

## Investigation of epoxy-resin-modified asphalt binder

Peiliang Cong,<sup>1</sup> Yu Tian,<sup>2</sup> Ning Liu,<sup>1</sup> Peijun Xu<sup>1</sup>

<sup>1</sup>Engineering Research Center of Transportation Materials of Ministry of Education and School of Materials Science and Engineering, Chang'an University, Xian 710064, China

<sup>2</sup>School of Civil Engineering, Purdue University, West Lafayette, Indiana 47906

Correspondence to: P. Cong (E-mail: congpl@chd.edu.cn) and Y. Tian (E-mail: tian7@purdue.edu)

**ABSTRACT:** Epoxy asphalt (EA) binder has been used extensively for paving long-span bridges in many countries because it shows excellent heat resistance, is free from bleeding, has a low-temperature cracking resistance, and has aggregate scattering resistance. EA binders were prepared by the mixture of asphalt, epoxy resin, and a new curing agent (CR) with functional groups. The properties of the EA binder were characterized by their viscosity, tensile strength, elongation at break, compatibility, morphology, glass transition temperature ( $T_g$ ), contact angle, and surface free energy. The curing process was analyzed. The results indicate that the curing temperature and asphalt content had significant effects on the properties of the EA binder. We observed that most of the strength was generated after the first 3 h at 165 °C; this provided good workability for EA pavement construction. The CR with various functional groups improved the compatibility and morphology of the EA binder. The test results show that  $T_g$  of the EA binder decreased and the contact angles increased with increasing asphalt content. It is worth noting the contact angles between water and the EA binder were always greater than 90°; this implied that the EA binder was hydrophobic and, hence, water repellent. The surface free energy and dispersion force increases with decreasing asphalt content. However, the polarity forces decreased with decreasing asphalt content.

© 2016 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2016**, *133*, 43401.

**KEYWORDS:** compatibilization; morphology; resins

Received 18 August 2015; accepted 2 January 2016

**DOI:** 10.1002/app.43401

### INTRODUCTION

Orthotropic steel decks have always been used for long-span bridges because of their light weight and good mechanical properties. A variety of materials have been used for the wearing surfaces on steel bridge decks.<sup>1–3</sup> One of the most commonly used is asphalt concrete. Asphalt binders can be divided into thermoplastic and thermosetting binders. At high temperatures, asphalt concrete needs to meet the stiffness requirement, whereas at low temperatures, it needs to be flexible enough to resist cracking and maintain bonding with the steel deck.<sup>4–6</sup> In reality, however, such requirements are hard to meet simultaneously, especially for thermoplastic asphalt binders. Some researchers have investigated the characteristics of various asphalt binders containing thermoplastic or thermosetting asphalt binders. Their studies have shown that the epoxy asphalt (EA) binder has the best performance at both high and low temperatures.<sup>7,8</sup>

EA binder is a thermosetting-polymer-modified asphalt binder. Its continuous phase is a thermosetting epoxy resin, and its discontinuous phase is asphalt. Some research has indicated that compared with regular asphalt concrete, EA concrete exhibits

some preferable features, such as a high resistance and flexibility, good bonding with the steel deck, perfect waterproofing features, and high fatigue life (i.e., EA concrete has a fatigue life that is four times longer than that of regular asphalt concrete).<sup>9</sup> Previous studies have also indicated that EA concrete does not exhibit distress, such as rutting, shoving, or bleeding.<sup>10–13</sup> Nonetheless, EA binder must undergo a curing process. The curing process is time and temperature dependent, exothermic, and irreversible; during this process, the low-molecular-weight liquid is converted into a high-molecular-weight and crosslinked into a solid.<sup>14</sup> An important change during curing is gelation. As the reaction proceeds, the epoxy resin becomes a flexible but nonflowing EA.<sup>15,16</sup> Gelation is always accompanied by the release of heat; this results in a temperature increase, and hence, the elevated temperature accelerates the curing. To provide good workability and high performance, EA concrete construction should be completed before gelation starts; therefore, the temperature and time should be closely monitored during mixing, transportation, paving, and compaction.<sup>17</sup> One of the most widely used EA binders requires a mixing temperature of 115–125 °C, with an allowable time period for mixing and transporting EA in the range of 45–94 min. A higher mixing temperature

**Table I.** Physical Properties of Asphalt

Physical property	Measured value
Penetration (25 °C, 0.1 mm)	92
Softening point (°C)	45.1
Ductility (15 °C, cm)	186
Ductility (5 °C, cm)	14.2
Viscosity (135 °C, mPa s)	420
Saturates (wt %)	12.86
Aromatics (wt %)	56.49
Resins (wt %)	22.07
Asphaltenes (wt %)	8.58

will accelerate the chemical reaction of EA and significantly reduce the time for mixing, transporting, laying, and compacting the EA mixture. However, a lower mixing temperature (115–125 °C) may not guarantee sufficient drying of the aggregates. In addition, after the EA mixture is laid, the full cure will take 30–60 days, and this greatly delays the opening travel time.

