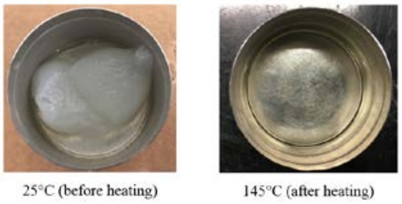

Fig. 1. The state of ESBO before and after heating

2) Curing Agents and Accelerator

The candidate curing agents selected in this study for the ESBO are MA, GA, and AA. The DMAP was also included as an accelerator for the ESBO. Samples of these four chemical products were acquired from the Sigma-Aldrich Company. As can be seen in Fig. 2, all these four products came in the form of white powder. The formula weights of the MA, GA, AA, and DMAP are 98.1, 114.1, 146.1, and 122.2 g/mol, respectively.

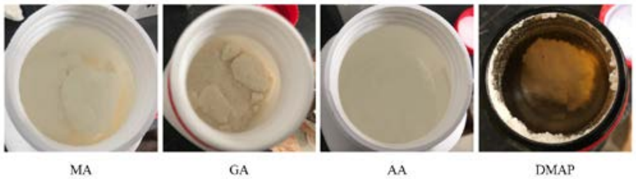

Fig. 2. The appearance of curing agents and accelerator

3) Asphalt Binder

One Superpave performance-graded (PG) asphalt binder, PG 67-22, was used as the base asphalt for formulating bio-based epoxy asphalt. The PG 67-22 sample was provided by a local asphalt supplier in Tampa, Florida. Based on the laboratory test methods specified in AASHTO T 49 and AASHTO T 316, 25°C penetration and 135°C viscosity of the PG 67-22 asphalt were measured, with average values being 38.3 (0.1 mm) and 462.5 mPa·s, respectively.

4) Aggregate

Granite aggregate samples obtained from a local pavement construction company in Tampa, Florida were used in this study. Following the test procedure of AASHTO T 96, the resistance to degradation of small-size coarse aggregate was measured using a Los Angeles testing machine. The result in terms of percentage loss of the aggregate was within the desired range of 10% to 45%.

2. Test Materials

Based on the above four types of raw materials, three types of test materials were fabricated, as explained below.

1) Bio-based Epoxy Resin (BER)

Bio-based epoxy resin was created by mixing curing agents with the ESBO. The curing process of BER is illustrated in Fig. 3, in which ESBO was mixed with MA and maintained at 145°C. As can be seen, the state of the BER changed from a colorless liquid to a tan solid when it was fully cured.

0 minute　5 minutes　30 minutes　60 minutes

Fig. 3. The curing process of bio-based epoxy resin

2) Bio-based Epoxy Asphalt Binder (BEAB)

Bio-based epoxy asphalt binder was prepared by mixing asphalt, ESBO, and curing agents together at certain proportions. Fig. 4 shows five samples of BER and their corresponding BEAB specimens.

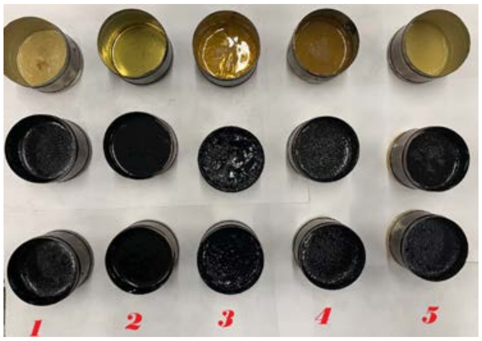

Fig. 4. Samples of BER and corresponding BEABs

3) Open-graded Friction Course (OGFC) Mixture

The OGFC mixture samples were prepared by mixing of asphalt binder and aggregates, followed by compaction with a Marshall compactor into cylindrical specimens with a diameter of 101 mm and a height of around 63.5 mm. During compaction, 75 blows were applied on each side of the specimens. Three aggregate gradations with different nominal maximum aggregate sizes (NMASs) (i.e., 4.75, 9.5, and 12.5 mm) were included in the study, as shown in Tab. 1 and Fig. 5. Their optimum binder contents (OBCs) were selected as 7.0%, 6.0%, and 5.5% (by mass of asphalt mixture) for OGFC-4.75, OGFC-9.5, and OGFC12.5 mixtures, respectively. These OBCs were determined in accordance with the literature [10, 20] that tried to allow as much as possible asphalt binder in the mixtures without causing excessive binder draindown during construction.

Tab. 1. Aggregate gradations for different OGFC mixtures

Size (mm)	Passing (%)		
	OGFC-4.75	OGFC-9.5	OGFC-12.5
19.0	100	100	100
12.5	100	100	92.5
9.5	100	95	65
4.75	91	32.5	20
2.36	14	12.5	7.5
1.18		5	5
0.6		5	5
0.3		4	4
0.15		3	3
0.075		1.5	3

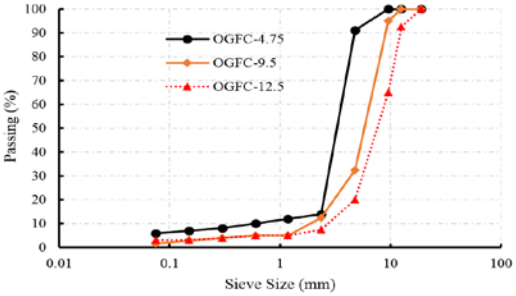

Fig. 5. Aggregate gradations for different OGFC mixtures

IV. TEST METHODS

1. Tests for Bio-based Epoxy Resin

The mechanical properties of BER are out of the scope of this research. In this study, therefore, the curing performance and stiffness of BER were only evaluated with visual inspection and manual compression, respectively.

1) Visual Inspection

The curing process of BER was visually inspected over a couple of hours. As shown in Fig. 3, the curing status of the BER can be distinguished by visual inspection.

2) Manual Compression

The relative relationship of the stiffness of different cured BERs may be roughly determined by compressing the samples with fingers. Based on comparative analysis, the sequence of stiffness over the samples may be roughly determined.

2. Tests for Bio-based Epoxy Asphalt Binder (BEAB)

1) Penetration Test

The penetration test is conducted as a measure of consistency. Higher values of penetration indicate lower consistency. The penetration of BEAB should better be lower than the penetration of base asphalt (PG 67-22) when the curing process is completed.

