Title

Performance Characteristics of Diluted Epoxy Asphalt Binders and Their Potential Application in Chip Seal

Permalink

https://escholarship.org/uc/item/3p19g8t5

Journal

Journal of Materials in Civil Engineering, 31(12)

ISSN

0899-1561

Authors

Yao, Bo
Chen, Can
Loh, Kenneth J

Publication Date

2019-12-01

DOI

10.1061/(asce)mt.1943-5533.0002943

Peer reviewed

Performance Characteristics of the Diluted Epoxy Asphalt Binders for Chip Seal Application

Bo Yao [a], Can Chen [b,*], Kenneth J. Loh [c]

[a] Assistant Professor, Department of Civil Engineering, Nanjing University of Science and Technology, 200 Xiaolingwei, Nanjing 210094, China

[b] Materials Engineer, ChemCo Systems, Inc., 2800 Bay Road, Redwood City, CA, 94063, USA

[c] Professor, Department of Structural Engineering, University of California-San Diego, La Jolla, CA, 92093, USA

*Corresponding author.

Tel./fax: 650-261-3790

E-mail address: *chen@chemcosystems.com*

ABSTRACT

Epoxy asphalt is a thermosetting paving material that can provide higher strength, stiffness, adhesion, high-temperature stability, and service life comparing to conventional asphalt. However, it has not been widely used on highway pavements, primarily due to the higher initial cost and limited operational window. In this paper, dilution of epoxy asphalt with SBS-modified asphalt was studied for the potential use for chip seal application. Performances such as workability, hardening process, uncured and fully-cured bond strength, fully-cured binder performance in both high and low temperatures were also investigated thoroughly. It was found that the diluted epoxy asphalt has higher initial adhesion feature and help provide a quicker opening to traffic after construction than the undiluted epoxy asphalt. Meanwhile, epoxy asphalt in the blend can enhance the final adhesive strengths to retain the chips under strain induced by vehicles in the long-term. The dilution level in 1:0.5 and 1:1 ratios showed a faster polymerization/curing rate than the 1:2 and 1:3 ratios. The diluted epoxy asphalt shows improved low-temperature performance compared to pure epoxy asphalt and better high-temperature performance compared to pure SBS-modified asphalt. Overall, this paper presents dilution of epoxy asphalt with SBS-modified asphalt could have significant practical benefits, and the 1:1 dilution ratio seems to be the most suitable one from the aspects of performance, cost and practical use.

Keywords: Epoxy asphalt, SBS-modified asphalt, Chip seal, Rheological properties, Mechanical performance

1. Introduction

Modifiers are frequently added to asphalt as an economical method to improve its mechanical properties, temperature stability, and durability for application in highways (Zhu, Birgisson and Kringos, 2014, Yidirim, 2007, Isacsson and Lu, 1995). Three types of modifiers are often used. The first is called thermoplastic plastomer, such as polyethylene and polycarbonates, which would be hot-melt and give a better high-temperature performance to the asphalt. The second is the thermoplastic elastomer, like styrene-butadiene-styrene (SBS) and styrene-butadiene rubber (SBR). The styrene has a high glass transition point while the butadiene is very flexible with a glass transition temperature at -90°C, the combination of which can help achieve a balanced high and low-temperature performance. The third is thermosetting materials including epoxy and polyurethane. Thermoset polymers are three-dimensional cross-linked and can rarely melt within the range of pavement service temperatures. Its unique properties can avoid rutting or shoving, and provide a high resistance to damages from traffic loads, fuels, moisture and oxidative degradation (Cubuk, Guru and Cubuk, 2009, Yu, Cong and Wu, 2009, Kang, Wu, Jin, Yu and Cheng, 2016, Hu, Qian, Xue and Yang, 2016).

Epoxy asphalt is one type of thermosetting binders which incorporates a reactive epoxy resin and curing agent in conventional asphalt. It typically comprises two parts. Part A is an epoxy resin and Part B is a mix of asphalt, curing agent and suitable additives. After Part A and Part B are mixed according to a stoichiometric ratio, a chemical reaction starts and ultimately leads to a cross-linked polymer structure in fully-cured condition. The typical laboratory curing process for epoxy asphalt is at 121 °C for 4 to 5 hours, and it usually takes up to 30 to 40 days to reach the same fully-cured condition in the field depending on the ambient temperature. The encapsulated asphalt in the polymer structure mainly acts as an extender and possibly contributes to the flexibility of the elastic structure (Chen, Eisenhut, Lau, Buss and Bors, 2018). The cured epoxy asphalt can provide much higher strength, stiffness, and adhesion compared to conventional asphalt. Due to the great mechanical property and high-temperature stability, epoxy asphalt has been a preferred paving material in heavily-trafficked and high-temperature conditions, including steel deck bridges, airport runway, tunnels, and intersections, to provide enhanced performance and extend the service life of pavement (Simpson, H.J., R.L. and K., 1960, Lu and Bors, 2015, Lv, Huang and Huang, 2014, Seim and Ingham, 2004, Luo, Qian, Yang and Lu, 2018, Huang, 2016).

Although epoxy asphalt has found its good application in providing very long-life asphalt surfacing on high-deflection steel bridge decks, it has not been widely used on roadways primarily because the material price is several times higher than conventional asphalt. In addition, as a reacting polymer-linked asphalt, epoxy asphalt shows a substantial viscosity imcrement especially at elevated temperatures and has a limited operational window from the plant production to construction paving. The mix is considered hard to work with once the epoxy asphalt viscosity increased above 3.0 Pa.s. In order to achieve a balance between the service performance and economic aspects, research and application on epoxy-modified asphalt have been on-going during the past several years. Wu and Herrington (Wu, Herrington and Alabaster, 2017, Herrington and Alabaster, 2008) used diluted epoxy asphalt with conventional asphalt graded as Pen 80-100 for porous asphalt pavement construction in New Zealand. A similar idea was adopted in the Netherlands (Zegard, Smal, Naus, Apostolidis and Liu, 2019). Recently, the emulsion of epoxy asphalt was studied by Li et al. (Li, Leng and Zhang, 2019). They used waterborne epoxy resins and emusified asphalt to lower the construction temperature and extend the operational time. Yu used foaming machine to prepare a foamed epoxy asphalt in the laboratory (Yu, Dong, Ding, Liu and Shen, 2016). His study showed that the addition of foaming water could improve the workability of foamed epoxy asphalt binder mixtures and prolong the allowable reserved time of construction process. Comparing with water foaming or emulsion methods, dilution of the epoxy asphalt with conventional asphalt seems to be the most straight-forward and practical one and around 50,000 tons of diluted epoxy asphalt mix had been laid down in New Zealand (Alabaster, Herrington and Waters, 2014). The diluted epoxy asphalt can provide both a long operational window and good mechanical performance.