The Shell Petroleum Co. developed an EA binder in the 1950s as an airport paving material because of its ability to resist oil and heat. In 1967, it was first used as a wearing surface on the orthotropic deck of the San Mateo–Hayward Bridge in San Francisco, California.<sup>18–20</sup> EA binder was introduced into China and first applied to the Nanjing Second Yangtze River Bridge in 2000. EA pavement has exhibited superior performance compared with regular asphalt mixtures paved on steel deck bridges.<sup>21</sup> Over decades, numerous articles and technical papers on the use of EA concrete paving on orthotropic bridge decks have been published. Mix design, mechanical and structural analysis, construction practice, performance evaluation, and maintenance techniques have been discussed extensively.<sup>22,23</sup> However, the major restriction of EA concrete is the incompatibility of epoxy resin and asphalt because epoxy resin is a polar material (dielectric constant = 3.9), whereas asphalt is a nonpolar material (dielectric constant = 2.6–3.0). In addition, differences in other material properties exist between epoxy resin and

asphalt; these include differences in the density, molecular weight, viscosity, and solubility parameter.

Although EA mixtures have been imported and used on several long-span bridges as deck pavement in most countries, some critical information is still kept confidential by the patent holder; this information includes the ingredients, parts, and components of the EA binders. Furthermore, additional investigation is needed to understand different construction conditions. The objective of this study was to investigate the feasibility of developing EA binders' methods with better compatibility and higher mixing temperatures for increased mixture transportation and compaction. The effects of the content of asphalt on the properties of EA binder were characterized, and the curing process was analyzed according to the maximum tensile strength.

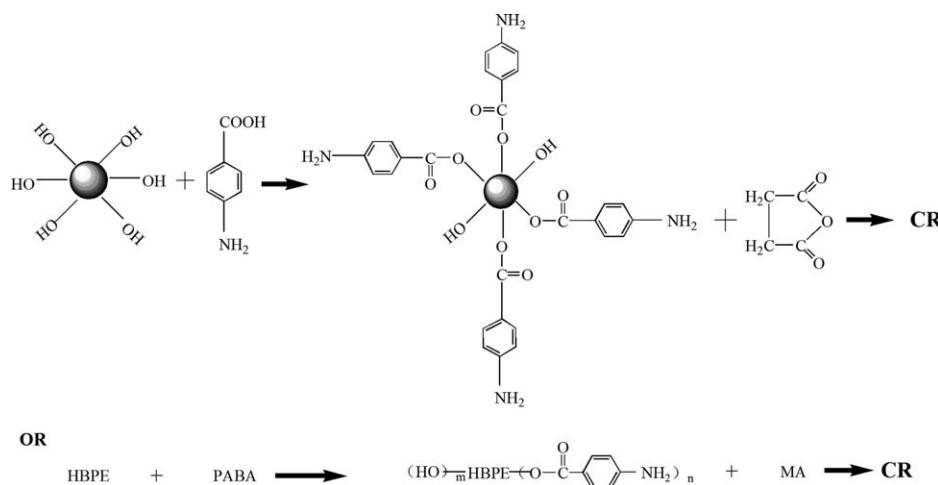
## EXPERIMENTAL

### Raw Materials

Asphalt with a pen grade of 80/100 was used, and the physical properties of the asphalt are listed in Table I. A diglycidyl ether of bisphenol A type liquid epoxy resin was used, and its epoxy value was 0.52 mol/100 g, the viscosity at 25 °C was 13.2 Pa s, and the density at 25 °C was 1.15 g/cm<sup>3</sup>. The resin was made in Nantong Xingchen Synthetic Material Co., Ltd. (Nantong, China). Hyperbranched polyether (HBPE) was produced by the Suzhou HyPerT Resin Science & Technology Co., Ltd. (Suzhou, China). The *p*-aminobenzoic acid (PABA) was provided by Changzhou Sunlight Pharmaceutical Co., Ltd. (Changzhou, China). Maleic anhydride (MA) was obtained from Jiaying Fine Chemical Co., Ltd. (Zhejiang Province, China). The curing agent (CR) was synthesized from HBPE in two steps, as shown in Figure 1. First, the aminated HBPE was obtained by the esterification reaction of hydroxyl-terminated HBPE and PABA. Second, the aminated HBPE was reacted with MA to prepare CR.

### Preparation of the EA Binder

The asphalt was heated to 165 ± 5 °C in an oil bath until it liquefied. The diglycidyl ether of bisphenol A type epoxy resin was mixed with 39 phr CR, and the mixture was added to asphalt and mixed at 500 rpm for 5 min to obtain a homogeneous blend.

**Figure 1.** Scheme for the synthesis of the CR.

**Table II.** Surface-Free-Energy Components of the Test Liquids for Asphalt (25 °C)

Probe liquid	Surface-free-energy components (mJ/m <sup>2</sup> )		
	Surface free energy	Dispersion force	Polarity force
Water	72.8	21.8	51.0
Glycerol	65.2	28.3.0	36.9
Formamide	59.1	39.2	19.9

The optimum amount of CR was selected according to the maximum tensile and impact strengths of the prepared EA binder. The test specimens were then molded in a silicone mold and cured in an air-circulating oven. The curing conditions were 4 h at 165 °C and 4 days at the 60 °C before the samples were subjected to final performance tests.

### Measurements

A Brookfield viscometer (model DV-II+, Brookfield Engineering, Inc.) was used to measure the viscosity of EA according to ASTM D 4402. Predetermined amounts of EA were poured into the sample chamber and placed inside the oven immediately to minimize the reaction between the epoxy resin and CR. The spindle was then lowered into the chamber that had been preheated to the testing temperature.