2) Viscosity Test

The viscosity is a measure of the resistance to flow of liquid. The viscosity of BEAB should increase with the curing process, because cured BER may gradually form a highly cross-linked, three-dimensional network.

Using the devices shown in Fig. 6, the penetration and viscosity of the BEAB can be measured according to the procedures specified in AASHTO T 49 and AASHTO T316, respectively.


Penetration Test
Viscosity Test

Fig. 6. Penetration and viscosity test for asphalt binder

3. Tests for Open-graded Friction Course (OGFC) Mixture

1) Air-void Content Test

Air-void content by itself is not a performance measure of OGFC mixture. However, a higher air-void content often results in a greater permeability of OGFC mixture [10]. The air-void content of each specimen was calculated from the theoretical maximum specific gravity measured in accordance with AASHTO T 209 and the bulk specific gravity measured based on the Paraffin method in AASHTO T 275. A Parafilm® film was used instead of paraffin. The specific test procedures for measuring the theoretical maximum specific gravity and bulk specific gravity of asphalt mixture are illustrated in Fig. 7 and Fig. 8, respectively.


Fig. 7. Theoretical maximum specific gravity test


Fig. 8. Paraffin-method based bulk specific gravity test

2) Marshall Stability (MS) Test

The Marshall stability test, as illustrated in Fig. 9, was conducted according to AASHTO T 245. It measures the maximum load supported by a cylindrical specimen (101 mm in diameter) in the diametrical direction at a loading rate of 51 mm/minute. Instead of using 60°C as the test temperature, however, the test was conducted at 25°C for OGFC mixtures to prevent excessive creep deformation during high-temperature conditioning. Three replicates were tested for each mixture. The nominal height of test specimens is 63.5 mm. When the specimen height varied from this value, a correction factor was applied to the test result.

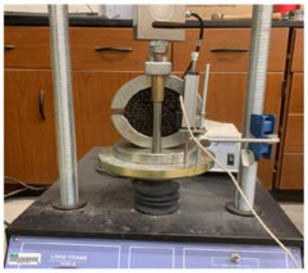
Fig.9. Marshall stability test for OGFC specimens

3) Indirect Tensile (IDT) Test

The indirect tensile test, as illustrated in Fig. 10, was conducted to evaluate the tensile properties of OGFC mixtures which are related to cracking resistance. The indirect tensile test for OGFC mixture samples was conducted following the procedure in ASTM D 6931. The test temperature and loading rate were 25°C and 51 mm/minute, respectively. Three replicates were tested for each mixture.

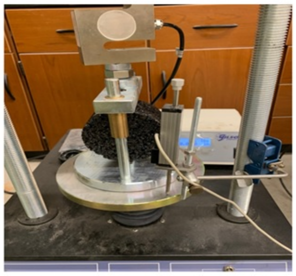
Fig. 10. Indirect tensile test for OGFC specimens

4) Cantabro Loss (CL) Test

The Cantabro loss test for OGFC specimens, as illustrated in Fig. 11, was conducted following the procedure in ASTM D 7064. Specifically, compacted specimens were put inside a Los Angeles abrasion machine drum without steel balls, and the drum was rotated at a speed of 30 revolutions per minute for 300 revolutions. The percentage of mass loss during this process was used to evaluate the resistance of asphalt mixtures to raveling. The test temperature was controlled at 25 ± 1°C. Aging effects of OGFC specimens were accomplished by placing specimens in a forced draft oven at 60°C for 14 days. Three replicates were tested for each mixture.


Fig. 11. Cantabro loss test for OGFC specimens

V.EXPERIMENTAL DESIGN

1. Preliminary Experimental Design for BER

The objective of the preliminary experimental design is to identify the potential curing agents for epoxidized soybean oil. First, the curing process of BER with different curing agents was observed and compared. Second, based on the result analysis of cured BER, a series of penetration tests for different BEABs were conducted and compared. Third, based on the penetration test results of BEABs, the viscosity of several typical BEABs was measured and compared. The test plan for the preliminary experimental design is summarized in Tab. 2.

Tab. 2. Preliminary Experimental Design for Identifying Curing Agent

Material Type	Test Plan		
	Curing	Penetration	Viscosity
ESBO:MA=1:0.45	×		
ESBO:AA=1:0.45	×		
ESBO:GA=1:0.45	×		
ESBO:AA:DMAP (D)=1:0.45:0.01	×		
ESBO:GA:D=1:0.45:0.01	×		
ESBO:GA:AA:D=1:0.3:0.3:0.01	×		
ESBO:GA:MA:D=1:0.3:0.45:0.01	×		
ESBO:AA:MA:D=1:0.3:0.45:0.01	×		
ESBO:PG 67-22 (PG)=2:8		×	
ESBO:MA:PG=1:0.45:8 [20]		×	
ESBO:GA:PG=1:0.45:8		×	
ESBO:GA:PG:D=1:0.45:8:0.02		×	
ESBO:GA:AA:PG:D=1:0.3:0.3:8:0.01		×	
ESBO:MA:GA:PG:D=1:0.45:0.25:8:0.02		×	
ESBO:GA:AA:PG=1:0.45:0.45:8			×
ESBO:MA:PG=1:0.45:0.45:8			×

Note: the symbol “x” represents the corresponding test to be performed.

2. Uniform Experimental Design for BEAB

Based on the analysis of preliminary design results, the optimum curing agent was identified as maleic anhydride (MA). To optimize the formula of BEAB, a uniform experimental design method was applied [22]. The uniform experimental design for BEAB formula is illustrated in Tab. 3.

Tab. 3. Uniform experimental design for BEAB formula

Scheme No.	Constituents			Test Plan	
	ESBO	MA	PG	Penetration	Viscosity
1	7%	5%	88%	×	×
2	15%	3%	82%	×	×
3	13%	7%	80%	×	×
4	17%	6%	77%	×	×
5	11%	4%	85%	×	×
6	9%	8%	83%	×	×

Note: the symbol “x” represents the test to be performed.