The application of chip seal surfacing which consists of asphalt binders and stone chips to improve vehicular traction has frequently been used as a temporary method for highway maintenance, but with relatively short life and requiring repeated applications. Common chip seal failures are due to problems such as chip loss, binder flushing, binder oxidation and cracking developing over time. Due to good adhesion, the epoxy-modified asphalt has the potential benefit of extending the service life of chip seals and other micro-surfacing. Epoxy asphalt bond coat binder has also been studied for chip seal application in New Zealand, and the results showed that although strong aggregate to aggregate bonding can be achieved, the initial viscosity and curing rate is currently too slow for chip seal applications (Bagshaw, Herrington and Wu, 2015). In order to meet the Chip Seal Best Practices requirement that road should be opened for traffic in about 3 to 4 hours after construction, epoxy chemical accelerators should be added into the binder for accelerated curing (Transportation Research Board, 2005). Polymer-modified asphalt and rubber asphalts have been used for chip seals in heavily-trafficked roads. Studies show that when the binders were compared on a basis of the cost versus traffic volume, hot polymer-modified asphalt binder seals furnished the lower cost per unit of annual daily traffic than general asphalt emulsions (Guirguis and Buss, 2017). In this research paper, dilution of epoxy asphalt with polymer-modified asphalt has been studied for the potential use on chip seals. The polymer-modified asphalt contains 5% SBS, grade in PG 70-28, is blended with epoxy asphalt in different ratios. The diluted epoxy asphalt contains linear SBS block copolymers and cross-linking epoxy polymer. Performance of the blend such as workability, hardening process, uncured and fully-cured bond strength, fully-cured binder performance in both high and low temperatures were investigated and the applicability of the diluted epoxy asphalt in chip seals was discussed.

The main objective of the study is to evaluate the performance of epoxy asphalt diluted with SBS-modified asphalt for the potential use in chip seal application. The results can be used to select the most appropriate dilution levels economically and mechanically useful for heavily-trafficked roads. Aggregates quality and chip seal structural design are not currently considered in this study.

2. Materials and methods

2.1 Materials

In this study, the rheological and mechanical properties of the diluted epoxy asphalt were investigated. Four epoxy asphalt to SBS-modified asphalt dilution levels were selected in this study: 1:0.5, 1:1, 1:2, and 1:3. Undiluted epoxy asphalt was used as the control with the weight ratio at 1:0. A commercial acid-curing epoxy asphalt product from ChemCo Systems was provided. Properties of epoxy asphalt Part A and Part B are presented in Table 1.

Table 1 – Properties of the epoxy asphalt

Epoxy asphalt Part A (Resin)		
Property	Measured value	Test Method
Viscosity at 23℃ (Pa·s)	0.14	ASTM D445
Epoxide equivalent weight	185	ASTM D1652
Color	Transparent amber	Visual
Epoxy asphalt Part B (asphalt and curing agents)		
Viscosity at 100℃ (Pa·s)	0.23	ASTM D2983
Acid value (mg KOH/g)	53	ASTM D664
Color	Black	Visual

A typical preparation and application process for chip seal application is shown in Fig. 1. The epoxy asphalt Part B is blended with the preheated PG 70-28 according to the dilution ratios mentioned above, and stored in the thermal controlled tank B. Part A resin is stored at a temperature between 80 to 90℃ suggested by the supplier. The two components pass through a static mixing pipe where they are thoroughly mixed and flow into a reaction coil tank for reheating purpose before spraying out of the nozzles. Finally, hot chips would be spread on the surfacing at a certain rate and be compacted. The diluted epoxy asphalt in the lab followed a similar procedure only with Part A and Part B were mixed by hands.

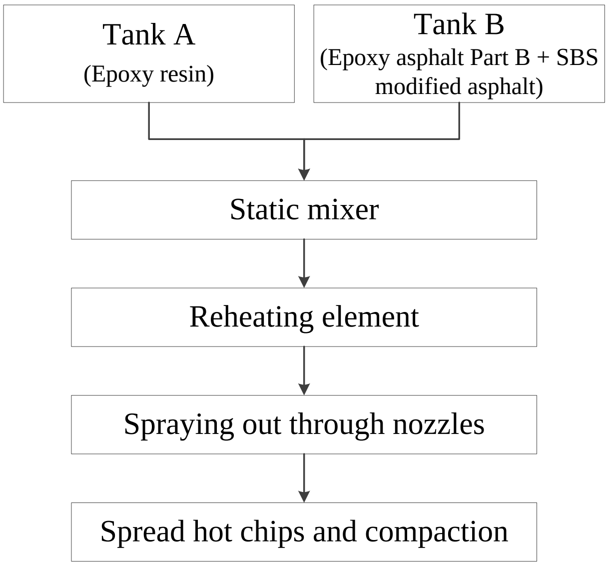


Fig. 1. Diluted epoxy asphalt chip seal construction process.

2.2 Experimental Plan and Test Method

To reveal the performance of the epoxy asphalt diluted with SBS-modified asphalt, test methods including rotational viscosity test, penetration test, Fourier-transform infrared spectroscopy - FTIR test, bond strength test, dynamic shear test and low-temperature creep test were used to characterize the workability, hardening process, uncured and fully-cured bond strength, fully-cured binder performance in both high and low temperatures of the diluted epoxy asphalts respectively. Fig. 2 illustrates the experimental program of this study.

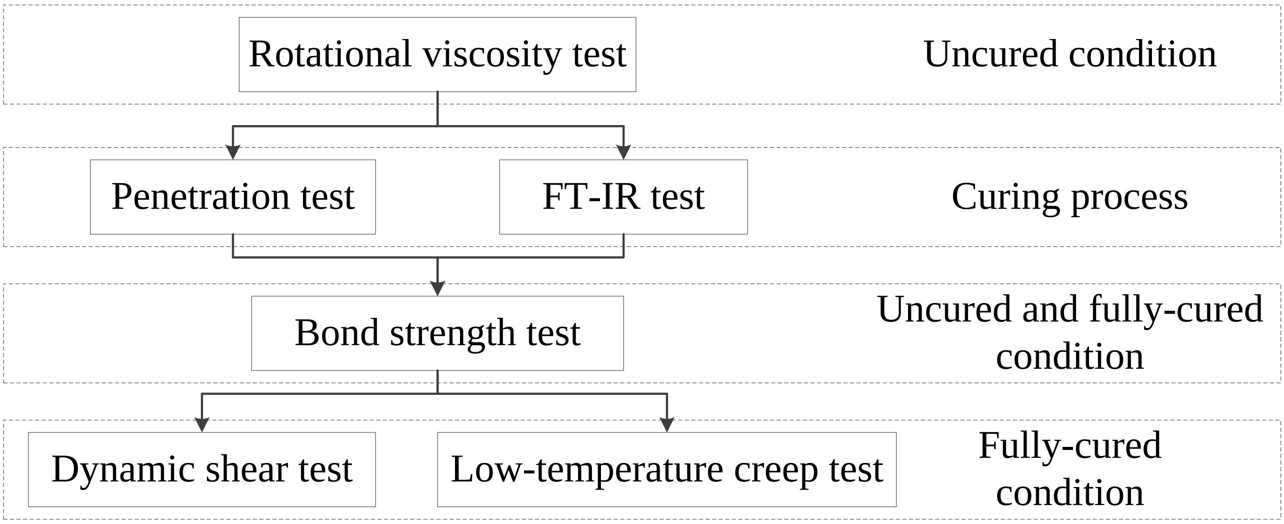


Fig. 2. Experimental program.

The binder viscosity tests were conducted to evaluate the workability of the diluted epoxy asphalts. A Brookfield Rotational Viscometer (RV) was used to measure the viscosities of binders as per ASTM D4402. The viscosity tests were performed at potential construction temperatures of 120℃, 135℃, 150℃, and 165℃ for all binders. The testing temperatures were selected according to the expected production temperatures of the diluted epoxy asphalt binders.