The tensile strength and elongation at break of the EA binders were tested on a universal testing machine (CMT 5105, Shenzhen SANS Test Machine Co., Ltd., China) with a tensile test method according to ASTM D 638. The strain rate was 500 mm/min. Each reported tensile strength and elongation at break is an average of five successive measurements.

The compatibility between the epoxy resin and the asphalt was verified as follows. The EA binder was poured into an aluminum foil tube (25 mm in diameter and 140 mm in height). After the tube was vacuum-sealed, it was stored vertically in an oven at 165 ± 5 °C for 3 h and at 25 ± 1 °C for 4 days. Then, it was left in the oven and allowed to cool to ambient temperature. The cylindrical asphalt specimen was cut horizontally into three equal height sections. The Soxhlet extraction method (ASTM C613-14) was used to extract the top 1/3 section and bottom 1/3 section in an aluminum foil tube. The solvent used was toluene. Control tests proved that toluene was able to dissolve asphalt, but it could not dissolve the cured epoxy resin. The residue was dried in an oven at 60 °C to a constant weight. The amount of residue in the specimens was calculated with eq. (1):

$$\% \text{ Residue} = \frac{m_1 - m_0}{m - m_0} \times 100 \quad (1)$$

where  $m$  is the weight of the total solid containing filter paper before extraction,  $m_0$  is the weight of the filter paper, and  $m_1$  is the weight of the total solid containing filter paper after extraction.

The morphology of the EA binder was observed with a fluorescence microscope (model BM2100, Nanjing Jiangnan Novel Optics Co., Ltd., China) at room temperature. The squashed slides of the

EAs were prepared with small amounts of heated specimen and observed with the microscope at 400 × magnification.

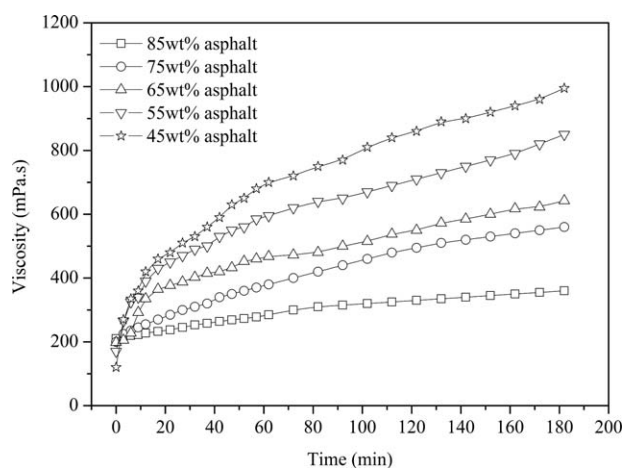
The glass-transition temperature ( $T_g$ ) of the EA binders was tested by dynamic mechanical analysis (DMA; model Q800/2980, TA Instruments, Inc., New Castle, DE) with single-cantilever bending mode. The specimen for DMA was prepared the same way as described earlier with dimension of 35 × 12 × 3 mm<sup>3</sup>. The tests were performed from -40 to 60 °C with a frequency of 1 Hz at a heating rate of 3 °C/min.

The contact angle and surface free energy of the EA binders were tested with a dropping shape analyzer (model JGW-360B-L, Chenghui Test Co., Ltd., China) at 25 °C. Water, ethylene glycol and glycerol were selected as probe liquids. Drop shape analysis is a convenient way to measure contact angles and, thereby, determine surface energy. The surface-free-energy component of the test liquids are shown in Table II. To assess the contact angle between the EA binder and the probe liquid, the aluminum plate with EA binder had to be prepared. Specimens were placed in a position so that they could be captured by an accurate camera before measurement. A small droplet of liquid was dropped on the surface of the EA binder by an accurate micropump, which was connected with a syringe located on the top of the specimen. The recorded image of the droplet was analyzed. The contact angle and surface energy were then obtained with image process software.

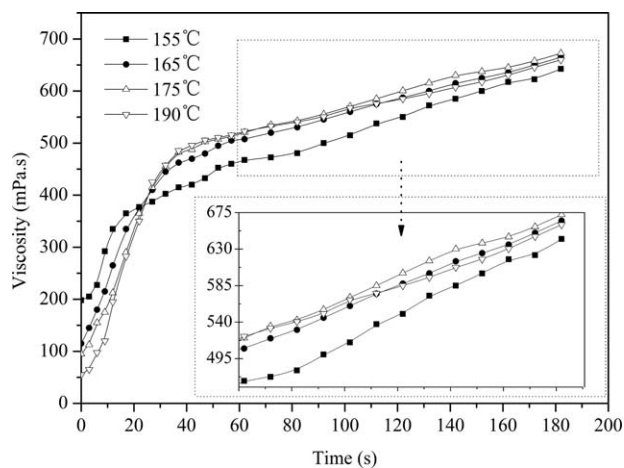
## RESULTS AND DISCUSSION

### Viscosity

Unlike thermoplastic asphalt, EA binder is a thermosetting material. The viscosity of an EA binder increased during curing, and the epoxy resin content of the EA binder affected the viscosity. Therefore, the mixing time and temperature were carefully controlled so that the aggregate particles were uniformly coated with the EA binder. The effects of the asphalt content on the viscosity of the EA binder at 165 °C are presented in Figure 2. As shown, the asphalt content had a significant effect on the viscosity of the EA binder. In the initial stage of curing, the viscosity of EA binder increased with increasing asphalt content. This was attributed to the high viscosity of asphalt. However, the