3. Validation-based Experimental Design for OGFC Mixture

Based on the result analysis of uniform experimental design, the optimum BEAB formula was identified as ESBO: MA: PG 67-22 = 7: 5: 88 (mass ratio). The performance of OGFC mixture with this BEAB formula was then evaluated and optimized using the validation-based experimental design summarized in Tab. 4.

Tab. 4. Validation-based experimental design for OGFC mixture

Scheme No.	Mixture Design			Test Plan		
	Asphalt binder	Binder Content	Aggregate Gradation	MS	CL	IDT
1	PG 67-22	7%	OGFC-4.75	×	×	×
2	BEAB	7%	OGFC-4.75	×	×	×
3	PG 67-22	6%	OGFC-9.5	×	×	×
4	BEAB	6%	OGFC-9.5	×	×	×
5	PG 67-22	5.5%	OGFC-12.5	×	×	×
6	BEAB	5.5%	OGFC-12.5	×	×	×

Note: the symbol “x” represents the test to be performed.

OGFC specimens fabricated with different mixture designs were tested in the laboratory. Three replicates were tested for each condition state of each test procedure for each mixture. For each mixture included in the validation-based experimental design, twelve specimens were fabricated with the Marshall compaction method. Six of them were used in the Cantabro test (three unaged and three aged); three specimens were used in the Marshall stability test; and the remaining three were used in the indirect tensile strength test. In addition, to identify the suitable curing time for BEAB-based OGFC mixtures, fifteen OGFC-9.5 specimens were used to conduct the Marshall stability test. A total of about 87 specimens were fabricated and tested.

VI. RESULTS AND ANALYSIS

1. Identification of Suitable Curing Agents

Based on the preliminary experimental design, the curing process of BER with different curing agents was assessed based on its appearance and physical state. The visual inspection and manual compression test results are illustrated as follows.

1) Curing Rate

The curing process of BER at 145°C with three different curing agents was visually assessed for 4 hours and illustrated in Fig. 12. As observed, the MA-based BER had cured completely after one hour since its phase had changed from liquid to solid. The status of GA-based BER did not change significantly, indicating a slow curing effect between GA and ESBO. The three curing agents ranked based on their curing rates from high to low are: maleic anhydride, adipic acid, and glutaric anhydride.

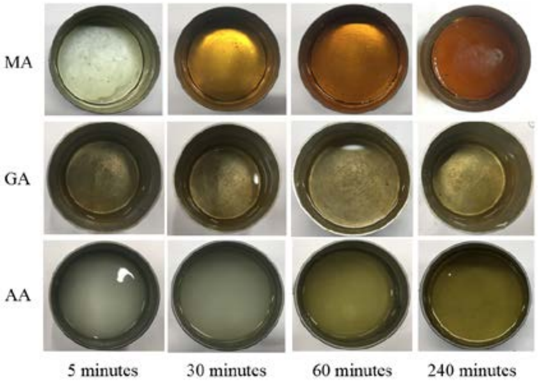

Fig. 12. Visual inspection for BER curing process

2) *Stiffness of Cured BER*

With the application of 1 mol% DMAP [16], the curing process of BER was accelerated. All five bio-based epoxy resins were fully cured within four hours. As shown in Fig. 13, the stiffness of five cured BERs (Tab. 2) was manually assessed and compared. It was found that the addition of MA increased the stiffness of two bio-based epoxy resins (ESBO+AA+DMAP and ESBO+GA+DMAP) significantly. In addition, the addition of GA increased the stiffness of AA-based epoxy resin (ESBO+AA+DMAP) significantly.

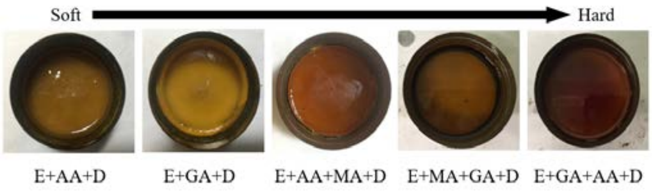

Fig. 13. Stiffness of different cured BERs

Based on the above results, the curing process of several typical BEAB formulas was evaluated by penetration and viscosity tests.

3) *Penetration of BEAB*

The penetration test results of BEABs under different curing conditions (Tab.2) were evaluated and summarized in Tab. 5 and Fig. 14. As we can see in Fig. 14, the penetration of BEAB cured with MA is the lowest, which is lower than that of the PG 67-22 asphalt. It indicates that BEAB cured with MA is stiffer than the base asphalt. In addition, the curing performance of MA on BEAB is much better than that of GA and AA.

Tab. 5. 25°C penetration for various asphalt binders

Material Type	Curing Time (hours)	Penetration (0.1 mm)
PG 67-22 (PG)	2	38.3
PG 67-22 (PG)	24	37.8
ESBO:PG=2:8	2	250.3
ESBO:PG=2:8	24	249.3
ESBO:MA:PG=1:0.45:8	2	35.4
ESBO:MA:PG=1:0.45:8	24	23.5
ESBO:GA:PG=1:0.45:8	2	128.1
ESBO:GA:PG:D=1:0.45:8:0.02	2	114.9
ESBO:GA:PG:D=1:0.45:8:0.02	24	50.8
ESBO:GA:AA:PG:D=1:0.3:0.3:8:0.01	2	69.4
ESBO:GA:AA:PG:D=1:0.3:0.3:8:0.01	24	38.3

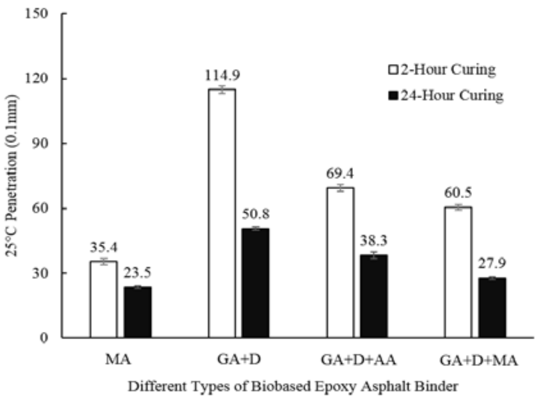

Fig. 14. 25°C penetration for various BEABs

4) *Viscosity of BEAB*

The 145°C viscosity of two typical BEABs and the base asphalt PG 67-22 was measured and illustrated in Fig. 15.