Binder penetration test as per ASTM D5 coupled with FT-IR test were applied to measure the curing and hardening process of the diluted epoxy asphalts. Since the polymerization/curing process significantly affect the mechanical performance including the hardness of the asphalt, the penetration test method was adopted. Epoxy asphalt binders were cured at 40 ℃ inside an incubator. This temperature was selected to simulate an average roadway surface temperature in common summer days. Samples were tested every two days at 25 ℃. At the same time, a tiny amount of the binder was retrieved for the FT-IR analysis. In this test, the test binder was first pressed to pellets with a thickness of approximately 1 mm, and then placed in a transmission holder and scanned.

Binder bond strength test was used to measure the binder adhesive bond strength to steel plates and stone slabs in both uncured and fully-cured conditions. Direct measurement of binder and aggregate chip adhesion is difficult, mainly because of the aggregate's irregular shape and different sizes. In this study, pull-off tests were used to quantify adhesive strength between the diluted epoxy asphalt and the substrates of steel plate and granite plate to reflect the adhesive interaction characteristics. The pull-off tests were performed following the ASTM D4541 method, and the pull-off bond strength is referred to as the binder "adhesion". In the first test, hot asphalt binders in uncured condition were spread on the steel plates and smooth granite plates, then steel pull-off heads were attached by pushing it directly onto the adhesive binder film. After four hours binders return back to room temperature, the tests were performed by pulling the steel heads out of the substrates vertically. In the second test, the samples were prepared in the same procedure as the first test, but samples were then stored in a 40℃ incubator for 14 days to reach a fully-cured condition before the pull-off test. The test speed for each type of substrate is 1.27 mm/min.

Binder high-temperature shear test using dynamic shear rheometer (DSR) was employed to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures as per ASTM D7175 for the diluted epoxy asphalts. The high-temperature performance of the diluted epoxy asphalts was further characterized by the rutting factor $G^*/\sin\delta$. This characterization method is utilized in the Superpave PG asphalt binder specification. All samples were in fully-cured condition. For all samples, the diameter of the plates was 25 mm and the gap between two plates was 2mm. A constant loading frequency of 10 rad/s (1.59 Hz) was applied to samples under the strain controlled mode within the linear viscoelastic range. Samples were tested at a starting temperature of 46 ℃ with 6 ℃ increments until reached the failure temperature. A sinusoidal torque was applied onto the cylindrical sample, while the resulting complex shear modulus and phase angle at different temperatures were recorded automatically during the test. The results are closely related to the rutting resistance of asphalt binders in medium to high temperatures.

To determine the low-temperature crack resistance of the diluted epoxy asphalt binders, the binder low-temperature flexibility test using bending beam rheometer (BBR) as per ASTM D4486 was applied to provide a measure of low-temperature stiffness and relaxation properties. The BBR tests are usually used in the Superpave asphalt binder specification as a means of assessing the low-temperature performance, by providing a measure of the binder stiffness and relaxation properties. The fully-cured specimens were tested at a starting temperature of -6℃ with 6℃ decrements until the samples reached the failure temperatures. A simply-supported binder beam (125 mm in length with a cross section of 6.35 mm by 12.7 mm) was placed in the controlled temperature ethanol bath and subjected to a constant load at the mid-span for duration of 240s. The test load (980±50mN) and the mid-span deflection of the beam were monitored versus time using a computerized data acquisition system. The creep stiffness of the binder ($S(t)$) at different temperatures and loading times, and the slope of the logarithm of the creep stiffness versus the logarithm of the time curve (known as m-value) were determined through classical beam theory. Each of the asphalt binders was tested at four temperatures: -6℃, -12℃, -18℃, and -24℃ - except for the undiluted epoxy asphalt since it failed to fulfill the Superpave criteria of the low-temperature grade at -12℃.