**Figure 2.** Effects of the contents of asphalt on the viscosity of the EA binder at 165 °C.

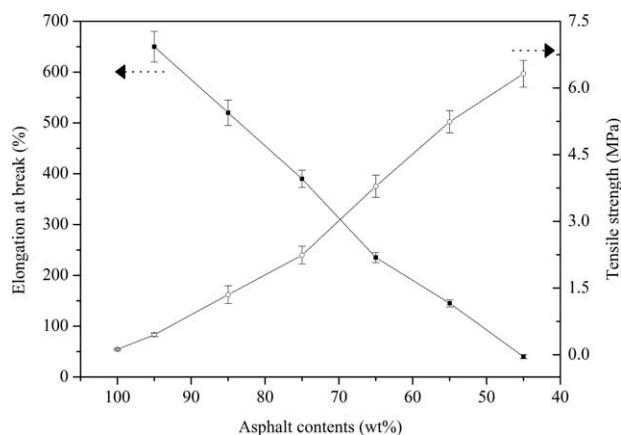


**Figure 3.** Effects of the temperature on the viscosity of EA binders containing 65 wt % asphalt.

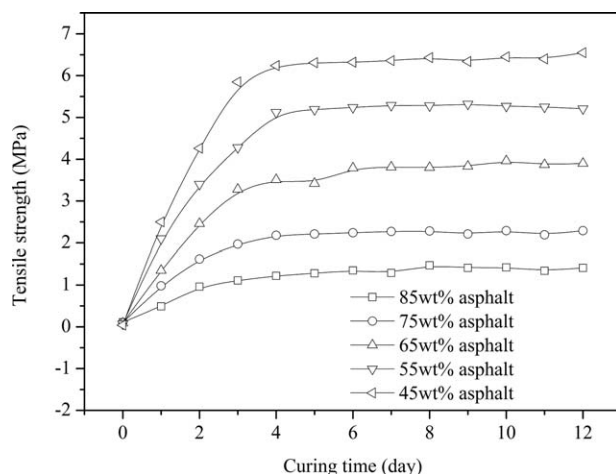
viscosity increased rapidly when the EA binder contained less asphalt. The initial viscosities were 120, 170, 198, 200, and 210 mPa s for the EA binders containing 45, 55, 65, 75, and 85 wt % asphalt, respectively. In addition, the effects of the temperature on the viscosity of the EA binders containing 65 wt % asphalt are shown in Figure 3. The results indicate that the temperature had a significant effect on the viscosity of the EA binder as well. In the initial stage of the curing reaction, the viscosity of the EA binder decreased with increasing temperature. The viscosity increase was faster at higher temperatures. According to Figures 2 and 3, the original viscosity of all of the EA binders was about 200 mPa s, and it was less than 1000 mPa s before the 180-min curing time at 165 °C. The initial viscosity met the requirements of the mix of EA and aggregates, and the viscosity before the 180-min curing time at 165 °C will ensure compaction during pavement construction. Therefore, the EA mixture had a sufficient time for mixing, transport, paving, and compaction.

### Mechanical Properties

The tensile strength and elongation at break of the EA binders containing different amounts of asphalt are presented in Figure 4. The results indicate that the tensile strength of the EA binder increased and the elongation at break decreasing with decreasing asphalt



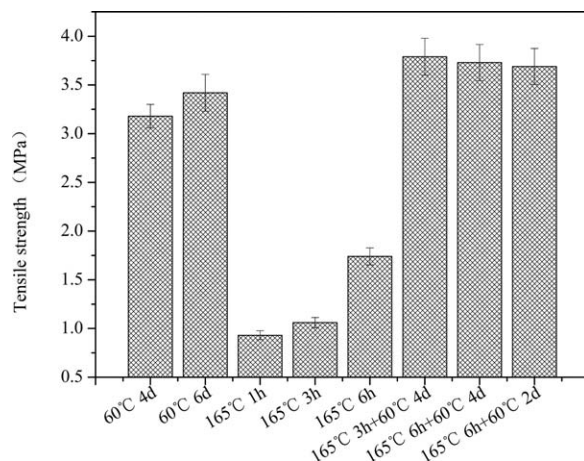
**Figure 4.** Effects of the asphalt content on the mechanical properties of the EA binder.



**Figure 5.** Effects of the curing time on the mechanical properties of the EA binder at 60 °C.

content. Unlike other composite materials, the tensile strength of an EA binder is linearly related to the asphalt content. The elongation at break is one of the most critical parameters predicting the ductility and flexibility of an EA binder. The elongation at break of EA binders containing 95 wt % asphalt is 650%, but it is only 40% when 45 wt % asphalt is mixed with the epoxy resin. Original asphalt is a rubberlike elastic material. The elongation at break of the original asphalt was much higher compared with that of the EA binder, but the cured epoxy resin had little ductility or flexibility. Therefore, the EA binder showed a lower elongation at break.