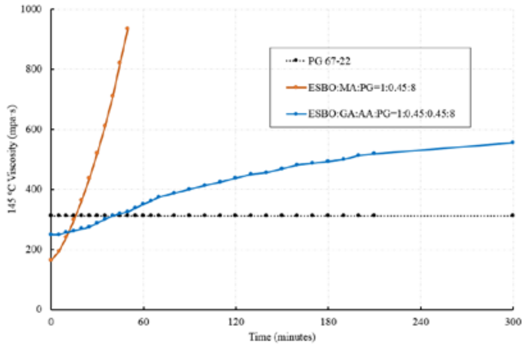

Fig. 15. Viscosity test of three typical asphalt binders

As can be seen in Fig. 15, the curing effect of MA on BEAB is much more significant than that of GA and AA. The viscosity of BEAB seems to increase with time exponentially when MA is selected as the curing agent, while, it seems to increase with time logarithmically when GA and AA are used as the curing agent. In addition, the initial viscosity of two BEABs is lower than the base asphalt. This is due to the dilution effect of uncured ESBO.

Based on the above results and analysis, the various combinations of GA, AA, and DMAP did not lead to better curing performance of ESBO compared to MA. Thus, the maleic anhydride (MA) was identified as the final curing agent of ESBO.

2. *Optimization of Bio-based Epoxy Asphalt Binder Formula*

The combination of ESBO, MA, and a base asphalt (PG 67-22), which is named as bio-based epoxy asphalt binder (BEAB), was then further studied at different proportions to achieve optimal viscosity feature for asphalt mixture production.

1) *Preparation Method*

The two preparation methods for BEAB, as shown in Fig. 16, were evaluated. In Method A, the first step is mixing ESBO and MA. Then, the mixture of ESBO and MA is added to the base asphalt. Since the curing process will begin instantly when ESBO and MA are mixed, the addition of cured epoxy resin may not form a highly crosslinked, three-dimensional network in the base asphalt.

Instead, the first step of Method B is to make MA uniformly dispersed in the base asphalt. Then, ESBO is added to the mixture of MA and base asphalt. After the curing of ESBO with MA, the cured epoxy resin can form a highly cross-linked, three-dimensional network in the base asphalt. Thus, Method B was selected as the suitable method for preparing BEAB.

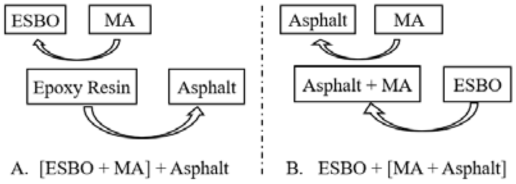

Fig. 16. Preparation methods for formulating BEAB

2) *Preparation Temperature*

The curing temperature is important for the curing process of bio-based epoxy asphalt. The viscosity of base asphalt was firstly measured over a temperature range from 135°C to 180°C, as shown in Fig. 17. To ensure the mixing efficiency of asphalt mixture, the viscosity of asphalt binder would better fall within the range of 150-190 mPa·s [23]. In addition, due to the dilution effect of uncured ESBO, the initial viscosity of BEAB would be lower than that of the base asphalt. Thus, the preparation temperature of bio-based epoxy asphalt would better be lower than 160°C.

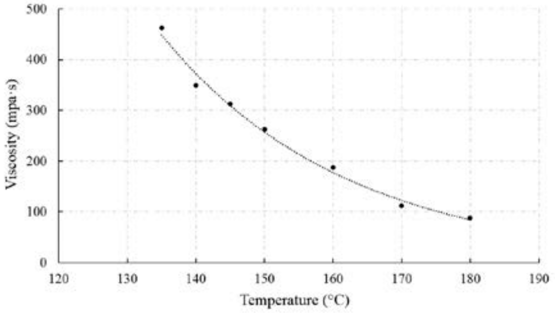

Fig. 17. Viscosity of base asphalt at different temperatures

To further select the suitable preparation temperature, the initial viscosity of various BEABs was measured at three different temperatures (135, 145, and 155°C). Based on the results, the 145°C was selected as the preparation temperature of bio-based epoxy asphalt binder. At this temperature, the initial viscosity of most BEABs generally fell into the desirable range, as shown in Tab. 6.

Tab. 6. 145°C initial viscosity of various BEABs

Scheme No.	Constituents			Viscosity (mPa·s)
	ESBO	MA	PG	
1	7%	5%	88%	212.5
2	15%	3%	82%	137.5
3	13%	7%	80%	187.5
4	17%	6%	77%	112.5
5	11%	4%	85%	187.5
6		8%	83%	187.5

3) *Penetration of BEAB*

Based on the identified preparation temperature and preparation method, a series of BEABs (Tab. 3) were formulated with the same curing time. Their penetration values were measured and summarized in Tab. 7 and Fig. 18. As shown in Fig. 18, the BEAB of Schemes 1, 3, and 6 has a lower penetration value than that of the base asphalt. It indicates that BEABs cured with Schemes 1, 3, and 6 for two hours are stiffer than the base asphalt.

Tab. 7. 25°C penetration for different BEAB formulas

Scheme No.	BEAB Formula	Curing Time (hours)	Penetration (0.1 mm)
1	ESBO: MA:PG=7:5:88	2	27.6
2	ESBO: MA:PG=15:3:82	2	81.3
3	ESBO: MA:PG=13:7:80	2	31.6
4	ESBO: MA:PG=17:6:77	2	49.9
5	ESBO: MA:PG=11:4:85	2	65.9
6	ESBO: MA:PG=9:8:83	2	20.5

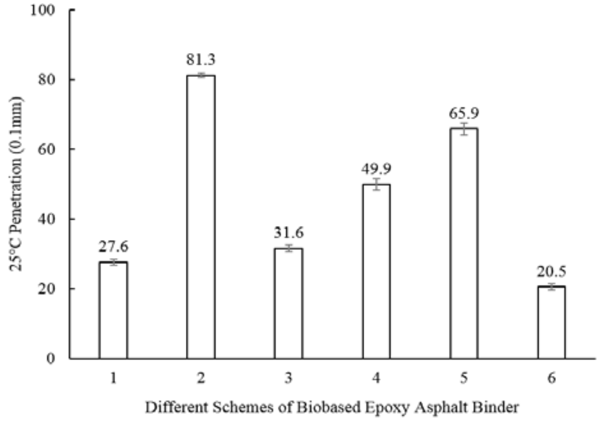

Fig. 18. 25°C penetration of different BEAB formulas

In addition, the effect of mass ratio of MA to ESBO on BEAB penetration was evaluated and illustrated in Fig. 19. As shown in Fig. 19, the penetration value of BEAB decreased with the increase of mass ratio (MA: ESBO), likely because the number of cross-links produced in the curing reaction between ESBO and MA would increase with an increase of the mass ratio (MA: ESBO).