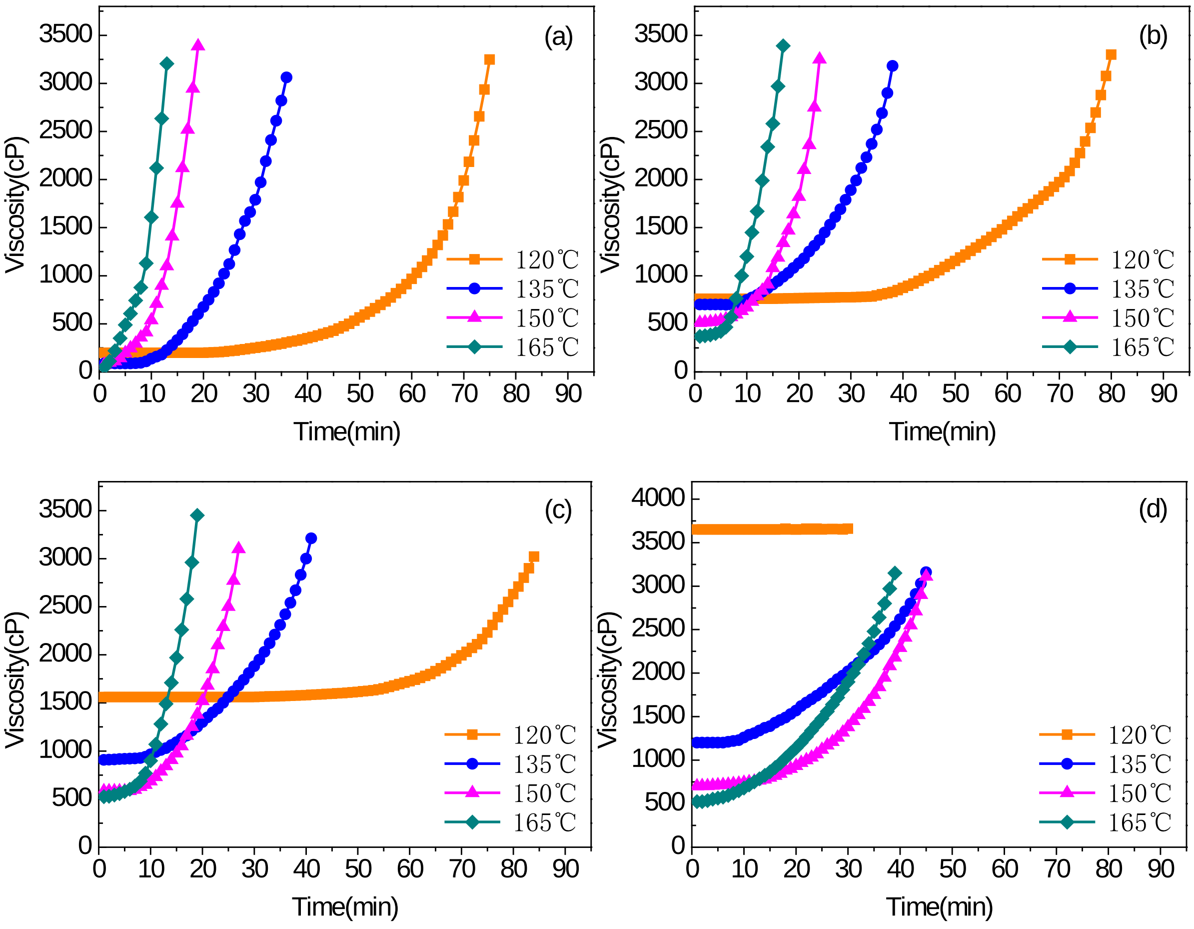
3. Results and discussion

3.1 Workability

Epoxy asphalts, unlike conventional asphalt, are chemically reacting materials. Epoxy resins react with the hardeners and form a three-dimensional cross-linked polymer network. After the components were mixed, the polymerization process begins and viscosity of the epoxy asphalt is a function of temperature and time. Diluted epoxy asphalts also experience the viscosity increment with the addition of the SBS-modified asphalt. For a chip seal application, a too low viscosity of the asphalt binder could lead to difficulties in aggregate embedment, while too viscous binders could cause an inappropriate aggregate wetting and asphalt spraying issues (Lawson and Senadheera, 2009). Therefore, careful selection and control of the blending ratio and mixing temperatures of the diluted epoxy asphalt are crucial for practical construction purpose. To reveal an optimal mixing temperature for the diluted epoxy asphalt, viscosities of the binders were measured at 120℃, 135℃, 150℃, and 165℃ immediately after Part A and B were mixed. In accordance with the Superpave binder specifications, the viscosity measured for unaged asphalt should not exceed 3000 cps for practical use (D'Angelo, 2009). Thus, the upper limit of the rotational viscosity testing was set at 3500 cps.

The viscosity versus time curves obtained from the rotational viscosity tests are plotted in Fig. 3. It is clear that the viscosity curves under all temperatures follow a similar pattern: the binders exhibit low viscosity values when the two components were mixed initially, then continuously increase with time. Fig. 3 also shows that the increase of the mixing temperatures will make the binder flow easier initially but accelerate the chemical reaction at the same time, which may lead to an even shorter operational window. Therefore, extra care is needed during the period of binder dwelling in the reaction coil tank.

The rotational viscometer gives a rapid and reproducible measurement of high-temperature viscosity and helps ensure that the asphalt binder is sufficiently fluid for pumping and mixing. The results indicate that only a few dilution levels and temperature combinations are acceptable for the application of the diluted epoxy asphalt in chip seals. For instance, the undiluted epoxy asphalt (dilution level: 1:0) gives the lowest initial viscosity, which is around 100 cps 5 minutes after mixing, as shown in Fig. 3 (a). However, asphalt binders at 100 cps are very easy to flow and too thin after cooling down for potential use in chip seals. On the other hand, the dilution level in 1:3 with much more SBS polymer asphalt have the viscosity around 4500 cps at 120℃ (Fig. 3 (e)), which is not realistic for pumping, spraying nor chip embedment. It implies that a high content of SBS polymer asphalt in the dilution may not lead to a satisfactory workability performance for chip seals. For practical purpose, the 1:1 diluted epoxy asphalt shows an initial viscosity with good application potentials: 1500 cps at 120℃, and 1000 cps at 135℃ (Fig. 3 (c)). The binders are easier for spraying and can have better hot chip embedment. Once mixing, the SBS-modified asphalt would provide the initial bond to the chips and epoxy polymer network would gradually develop over a longer period of time until maximum bond strength is reached.



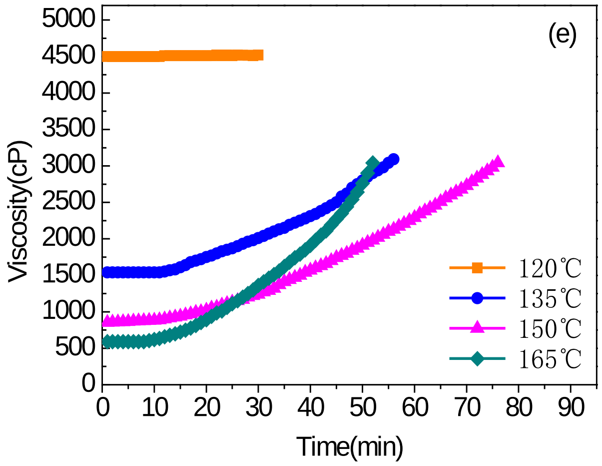


Fig. 3. Viscosity-time-temperature relationship for the diluted epoxy asphalt with dilution ratios: (a) 1:0; (b) 1:0.5; (c) 1:1; (d) 1:2; (e) 1:3 levels

3.2 Penetration Test coupled with FT-IR

The chemical hardening of the epoxy asphalt and diluted epoxy asphalts can be analyzed for different time intervals with penetrometer and FT-IR spectrometer. The penetration values provide some insights to the hardness of asphalt binders.

The effect of the curing process on the penetration value is shown in Fig. 4. It can be seen that undiluted epoxy asphalt is the softest with penetration value above 300, and the higher the dilution, the lower the initial penetration values are. The figure also illustrates three different curing patterns.

1. The hardening curve for undiluted epoxy asphalt tends to suggest the epoxy/carboxylic acid reaction is relatively slow. Isolated epoxy polymers were present in the first few days surrounding by unreactive asphalt and plasticizer, and a cross-linked backbone structure was formed about 4 to 6 days after the initial chemical reaction. This reflects on the significant decrease on penetration value between 4 to 6 days.
2. The diluted epoxy asphalt in 1:0.5 and 1:1 ratios hardened faster under the same temperature condition, and an accelerated hardening was noticed from the day first after initial reaction. The addition of high molecular weight SBS modified asphalt seems to contribute to an advanced stability in the early stage of the curing.
3. Too much asphalt in the system could have negative effect on the stability of the polymer asphalt. The penetration values for diluted epoxy asphalt in 1:2 and 1:3 ratios are fairly

constant, and the values are even higher than neat PG 70-28 asphalt. Cross-linked polymer may not be formed in the asphalt and isolated polymer structures do not provide much benefit to the overall hardness of the binder.

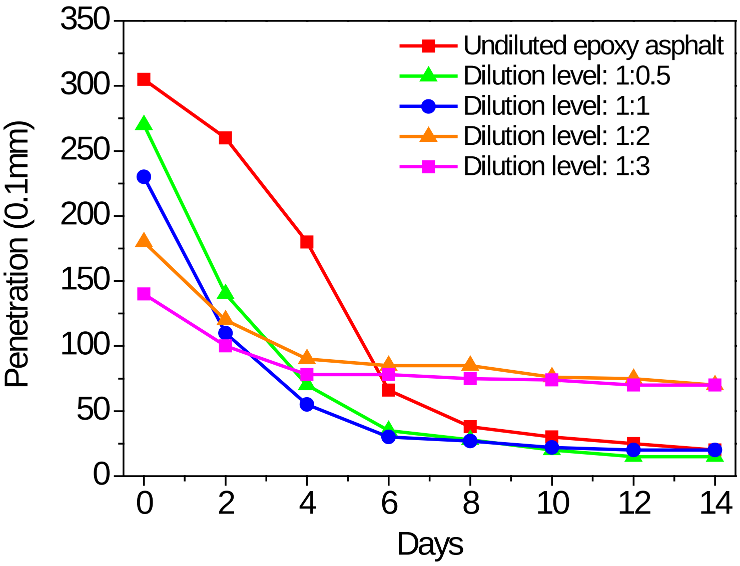


Fig. 4. Penetration values change during the curing process

As an acid-curing polymer asphalt, the carbonyl acid components in epoxy asphalt would react with epoxy resin and transfer into carbonyl ester (Wei and Zhang, 2012). FT-IR offers a convenient method to track the acid to ester conversion overtime, by virtue of their strong and distinctive absorptions. Therefore, an absorbance intensity decrease could be tracked on the acid group region (at 1708 cm-1) and an increase on the ester group region (at 1735 cm-1) during the curing process, as demonstrated in Fig. 5. Fig. 6 further lists out the carbonyl acid group absorbance changing for both undiluted and diluted epoxy asphalts during the whole curing process. As can be seen, the higher the dilution, the lower the absorbance of the acid functional group can be measured. In addition, undiluted epoxy asphalt and the dilution in 1:0.5 and 1:1 ratios showed a faster polymerization/curing rate than the 1:2 and 1:3 ratios. Figure 6 also shows that the absorbence change can hardly be detected after 14 days curing for all the binders, and it is considered reactions are all approximately complete by then.