The tensile strength of the EA binder was attributed to the cured epoxy resin. Epoxy resin is a typical thermosetting material, so the epoxy resin content and curing time influenced the tensile strength. Figure 5 shows the effect of curing on the mechanical properties of the EA binders containing different contents of asphalt at 60 °C. The results indicate that the tensile strength increased with decreasing asphalt content and increased with longer curing times. Furthermore, during the first 4 days, the tensile strength increased rapidly. After 4 days, the cure was completely redundant. The curing conditions also affected the tensile strength. Figure 6 shows the effects of the curing conditions on



**Figure 6.** Effects of the curing process on the mechanical properties of the EA binder.

**Table III.** Compatibility of EA Binders Containing Different Contents of Asphalt

Sample	% Residue				Difference (%)
	Top	Coefficients of variation (%)	Bottom	Coefficients of variation (%)	
Epoxy resin	99.78	0.12	99.77	0.09	-0.01
Asphalt	0.01	0.22	0.01	0.14	0
EA-85% asphalt	13.32	1.27	16.77	0.94	3.45
EA-75% asphalt	22.83	0.69	27.35	1.12	4.52
EA-65% asphalt	32.27	0.86	38.68	0.64	6.41
EA-55% asphalt	41.68	2.59	49.82	1.41	8.14
EA-45% asphalt	49.53	3.49	61.76	1.16	12.23

the mechanical properties of the EA binder. The results indicate that the curing conditions significantly affected the tensile strength. High curing rates could be obtained either at high temperatures or longer curing times. As shown in Figure 6, the curing rate of the EA binder was neither too high at high temperatures nor too low at low temperatures. The tensile strengths were high when the blends were cured at 165 °C for 3 h and 60 °C for 4 days. Such curing conditions are appropriate for EA concrete construction as the temperature of mixing and transportation is 165 °C, and such processes usually take less than 3 h. Most of the strength is generated after 3 h at 165 °C, and this ensures the workability of EA concrete.

#### Compatibility

One of the main problems for the industrial application of modified asphalt binders is the potential phase separation that can occur after the preparation of the modifier/asphalt blend. Because of the lack of compatibility of some modifiers with asphalt, once the modifier is dispersed into the asphalt phase, the modified asphalt binder will undergo phase separation when the binder is stored/or applied at elevated temperatures. EA is a thermodynamically immiscible mixture. When epoxy resin is blended with asphalt, the epoxy resin is not soluble in asphalt, or asphalt is not soluble in the epoxy resin. In practice, once the epoxy resin and asphalt are mixed, it is a liquid state at the paving application temperature. Because of the differences in the molecular weight, density, viscosity, solubility parameter, and polarity between the epoxy resin and asphalt, phase separation would take place in EA. Droplets of the epoxy resin dispersed in EA binder are usually accumulated and slunk down asphalt during transportation. In addition, the use of compatible epoxy resin and asphalt may facilitate the preparation of EA binder; this means that homogeneous EA binders can be obtained with a rapid blending time. It is a major factor to prepare EA mixture quickly and to prolong the working time of the EA mixture for construction. A combination of storage testing and Soxhlet extraction was used to evaluate the compatibility of EA in this study. The compatibility of EA binders containing different contents of asphalt is given in Table III. We observed from the results that the coefficients of variation for all of the test data were in the range from 0.12 to 3.49%; this indicated that the experimental data were repeatable. Furthermore, the residue gap between the top and bottom of the tube was almost zero. The residue was 0.01 for asphalt; the residues

were 99.78 and 99.77% for the top and bottom epoxy resins. Thus, this experiment was a simple and practical method to research the compatibility of the EA binder. The residue gaps between the top and bottom of the tube were 3.45, 4.52, 6.41, 8.14, and 12.23% when 85, 75, 65, 55, and 45 wt % of asphalt were added to the EA binder, respectively. The result shows that the residue gap between the top and bottom of the tube decreased when the contents of asphalt increasing and the residue gap between the top and bottom of the tube were larger when the EA binder contained 45 wt % asphalt. In previous research, the compatibility of EA binder was poor, and the solubilizer had to be added to improve the compatibility of EA.<sup>11</sup> However, the experimental results indicated that an EA binder with better compatibility was prepared successfully. This may have been due to the use of a various functional group CRs.

#### Morphology

Fluorescence microscopy is probably the most frequently used techniques for assessing the status of dispersion of a polymer in a polymer-modified asphalt binder. The technique is extremely useful and well validated for the study of the morphology of polymer-modified asphalt and for determining the quality and nature of the dispersion of the polymer within the modified binder. The asphalt-rich phase appears dark or black, whereas the polymer-rich phase appears light or yellow-green. The polymer-rich phase is gray if viewed in black and white. Figure 7 shows that the fluorescence micrographs of the EA binders containing different amounts of asphalt. In the fluorescence micrographs, as shown in Figure 7(a,b), the epoxy resin phase appeared light gray, whereas the asphalt phase appeared dark black. A distinction could be made between the EA binders, whose continuous phase was an asphalt matrix with dispersed epoxy resin when high contents of asphalt were added to the asphalt. The continuous phase was an epoxy resin matrix with dispersed asphalt globules when the EA binder contained higher contents of epoxy resin. As illustrated in Figure 7, the images showed a clear change in the morphology of the EA binder as the epoxy resin content increased. At high asphalt content (>75 wt %), the epoxy resin phase was spread homogeneously in a continuous asphalt binder phase, especially 95 wt % asphalt in EA binder, as shown in Figure 7(c). At lower asphalt content (<75 wt %), a continuous epoxy resin phase dispersed asphalt phase was observed, as shown in Figure 7(f-h). In this situation, the properties of the blend were primarily determined by the