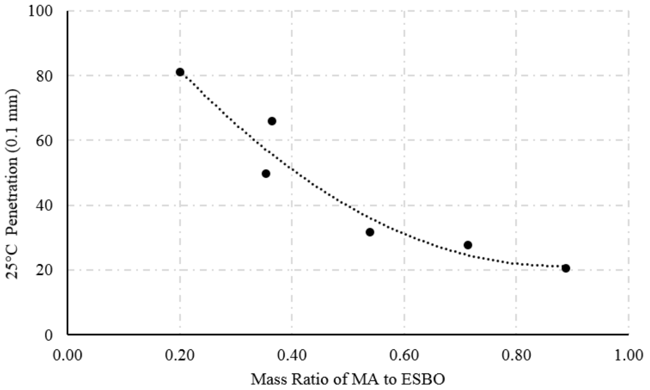

Fig. 19. The relationship between mass ratio and penetration

4) *Viscosity of BEAB*

The 145°C viscosity test results for different BEABs are illustrated in Fig. 20. As can be seen, the curing processes of BEABs are significant since their viscosity increased significantly over curing time. Among all six BEAB formulas, the curing rate of Scheme 2 is very low. This seems to be related to a low mass ratio of MA to ESBO (i.e., low curing effect) and a high proportion of ESBO (i.e., high dilution effect). As can be seen in Fig. 20, the BEAB viscosity of Schemes 3, 4, and 6 increased dramatically with the time, which may not be good for efficient mixing of asphalt mixture.

In addition, only BEABs cured with Schemes 1, 3, and 6 were found to be stiffer than the base asphalt. Thus, by combing the results of penetration test, Scheme 1 (7% ESBO, 5% MA, and 88% PG 67-22) was finally selected as the optimum BEAB formula.

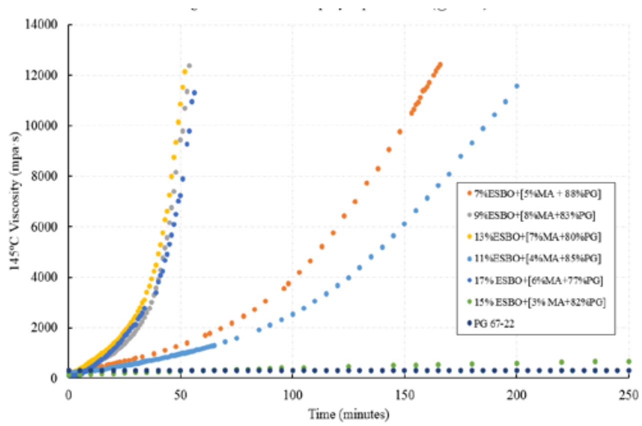

Fig. 20. The 145°C viscosity for different BEAB formulas

3. Evaluation of OGFC Mixture Performance

Based on the identified optimum BEAB formula, the OGFC mixture with different mixture designs (Tab. 4) might be formulated. To evaluate the effect of BEAB on performance of OGFC mixtures, the base asphalt was used as the control group.

Different from regular OGFC mixtures, the OGFC mixtures containing BEAB are significantly affected by the curing temperature and time.

1) Curing Temperature and Time

The curing temperature of BEAB-based OGFC mixture was selected as 60°C because it is commonly the highest pavement temperature. Curing of OGFC specimens was achieved in an oven with perforated metal sheet confinement, as shown in Fig. 21.

Fig. 21. Curing process of BEAB-based OGFC specimens

To identify the suitable curing time for BEAB-based OGFC, three replicates were tested for each curing period in the Marshall stability test. The Marshall stability of OGFC specimens cured with different periods was tested and summarized in Tab. 8.

Tab. 8. Marshall stability of OGFC-9.5 with different curing times

Material Type	Curing Time (days)	Marshall Stability (kN)
OGFC-9.5 (BEAB)	1	18.3
OGFC-9.5 (BEAB)	4	25.6
OGFC-9.5 (BEAB)	7	23.3
OGFC-9.5 (BEAB)	10	24.2
OGFC-9.5 (BEAB)	14	25.5

The trend of Marshall stability of OGFC-9.5 mixture over time is plotted in Fig. 22. As can be seen, the Marshall stability of OGFC mixture increased significantly from Day 1 to Day 4. After 4-day curing, it did not change significantly with curing time. Thus, 4-day oven bath was identified as the curing procedure for formulating BEAB-based OGFC specimens.

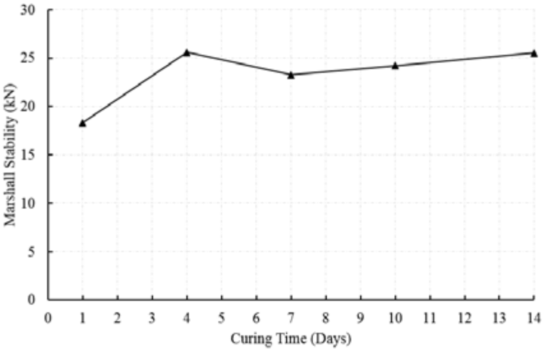

Fig. 22. Impact of curing time on OGFC-9.5 Marshall stability

2) Permeability Analysis

Since higher air-void content often results in greater permeability [10], the air-void content was selected as the proxy variable for evaluating permeability of OGFC mixture. The mean value and standard deviation of air-void content for the six OGFC mixtures (Tab. 4) after Marshall compaction are summarized in Tab. 9.