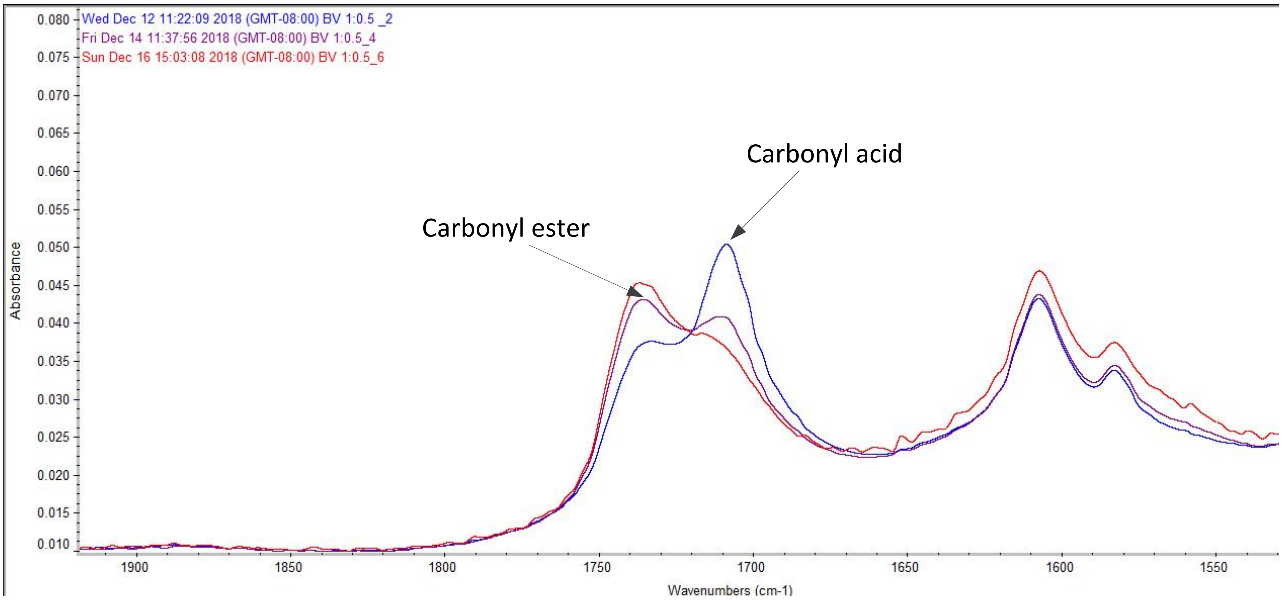


Fig. 5. FTIR spectra peaks at different curing times

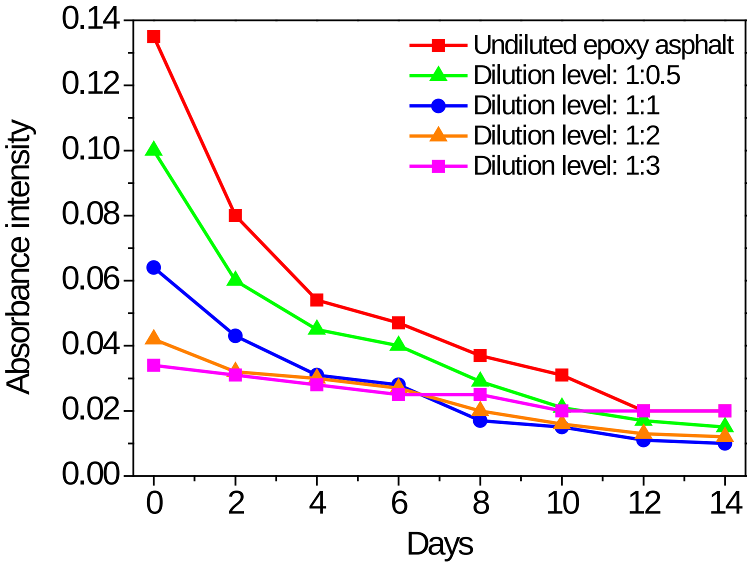


Fig. 6. Absorbance intensity decrease of carbonyl acid group during the curing process

3.3 Bond strength

Bond adhesion is considered that the adhesion property could be one of the most important contributors for the long-life chip seal performance (Gransberg and Zaman, 2005). Fig. 7 presents the pull-off bond strength for the uncured epoxy asphalt for all five dilution levels. Results show that the addition of SBS-modified asphalt in the blend does help provide high initial bond strength. The diluted epoxy asphalt in 1:3 ratio gives the highest value. Whereas, the undiluted epoxy asphalt does not lead to a satisfied performance and the initial bond strength values measured are around 0.03 MPa on a steel plate, which is almost out of the device testing range. The reason could be the epoxide chemical bonding has not yet started and the plasticizer contained in epoxy asphalt further reduced the initial bond strength and viscosity.

For the fully-cured bond strength test, the undiluted epoxy asphalt gives the highest bond strength values at about 3.0 MPa on both steel plate and granite stone substrates. As shown in Fig. 8, the dilution level also significantly affects the bond strength to the steel substrate and granite stone substrates. All binders show good adhesion bond to the granite aggregate system, which ranges from 1.5 to 3.0 MPa. The binder adhesion to granite stone substrate provides a direct indication of the adhesive characteristic for the real chip seal bonding. The higher bond strength to granite slab could be due to a rougher granite surface comparing to the treated steel plate surface, thus give slightly higher results. Fig. 9 further shows that fully-cured epoxy asphalt pulled the granite out of the substrate and left a bond failure on the aggregate side. White colors are the signs of quartz and feldspar breakdown on the granite substrate, while highly diluted epoxy asphalt (1:3 ratio) would have the adhesion failure mainly occur inside the bond film rather than the substrates. Due to the relatively low sensitivity of this test, only uncured and fully-cured bond strengths were determined. The diluted epoxy asphalt binders show satisfactory results in Fig. 8(b) that all the adhesive strengths are above 1.0 MPa. The more epoxy asphalt exists in the blends, the higher adhesive strengths can be obtained to retain the chips under strain induced by vehicle tires.