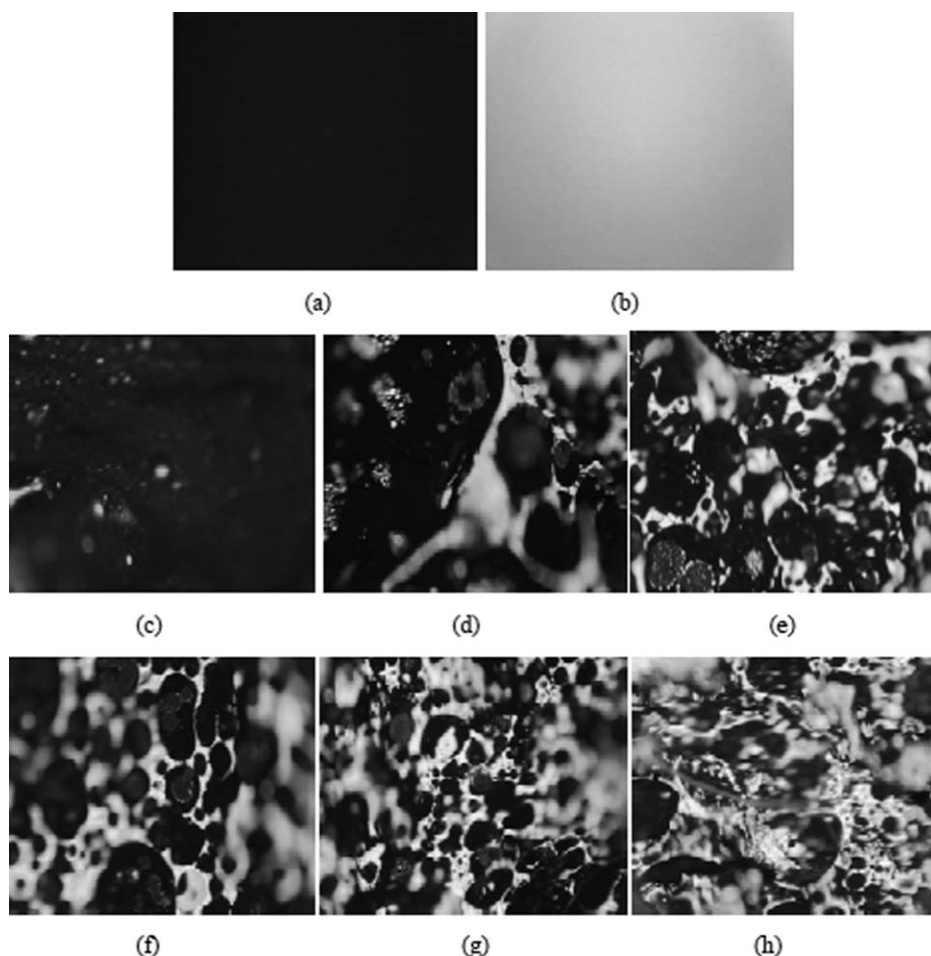


Figure 7. Fluorescence micrographs of the EA binder containing different asphalts.

epoxy resin phase. EA binders with this phase morphology have high mechanical properties, bonding performance, and softening points; this made the EA mixture show better performance and resulted in improved durability. At an epoxy resin content of 75 wt %, two twisted continuous phases were observed, as shown in Figure 7(e). The two interlocked phases formed a network structure, which could improve the properties of the asphalt. Some research has indicated that the phase morphology of two interlocked continuous phases is an ideal macrostructure for polymer-modified asphalt binders, and the optimum polymer content was determined on the basis of the formation of the critical network between the asphalt and polymer.

### $T_g$

Viscoelastic materials typically exist in two distinct states. They exhibit properties of a glass (high modulus) at low temperatures and those of a rubber (low modulus) at higher temperatures. By scanning the temperature during DMA measurement, we could observe this change of state, the glass transition. The DMA technique is more susceptible and yields more easily interpreted data. Thus,  $T_g$  was calculated by DMA. In addition, DMA is also useful for evaluating viscoelastic materials that have mechanical properties that exhibit time, frequency, and/or temperature effects. DMA is the most sensitive of all thermal analytical techniques. The EA binder is a blend of thermosetting

epoxy resin and thermoplastic asphalt. The mechanical properties can be enhanced for epoxy resin.  $T_g$  of the EA binder provides important data that assist designers or engineers in the choice of material for their pavement related to the required service temperature. The loss tangent ( $\tan \delta$ ) of EA binder containing different asphalts as a function of the temperature is illustrated in Figure 8. The temperature at which  $\tan \delta$  is a

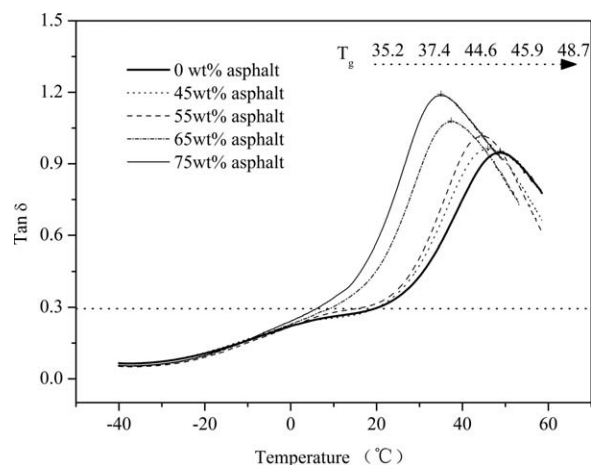
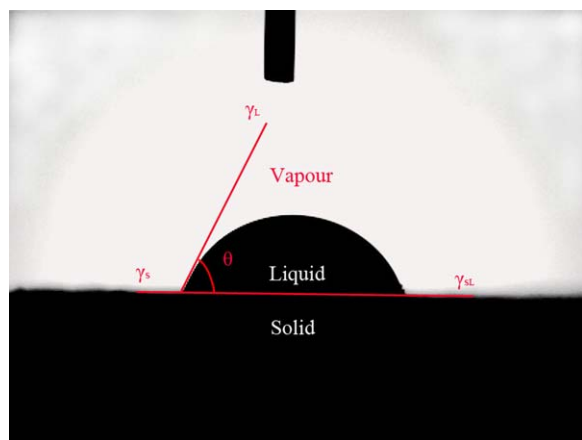


Figure 8. Temperature dependence of  $\tan \delta$  on the EA binder.