Tab. 9. Air-void content of different OGFC mixtures

Material Type	Mean (%)	Standard Deviation (%)
OGFC-4.75 (PG)	16.0	0.21
OGFC-4.75 (BEAB)	15.7	0.36
OGFC-9.5 (PG)	17.7	0.15
OGFC-9.5 (BEAB)	18.3	0.04
OGFC-12.5 (PG)	20.5	0.02
OGFC-12.5 (BEAB)	19.9	0.62

Fig. 23 shows the average air-void content, as well as the range of one standard deviation, of the six OGFC mixtures. It can be seen that asphalt binder type does not significantly affect the air-void content of OGFC specimens fabricated with the same aggregate gradation design. This indicates that the permeability of porous asphalt mixtures would not be significantly affected by asphalt binder type. While, the aggregate gradation is a significant contributing factor for permeability of porous asphalt mixtures. As shown in Fig. 23, the permeability of porous asphalt mixtures would increase with the increase of NMAS.

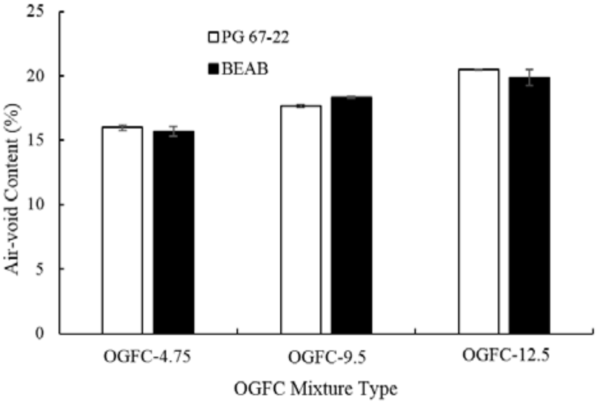

Fig. 23. Air-void contents of different OGFC mixtures

3) *Durability Analysis*

The durability of porous asphalt mixture can be evaluated with the Cantabro loss test. A lower Cantabro loss indicates a greater resistance to raveling. The mean value and standard deviation of Cantabro loss of the six OGFC mixtures are summarized in Tab. 10.

Tab. 10. Cantabro loss of different OGFC mixtures

Material Type	Mean (%)	Standard Deviation (%)
OGFC-4.75 (PG)	3.5	0.32
OGFC-4.75 (BEAB)	1.7	0.74
OGFC-9.5 (PG)	13.8	1.80
OGFC-9.5 (BEAB)	10.7	1.40
OGFC-9.5 (PG, Aging)	21.6	1.51
OGFC-9.5 (BEAB, Aging)	17.8	1.30
OGFC-12.5 (PG)	23.1	3.29
OGFC-12.5 (BEAB)	18.7	3.21

The average Cantabro loss of each OGFC mixture, along with the corresponding one standard deviation range, is shown in Fig. 24. As can be seen, compared to the base asphalt binder, BEAB can improve the durability of porous asphalt mixture. But, the relative improvement effect (i.e., the ratio of reduced Cantabro loss to regular Cantabro loss) decreases with the increase of NMAS. In addition, the durability of porous asphalt decreases dramatically with the increase of NMAS, which is consistent with findings from a previous study [10].

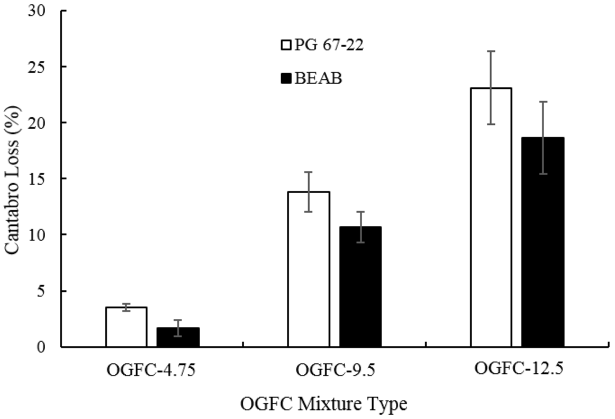

Fig. 24. Cantabro loss of different OGFC mixtures

The average value and one standard deviation of Cantabro loss for aged and unaged specimens of OGFC-9.5 mixture are shown in Fig. 25.

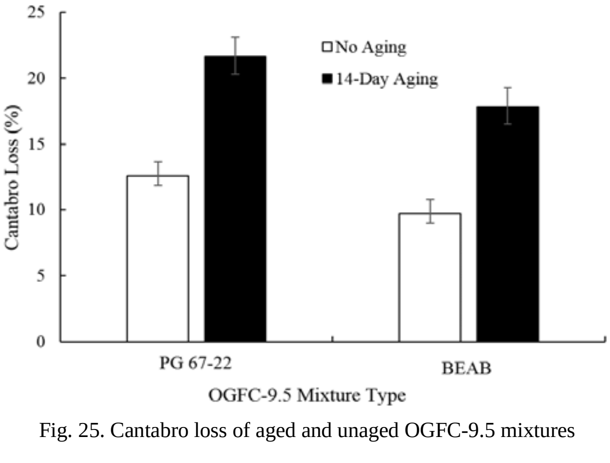

Fig. 25. Cantabro loss of aged and unaged OGFC-9.5 mixtures

As can be seen in Fig. 25, the Cantabro loss for aged specimens is higher than that of unaged specimens. This is because the 14-day aging at 60°C makes the asphalt binder stiffer and more prone to abrasion loss in the test. In addition, BEAB can improve the durability of aged and unaged porous asphalt mixture. Among all six OGFC mixture types, OGFC-4.75 mixture formulated with the bio-based epoxy asphalt provides the best resistance to raveling.

4) *Mixture Strength Analysis*

The strength of porous asphalt mixture was evaluated by its Marshall stability. The average value and standard deviation of Marshall stability of the six OGFC mixtures are summarized in Tab. 11.