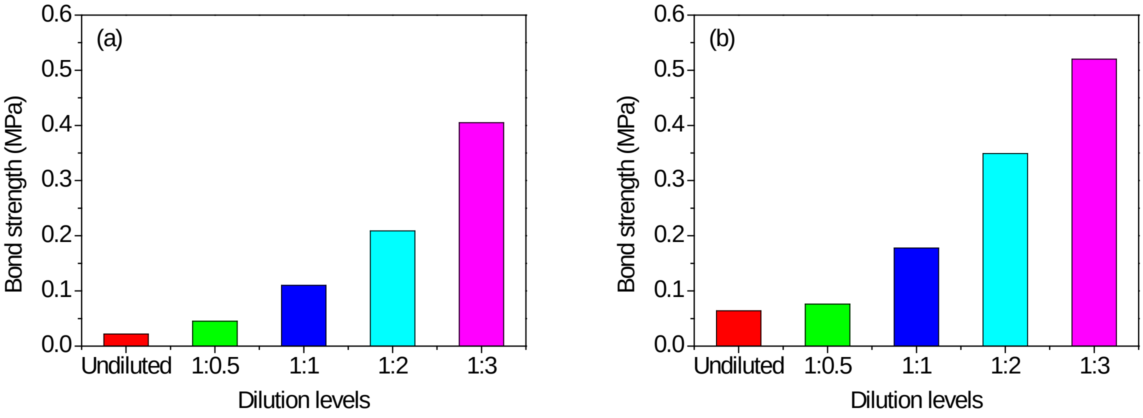


Fig. 7. Uncured bond strength test on substrates: (a) Steel plate; (b) granite plate

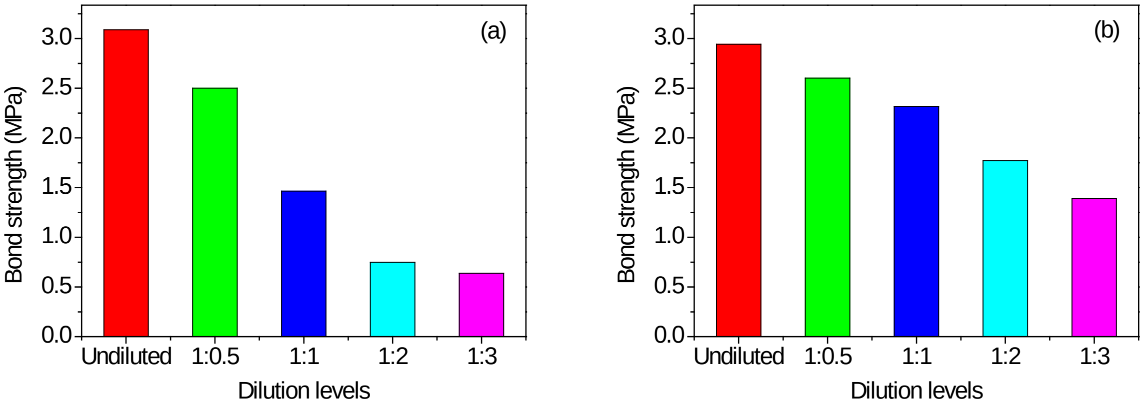


Fig. 8. Fully-cured bond strength test on substrates: (a) Steel plate; (b) granite plate

Fig. 9. Failure conditions of the granite plate substrates after fully-cured bond strength tests: undiluted epoxy asphalt (above) and diluted epoxy asphalt in 1:3 ratio (below).

3.4 Permanent deformation

The complex shear modulus (G*) and phase angle (δ) of the binders measured via the DSR test were shown in Fig. 10. It is observed from Fig. 10(a) that the complex shear modulus (G*) shows a considerable temperature dependency. G* continuously decreases with increasing test temperatures. In all cases, the results show that a higher SBS-modified asphalt content leads to a lower G^* value. The slopes of curves for the diluted epoxy asphalt containing more SBS-modified asphalt are steeper, especially at elevated temperatures. Reason for this can be attributed to the decreasing relative volume ratio of the chemically crosslinked networks while the asphalt fraction increases. Phase angle is the lag between the applied shear stress and the resulting shear strain. As shown in

Fig. 10 (b), in the same way, the addition of SBS-modified asphalt significantly increase the phase angle of the blends, thus decreases the elasticity of the binder. The more SBS-modified asphalt added, the larger phase angles were obtained for the diluted epoxy asphalt binders.

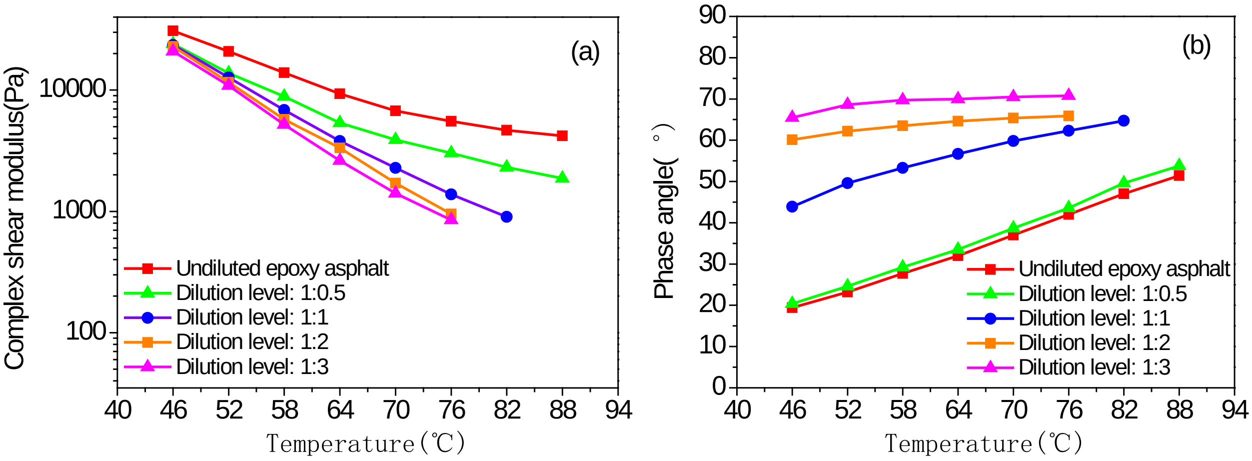


Fig. 10. The DSR test results: (a) complex shear modulus; (b) phase angle.

The rutting factor $G^*/\sin\delta$ obtained from DSR tests can be further used to determine the PG grade of the diluted epoxy asphalts. Plots of $G^*/\sin\delta$ versus temperatures are displayed in Fig. 11. According to the SHRP specification, the failure temperature of an asphalt binder is the temperature at which $G^*/\sin\delta$ is less than 1.0 kPa (Domingos and Faxina, 2016). Results reveal that the failure temperatures are decreased when the epoxy asphalt is diluted with SBS-modified asphalt. The failure temperatures for the undiluted epoxy asphalt and the epoxy asphalt in the dilution level of 1:0.5 are beyond 88 °C. It should be noted that the highest testing temperature used in the DSR is 88 °C. In the case of epoxy asphalt to SBS-modified asphalt is 1:1 blended, the failure temperature is 82℃, as well as those for the diluted epoxy asphalt binders at ratio of 1:2 and 1:3 are 76 °C. This indicates that the hardness and resistance to flow and deformation of epoxy asphalt binder at high temperatures would drop when more SBS-modified asphalt was added. The failure temperatures for the diluted epoxy asphalt with 1:2 and 1:3 dilution levels were elevated to 76℃ comparing to the original SBS-modified asphalt with 70 °C as the highest temperature.