**Figure 9.** Schematic diagram of the contact angle test ( $\gamma_{LV}$  is Interfacial energies of liquid-vapor,  $\gamma_s$  is interfacial energies of solid-vapor,  $\gamma_{SL}$  is interfacial energies of liquid-solid). [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).]

maximum is defined as  $T_g$ . The results indicate that the asphalt contents had a remarkable effect on the  $T_g$  of EA binder. As shown in Figure 8, the EA binder with high asphalt content (>65 wt %) had a single  $\tan \delta$  peak. However, the EA binder with low asphalt content (<65 wt %) had two  $\tan \delta$  peaks. Although the peak that appeared at 5 °C was very small, it could be attributed to the phase separation between the asphalt phase and the epoxy resin. A larger peak around 40 °C was obviously observed. The  $T_g$  of the epoxy resin was 48.7 °C, but the  $T_g$  values of the EA binder were 45.9, 44.6, 37.4, and 35.2 °C when 45, 55, 65, and 75 wt % of asphalt was blended with epoxy resin. In comparison with epoxy resin, the  $T_g$  of EA was lower. Therefore, we concluded that the addition of asphalt had a significant influence on the  $T_g$  of EA. To obtain a better compatible EA binder, the content of asphalt could not be lower than 55 wt % in an EA binder.

#### Contact Angle and Surface Free Energy

The sessile drop method is an optical measurement method based on the contact angle and can be used to evaluate the solid surface wettability. The schematic diagram of the contact angle test is shown in Figure 9, and it has two fundamental assumptions. First, the droplet has vertical symmetry. Second, the droplet shape was only related to the interfacial tension and the droplet gravity. The contact angles between the EA binder and

the three test liquids are given in Table IV, and the coefficients of variation of the contact angles are shown as well. We observed from the results that the coefficients of variation for all of the test data were in the range from 0.29 to 2.84%; this indicated that the experimental data were repeatable. The contact angle was determined by the results between the adhesive and cohesive forces at equilibrium. When the tendency of the drop to spread out over a flat, solid surface increased, the contact angle decreased. The contact angle provided a force balance between the adhesive and cohesive forces; this resulted from intermolecular interactions when the two materials were brought together in contact. A contact angle of less than 90° usually indicates that wetting of the surface is very favorable, and the fluid will spread over a large area of the surface. Contact angles greater than 90° generally mean that wetting of the surface is unfavorable, so the fluid will minimize contact with the surface and form a compact liquid droplet. Moisture damage is one of the main failures of asphalt pavement. It is important to analyze the contact angle between water and the EA binder. Table IV indicates that the contact angles between water and EA binder were all greater than 90°; this implied that the EA binder was hydrophobic and could not be wetted by water. Furthermore, the contact angles increased in general when the content of asphalt decreased. The polar part of the surface free energy for water was 51.0 mJ/m<sup>2</sup> at 25 °C. Thus, the polarity of water was high. The polarity of the EA binder was expected to be reduced after curing, and the greater the increment was, the lower the content of asphalt was.

The failure of asphalt concrete caused by moisture could be attributed to adhesive and/or cohesive damage within the asphalt concrete. Adhesion between the asphalt binder and aggregate could be described mainly as a fundamental characteristic. Fundamental adhesion refers to the forces that exist on the surface, and it affects the bond strength between the asphalt and aggregate. The tendency of these forces to form a surface is known as the surface energy and is defined as the work required to create a unit area of new surface of a material in a vacuum. The surface-free-energy components of EA binders containing different contents of asphalt are shown in Table V. As the results show, the surface free energy and dispersion force increased when the content of asphalt decreased. However, the polarity forces decreased when the content decreased. This was in accordance with the results of the contact angle. In addition,

**Table IV.** Contact Angle of EA Binders Containing Different Contents of Asphalt

Sample	Water		Glycerol		Formamide	
	Average (°)	CV (%)	Average (°)	CV (%)	Average (°)	CV (%)
Asphalt	105.6	1.26	96.7	0.83	89.1	0.49
EA-85% asphalt	105.9	1.03	97.1	1.59	88.6	0.84
EA-75% asphalt	106.3	1.68	97.4	1.36	88.2	1.13
EA-65% asphalt	107.5	0.73	98.6	0.74	86.8	2.84
EA-55% asphalt	107.4	0.92	98.9	0.62	86.2	0.31
EA-45% asphalt	108.1	0.29	99.1	0.65	86.1	1.03

**Table V.** Surface-Free-Energy Components of EA Binders Containing Different Contents of Asphalt (mJ/m<sup>2</sup>)

Sample	Surface free energy	Dispersion force	Polarity force
Asphalt	17.64	16.40	1.24
EA-85% asphalt	18.20	17.17	1.03
EA-75% asphalt	18.86	18.03	0.83
EA-65% asphalt	21.21	20.88	0.33
EA-55% asphalt	21.73	21.45	0.28
EA-45% asphalt	22.57	22.40	0.17

the dispersion part of the surface energy was dominant compared to the polar part of the total surface energy.