Tab. 11. Marshall stability of different OGFC mixtures

Material Type	Mean (kN)	Standard Deviation (kN)
OGFC-4.75 (PG)	21.6	1.28
OGFC-4.75 (BEAB)	26.1	0.97
OGFC-9.5 (PG)	21.4	1.09
OGFC-9.5 (BEAB)	25.2	0.53
OGFC-12.5 (PG)	20.7	0.55
OGFC-12.5 (BEAB)	23.7	0.65

Fig. 26 shows the average and range of one standard deviation of the Marshall stability for six porous asphalt mixtures. As can be seen, the BEAB increased the Marshall stability of porous asphalt mixtures, and the relative improvement effect (i.e., the ratio of improved Marshall stability to regular Marshall stability) decreased with the increase of NMAS. In addition, the effect of aggregate gradation on Marshall stability is insignificant.

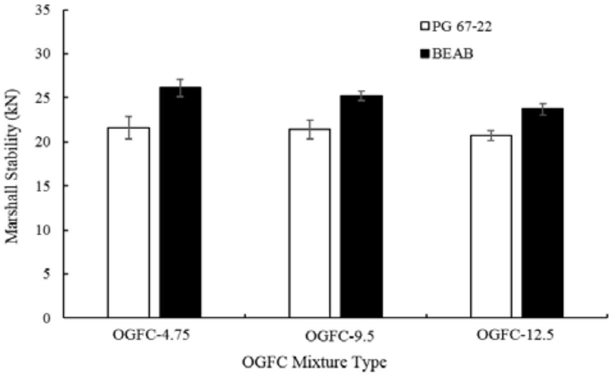

Fig. 26. Marshall stability of different OGFC mixtures

The average value and one standard deviation of Marshall stability for aged and unaged OGFC-9.5 specimens are shown in Fig. 27.

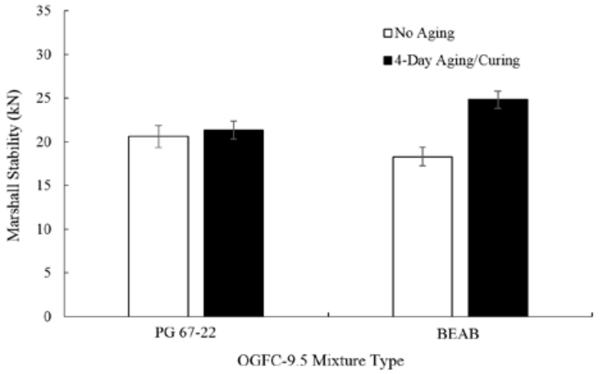

Fig. 27. Marshall stability of aged and unaged OGFC-9.5 mixtures

As can be seen in Fig. 27, the 4-day aging at 60°C did not significantly improve the Marshall stability of regular porous asphalt mixtures. While, 4-day curing at 60°C did improve the Marshall stability of bio-based porous asphalt mixtures significantly. This indicates that the curing effect of BEAB on the strength of OGFC mixture is significant.

5) *Cracking Resistance Analysis*

The cracking resistance of porous asphalt mixture was evaluated by the indirect tensile strength test. The average value and standard deviation of indirect tensile strength of the six OGFC mixtures are summarized in Tab. 12.

Tab. 12. Indirect tensile strength of different OGFC mixtures

Material Type	Mean (kPa)	Standard Deviation (kPa)
OGFC-4.75 (PG)	489.0	2.90
OGFC-4.75 (BEAB)	545.8	8.27
OGFC-9.5 (PG)	420.9	4.98
OGFC-9.5 (BEAB)	438.1	3.75
OGFC-12.5 (PG)	324.0	3.10
OGFC-12.5 (BEAB)	336.0	10.80

Fig. 28 shows the average value and range of one standard deviation of the indirect tensile strength for six porous asphalt mixtures. As can be seen, the bio-based epoxy asphalt increased the indirect tensile strength slightly for porous asphalt mixtures with a small NMAS, but not for mixtures with larger NMAS. In addition, the indirect tensile strength of porous asphalt mixture decreased with the increase of NMAS.

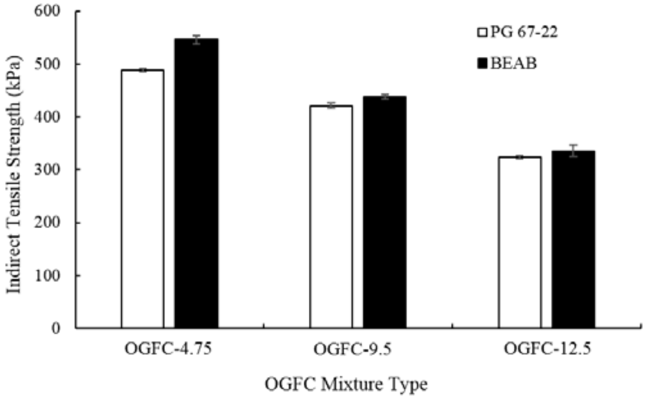

Fig. 28. Indirect tensile strength of different OGFC mixtures

Overall, the bio-based epoxy asphalt may increase the durability and strength of porous asphalt mixtures. It would also improve the cracking resistance for porous asphalt mixture with a small nominal maximum aggregate size. Meanwhile, the bio-based epoxy asphalt does not adversely affect the permeability of porous asphalt mixture.

4. *Optimization of OGFC Mixture Design*

Current porous asphalt mixture designs are mainly targeted towards high permeability [21], while giving less consideration to the other functions (e.g., cracking resistance). To fully consider the overall performance of porous asphalt mixture, the authors developed a tool for practice to choose the most suitable design for porous asphalt mixture.

A simple ranking approach was introduced to the current porous asphalt mixture design. To be specific, alternative mixture designs are ranked for each performance test. The ranking sequence is determined by the performance sequence of asphalt mixture design. The highest-ranked mixture design obtained a ranking value of 6, and the least one obtained a ranking value of 1. Based on the four performance indicators, each porous asphalt mixture design can be evaluated for four times. Then, the total ranking value of each mixture design can be calculated by summing up its ranking value of each test. The ranking values of different OGFC mixture designs are summarized in Tab. 13.