For chip seals, a suitable aggregate retention is critical and related to the cohesive contribution provided by the asphalt binder as a function of its rheological properties (Pasquini, Bonati, Giuliani and Canestrari, 2014). Results presented in Fig. 10 and Fig. 11 suggest that the epoxy asphalt has a positive effect on rutting resistance of the SBS-modified asphalt. The diluted epoxy asphalt gave the complex modulus more than 21000 Pa at 46℃, which approximately equals to those obtained by emulsion asphalt at 25℃ in the literature (Islam, King and Wasiuddin, 2016). It implies that even a small amount of epoxy asphalt was added to the blends, partial three-dimensional cross-linked polymer networks could still be constructed that confine the movement of base asphalt and allow the binder to accumulate less permanent deformation due to higher elasticity. It is helpful for the chip seals to maintain enough contact areas between seal and chip aggregates and to recover deformation after unloading. Thus, the resistance of the diluted epoxy asphalt to chip loss could be improved.

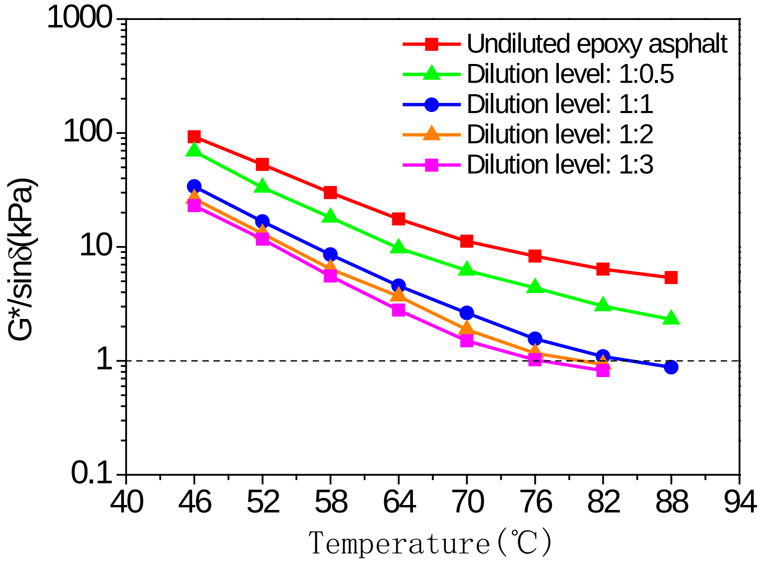


Fig. 11. Relationship of temperature and rutting factors for the diluted epoxy asphalt binders.

3.5 Low-temperature cracking

In the BBR tests, the *S(t)* and *m*-value for the undiluted and diluted epoxy asphalt binders were measured, as shown in Fig. 12. Each graph includes a horizontal black dash line indicating the Superpave criteria for *S(t)* and *m*-value. In terms of *S(t)*, the criteria line represents the maximum stiffness value of 300 MPa, and for the *m*-value the criteria line represents the minimum slope of 0.30.

The data in Fig. 12 shows an increase in the *S(t)* and a decrease in the *m*-value with decreasing testing temperatures, indicating that the binders are becoming more brittle at lower temperatures. In all cases, the stiffness S(t) decrease and the m-values increase with increasing SBS-modified asphalt contents for the diluted epoxy asphalt binders in the same temperature conditions. This implies that the diluted epoxy asphalt containing more SBS-modified asphalt has better toughness and could reduce the possibility of the pavement cracking in extremely low temperature condition. Both SBS rubber and lower polymer cross-linking density in the highly-diluted epoxy asphalt could be attributed to the better low-temperature performance.

Test results were verified at their low-temperature PG grades according to the ASTM D4486 specification. It shows that all binders have the *m*-values higher than the minimum requirement, however, the undiluted epoxy asphalt reached the m-value specification thresholds only at -12℃. It should be noted that the standard BBR testing temperature is 10℃ warmer than the low-temperature grade of the binder according to Superpave specification (Aflaki and Hajikarimi, 2012). Therefore, the low-temperature grade of the undiluted epoxy asphalt is assigned at -16°C, while diluted epoxy asphalts in 1:1, 1:2 and 1:3 ratios are graded as -28°C. SBS-modified asphalt and diluted epoxy asphalt seem to outperform pure epoxy asphalt in low temperature. However, conducting solely binder tests could be insufficient for comprehensive low-temperature evaluation, and some other studies show that pure epoxy asphalt have higher fracture energy than PG 70-28 asphalt in low-temperature mixture semi-circular bend test (OEDC, 2008).

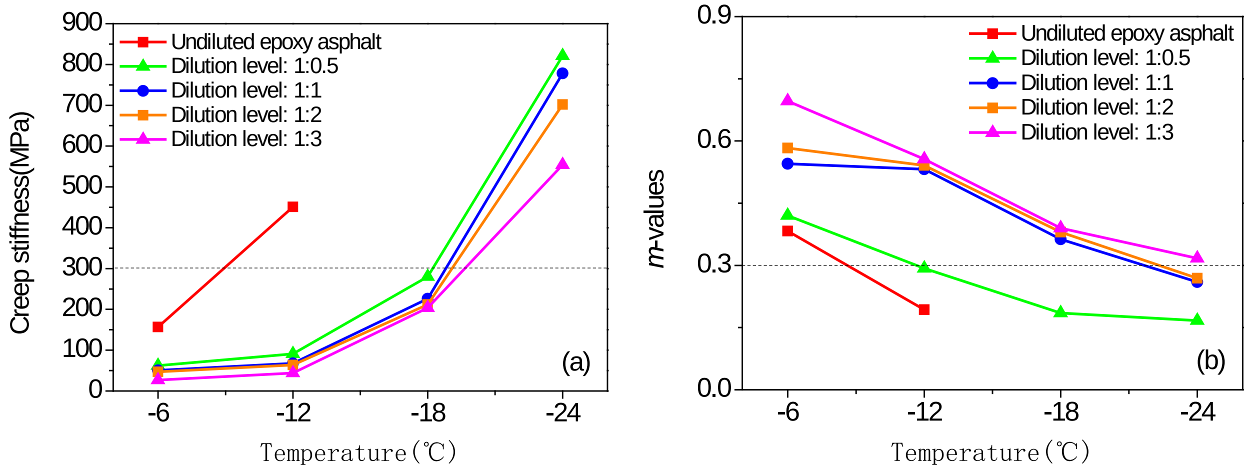


Fig. 12. The BBR test results: (a) creep stiffness; (b) *m*-values.

4. Conclusions

The study presents use of the diluted epoxy asphalts for potential chip seal application from the aspects of binder performance tests. The influence of SBS-modified asphalt contents diluted in epoxy asphalt was systematically investigated. The findings are as follows.

1. The binder viscosity test suggests that only a few dilution level and temperature combinations are workable in the chip seal application. The 1:1 diluted epoxy asphalt shows a lower viscosity, which looks more practical for spraying through the nozzles or wand. A certain amount of SBS polymer in epoxy asphalt is helpful for providing a good initial bond and embedment to the chips as well.
2. Binder penetration test also shows that undiluted epoxy asphalt may be susceptible to early traffic damage and acts very soft at the beginning. However, as the cross-linking polymer network formed, the binder becomes very hard. The hardening/curing process in 40℃ is about 2 weeks detected by FT-IR.
3. Binder pull-off bond strength is an important indicator on the cohesion and adhesion for diluted epoxy asphalts. The test demonstrates that the more epoxy asphalt exists in the dilution, the higher adhesive strength can be obtained in the long-term. However, undiluted epoxy asphalt does not give a satisfactory initial adhesive strength, while the SBS-modified asphalt in the blend has high initial adhesion feature and can help provide a quick opening to traffic after construction.
4. The binder DSR test in high-temperature tests for diluted epoxy asphalts in the ratio of 1:0.5, 1:1, 1:2, and 1:3 are beyond 88 ℃, 82℃, 76℃, and 76℃, compared that of the SBS-modified asphalt is 70℃, which implies that the presence of a small amount epoxy asphalt still has a positive rutting resistance effect in the blend.
5. The binder BBR test in low-temperatures, on the other hand, shows that the undiluted epoxy asphalt could become brittle at temperatures lower than -16℃, while the dilution level of epoxy asphalt and SBS asphalt in 1:1 showed an improvement in low-temperature performance.