## CONCLUSIONS

EA binders were prepared by the mixture of asphalt, epoxy resin, and a new CR. A series of material properties was investigated. The viscosity of EA met the requirements of the EA mixture, and EA mixture had sufficient time for mixing, transport, paving, and compaction. Most strength was generated after 3 h at 165 °C and before 4 days at 60 °C. Two twisted continuous phases were observed, and it was an ideal macrostructure for an EA binder containing 75 wt % asphalt. EA binder with better compatibility was prepared successfully with the CRs containing various functional groups. Compared with epoxy resin, the  $T_g$  of EA was lower. Therefore, the addition of asphalt significantly improved the  $T_g$  of EA. The epoxy resin in EA increased the surface free energy and dispersion force of EA, but the polar forces decreased.

## ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (contract grant number 51208050) and the Special Fund for Basic Scientific Research of the Transportation Department (contract grant number 2013 319 812 020). It was also supported by the Overall Innovation Project of the Shaanxi Province Science and Technology Plan Project (contract grant number 2013KTCQ01-40).

## REFERENCES

- Lu, Q.; Bors, J. *Constr. Build. Mater.* **2015**, *78*, 18.
- Gürü, M.; Kürşat Çubuk, M.; Arslan, D.; Farzarian, S. A.; Bilici, İ. *J. Hazard. Mater.* **2014**, *279*, 302.
- Sengoz, B.; Isikyakar, G. *J. Hazard. Mater.* **2008**, *150*, 424.
- Moghaddam, T. B.; Soltani, M.; Karim, M. R. *Mater. Des.* **2015**, *68*, 88.
- Fondriest, F. F. Final Report on Laboratory Evaluation of Various Paving Materials for Orthotropic Steel Deck Bridges; Battelle Memorial Institute: Columbus, OH, **1969**.
- Moghaddam, T. B.; Soltani, M.; Karim, M. R. *Mater. Des.* **2014**, *53*, 317.
- Moreno, F.; Rubio, M. C. *Mater. Des.* **2013**, *47*, 61.
- Moreno, F.; Sol, M.; Martín, J.; Pérez, M.; Rubio, M. C. *Mater. Des.* **2013**, *47*, 274.
- Modarres, A.; Hamed, H. *Mater. Des.* **2014**, *61*, 8.
- Cong, P. L.; Chen, S.; Yu, J. *J. Appl. Polym. Sci.* **2011**, *121*, 2310.
- Cong, P. L.; Chen, S.; Yu, J.; Chen, H. *Int. J. Pavement Res. Technol.* **2011**, *4*, 118.
- Cong, P. L.; Yu, J.; Chen, S. *J. Appl. Polym. Sci.* **2010**, *118*, 3678.
- Yu, J.; Cong, P. L.; Wu, S. *J. Appl. Polym. Sci.* **2009**, *113*, 3557.
- Larrard, F. D.; Garcin, O.; Hammoum, F.; Travers, F. Preliminary Tests on a Hydraulic Surface Dressing for Wearing Courses with a Long Life Cycle; Research Board, No. 1654, TRB; National Research Council: Washington, DC; Paper No. 99-1049. p 141, **1999**.
- Yu, J.; Cong, P. L.; Wu, S.; Cheng, S. *J. Wuhan Univ. Tech. Mater. Sci. Ed.* **2009**, *24*, 462.
- Cong, P. L.; Chen, S.; Chen, H. *Highway* **2012**, *10*, 167.
- Herrington, P.; Alabaster, D.; Arnold, G.; Cook, S.; Fussell, A.; Reilly, S. Epoxy Modified Open-Graded Porous Asphalt: Economic Evaluation of Long-Life Pavements: Phase II, Design and Testing of Long-Life Wearing Courses; Land Transport New Zealand Research Report 321; Land Transport New Zealand: Wellington, New Zealand, **2007**.
- Simpson, W. C.; Sommer, H. J.; Griffin, R. L.; Miles, T. K. *J. Air Transport Div. Proc. Am. Soc. Civ. Eng.* **1960**, *86*, 57.
- Joseph, A. H. Behavior of Epoxy-Asphalt Airfield Pavements 1963 Inspections; Miscellaneous Paper No. 4-704; USA Army Engineer Waterways Experiment Station: Vicksburg, MS, **1965**.
- EAPA. Airfield Uses of Asphalt. Reference (3)2-03-00.015; Breukelen, Netherlands, **2003**.
- Cong, P. L.; Liu, J.; Zhao, Z.; Chen, S. *J. Zhengzhou Univ. (Eng. Sci.)* **2014**, *35*, 78.
- Simpson, R. L.; Griffin, W. C.; Sommer, H. J.; Miles, T. K. Design and Construction of Epoxy Asphalt Concrete Pavements. Presentation at the Meeting of the Highway Research Board of the National Research Council, Washington, DC, **1960**.
- Herrington, D. Epoxy-Modified Porous Asphalt; NZ Transport Agency Research Report 410; NZ Transport Agency; Wellington, New Zealand, **2010**.