Tab. 13. Ranking values of different OGFC mixture designs

Material Type	Permeability	Durability	Strength	Cracking Resistance	Overall
OGFC-4.75-P	2	5	5	5	17
OGFC-4.75-B	1	6	6	6	19
OGFC-9.5-P	3	3	3	4	13
OGFC-9.5-B	4	4	4	3	15
OGFC-12.5-P	6	1	1	1	9
OGFC-12.5-B	5	2	2	2	11

Note: the symbols "B" and "P" represent "Bio-based epoxy asphalt" and "PG 67-22", respectively.

As can be seen in Tab. 13, the optimum mixture design for improving the permeability of porous asphalt mixture is regular asphalt, 5.5% asphalt content, and OGFC-12.5 aggregate gradation. Similarly, the optimum mixture design for improving the durability of porous asphalt mixture is bio-based epoxy asphalt, 7% asphalt content, and OGFC-4.75 aggregate gradation.

If multiple performance measures are considered equally in the mixture design, the overall ranking score can serve as a reference. To achieve the balanced porous pavement performance for water permeability, mixture durability, strength, and cracking resistance, a 4.75 mm nominal maximum aggregate size open gradation with the 7% bio-based epoxy asphalt of formula (ESBO: MA: PG 67-22 = 7%: 5%: 88%) is recommended. The optimum design may also be altered if other performance or evaluation measures are included in the ranking matrix, such as cost, noise reduction effect, and environmental sustainability.

VII. FINDINGS AND IMPACTS

1. *Major Findings*

The purpose of this study is to improve the durability, strength, and sustainability of porous asphalt mixture by formulating bio-based epoxy asphalt binder and improving its current mixture design. In the study, a bio-based epoxy asphalt binder (BEAB) formula was firstly developed. Then, the performance of porous asphalt mixture containing the BEAB was tested and evaluated along with the regular porous asphalt mixture. Finally, based on the analysis results for different porous asphalt mixture designs, a simple ranking approach was introduced to improve the current porous asphalt mixture design approach. Based on results and analysis, the major conclusions are summarized as follows.

The optimum BEAB formula is identified as 7% epoxidized soybean oil (ESBO), 5% maleic anhydride (MA), and 88% base asphalt (PG 67-22). Its mixing temperature during pavement construction is suggested as 145°C and its mixing sequence is to mix MA with asphalt first and then followed by mixing with ESBO.

Relative to the base asphalt, the formulated BEAB is validated to improve the strength, durability, and environmental sustainability (by introducing a biobased modifier) of porous asphalt mixture without reducing its permeability and cracking resistance.

To achieve the balanced porous pavement performance for water permeability, mixture durability, strength, and cracking resistance, a 4.75 mm nominal maximum aggregate size (NMAS) open gradation with the 7% optimum BEAB (by mass of asphalt mixture) is recommended.

2. Potential Applications and Impacts

The proposed bio-based porous asphalt mixtures may be applied in two pavement scenarios. First, a thin layer of open-graded friction course (OGFC) can be placed on top of pavements to reduce water film thickness during rain and so to reduce hydroplaning related accident risk. The OGFC is recommended for roads with high speed limits. Second, a porous asphalt pavement (i.e., "green pavement") may be constructed by paving a thick layer of porous asphalt mixture over a stone reservoir. Rainwater may drain through the porous asphalt mixture into the stone reservoir where it can be stored, treated, or further processed. Due to its weak strength, porous asphalt pavement is typically recommended for pedestrian walkways, sidewalks, bike lanes, shoulders, parking areas, or low-volume roadways.

The BEAB may significantly improve the durability and strength of porous asphalt mixtures, and so may promote further applications of porous asphalt pavements and OGFC layer in various scenarios, particularly in those related to community health and development, as summarized in Tab. 14.

In addition, the incorporation of bio-based soybean oil into epoxy asphalt also adds to the application of green or sustainable materials in transportation infrastructure.

Tab. 14. Community-related benefits of green pavement practices

Benefit	Green Pavement Practices
Managing Stormwater Efficiently	With proper installation and maintenance, porous asphalt pavement can allow for infiltration of up to 80% of annual runoff volume [24, 25]. The lowest measured flow rate through the porous asphalt pavement is over 0.5 inches per second [26]. Regarding the runoff of OGFC layer, 29% to 47% of the total precipitation can be retained [27].
Managing Stormwater Economically	The need for construction and maintenance of traditional stormwater infrastructures, such as detention basin, pipes, storm ponds [28-30], is reduced. In areas where storm-water impact fees are imposed by local governments, such fees may be reduced by using porous asphalt pavement [31].
Improving Runoff Water Quality	Several studies have found that porous asphalt pavement can effectively remove contamination, suspended solids, metals, oils, and grease [26, 28, 30]. Compared to conventional pavements, the retention efficiencies of oil, suspended soils, lead, and heavy metals in the porous asphalt pavement are about 97%, 90%, 70%, and 95%, respectively [32]. Compared to conventional pavements, the OGFC can improve the runoff water quality by reducing 96% of suspended soils, 78% of phosphorus, 69% of copper, 90% lead, and 90% zinc [27].
Improving Wet-weather Traffic Safety	Porous asphalt pavement and OGFC can improve wet-weather traffic safety by reducing stormwater runoff volume, reducing spray from traveling vehicles, and increasing wet-weather skid friction. The porous asphalt pavement has about 50% better wet-weather skid resistance than dense-graded asphalt pavement [26].
Reducing Community Noise	Porous asphalt pavement has over five times the sound absorption ability of traditional dense-graded asphalt pavement [26]. For newly paved overlays, OGFC can have lower tire/pavement noise than traditional dense-graded mixtures by average levels of 2.7 dB(A) and 2.8 dB(A), respectively [33].
Mitigating Urban Heat Island Effect	The urban heat island effect can be mitigated due to less stored pavement energy and rapid cooling via evaporation in porous pavements [26, 29, 34, 35]. Compared to traditional pavements, the cooling effect of permeable pavements for near-surface air was approximately 0.2°C to 0.45°C [34].
Improving Urban Land Use	Porous asphalt pavement can effectively increase the developable area and encourage robust vegetation in the area near the roadway by reducing the need for construction of storm water facilities [26].

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