Overall, this study suggests that dilution of epoxy asphalt with SBS-modified asphalt may have significant practical benefits. The blend comprising both epoxy and SBS polymers shows an improved low-temperature performance for epoxy asphalt and better high-temperature performance for SBS-modified asphalt without any miscibility issue. In addition, an appropriate dilution ratio allows good applicability for chip seal and improve binder to chip adhesion in both short-term and long-term. This study presented here is thus a preliminary investigation from the aspect of binder tests, mixture and field performance needs to be further studied in the future.

References

Zhu, J. Q., Birgisson, B., and Kringos, N. (2014). "Polymer modification of bitumen: Advances and challenges." *Eur Polym J*, 54, 18-38.

Yidirim, Y. (2007). "Polymer modified asphalt binders." *Constr Build Mater*, 21(1), 66-72.

Isacsson, U., and Lu, X. (1995). "Testing and Appraisal of Polymer-Modified Road Bitumens - State-of-the-Art." *Mater Struct*, 28(177), 139-159.

Cubuk, M., Guru, M., and Cubuk, M. K. (2009). "Improvement of bitumen performance with epoxy resin." *Fuel*, 88(7), 1324-1328.

Yu, J. Y., Cong, P. L., and Wu, S. P. (2009). "Laboratory Investigation of the Properties of Asphalt Modified with Epoxy Resin." *J Appl Polym Sci*, 113(6), 3557-3563.

Kang, Y., Wu, Q., Jin, R., Yu, P. F., and Cheng, J. X. (2016). "Rubber-like Quasi-thermosetting Polyetheramine-cured Epoxy Asphalt Composites Capable of Being Opened to Traffic Immediately." *Sci Rep-Uk*, 6.

Hu, J., Qian, Z. D., Xue, Y. C., and Yang, Y. M. (2016). "Investigation on Fracture Performance of Lightweight Epoxy Asphalt Concrete Based on Microstructure Characteristics." *J Mater Civil Eng*, 28(9).

Chen, C., Eisenhut, W. O., Lau, K., Buss, A., and Bors, J. (2018). "Performance characteristics of epoxy asphalt paving material for thin orthotropic steel plate decks." *Int J Pavement Eng*, 1-11.

Simpson, W. C., H.J., S., R.L., G., and K., M. T. (1960). "Epoxy Asphalt Concrete for Airfield Pavements." *Journal of the Air Transport Division*, 86(1), 57-72.

Lu, Q., and Bors, J. (2015). "Alternate uses of epoxy asphalt on bridge decks and roadways." *Constr Build Mater*, 78, 18-25.

Lv, Q., Huang, M., and Huang, W. D. (2014). "A Conception of Application Epoxy Asphalt Mixture on Airport Pavement." *Adv Mater Res-Switz*, 838-841, 1240-1244.

Seim, C., and Ingham, T. (2004). "Influence of Wearing Surfacing on Performance of Orthotropic Steel Plate Decks." *Transportation Research Record: Journal of the Transportation Research Board*, 1892, 98-106.

Luo, S., Qian, Z. D., Yang, X., and Lu, Q. (2018). "Laboratory Evaluation of Double-Layered Pavement Structures for Long-Span Steel Bridge Decks." *J Mater Civil Eng*, 30(6).

Huang, W. (2016). "Integrated Design Procedure for Epoxy Asphalt Concrete-Based Wearing Surface on Long-Span Orthotropic Steel Deck Bridges." *J Mater Civil Eng*, 28(5).

Wu, J. P., Herrington, P. R., and Alabaster, D. (2017). "Long-term durability of epoxy-modified open-graded porous asphalt wearing course." *Int J Pavement Eng*, 1-8.

Herrington, P., and Alabaster, D. (2008). "Epoxy modified open-graded porous asphalt." *Road Mater Pavement*, 9(3), 481-498.

Zegard, A., Smal, L., Naus, R., Apostolidis, P., and Liu, X. Y. (2019). "Field Trials with Epoxy Asphalt for Surfacing Layers Province of North Holland Case Study." *The 99th Transportation Research Board Conference*Washington D.C., USA.

Li, R., Leng, Z., and Zhang, Y. (2019). "Preparation and Characterization of Waterborne Epoxy Modified Bitumen Emulsion as a High-Performance Cold Binder." *The 99th Transportation Research Board Conference*Washington D.C., USA.

Yu, X., Dong, F. Q., Ding, G. Y., Liu, S. J., and Shen, S. H. (2016). "Rheological and microstructural properties of foamed epoxy asphalt." *Constr Build Mater*, 114, 215-222.

Alabaster, D., Herrington, P., and Waters, J. (2014). *Optimising long life low noise porous asphalt*, Crc Press-Taylor & Francis Group, Boca Raton.

Bagshaw, S. A., Herrington, P. R., and Wu, J. P. (2015). "Preliminary examination of chipseals prepared with epoxy-modified bitumen." *Constr Build Mater*, 88, 232-240.

Guirguis, M., and Buss, A. (2017). "Performance Evaluation of Emulsion and Hot Asphalt Cement Chip Seal Pavements." *J Mater Civil Eng*, 29(11).

Lawson, W. D., and Senadheera, S. (2009). "Chip Seal Maintenance Solutions for Bleeding and Flushed Pavement Surfaces." *Transport Res Rec*(2108), 61-68.

D'Angelo, J. (2009). "Current Status of Superpave Binder Specification." *Road Mater Pavement*, 10, 13-24.

Wei, J. M., and Zhang, Y. Z. (2012). "Study on the Curing Process of Epoxy Asphalt." *J Test Eval*, 40(7), 1169-1176.

Gransberg, D. D., and Zaman, M. (2005). "Analysis of emulsion and hot asphalt cement chip seal performance." *J Transp Eng-Asce*, 131(3), 229-238.

Domingos, M. D. I., and Faxina, A. L. (2016). "Susceptibility of Asphalt Binders to Rutting: Literature Review." *J Mater Civil Eng*, 28(2).

Pasquini, E., Bonati, A., Giuliani, F., and Canestrari, F. (2014). "Advanced Characterization of Clear Chip Seals." *J Test Eval*, 42(5), 1213-1227.

Islam, R. M., King, W., and Wasiuddin, N. M. (2016). "Correlating Long-Term Chip Seals Performance and Rheological Properties of Aged Asphalt Binders." *J Mater Civil Eng*, 28(5).

Aflaki, S., and Hajikarimi, P. (2012). "Implementing viscoelastic rheological methods to evaluate low temperature performance of modified asphalt binders." *Constr Build Mater*, 36, 110-118.