Construction and Building Materials 176 (2018) 165–171

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Comparative analysis of cold-mixed epoxy and epoxy SBS-modified asphalts: Curing rheology, thermal, and mechanical properties

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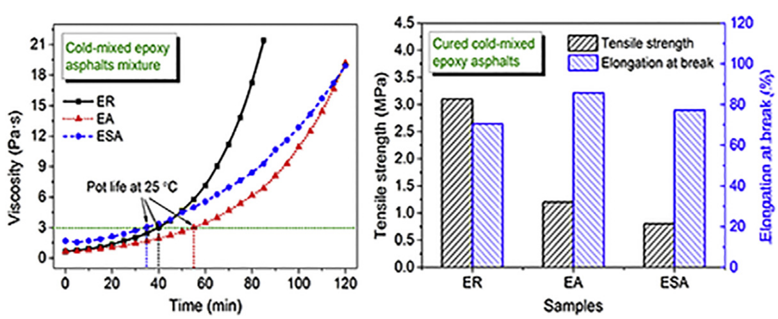
HIGHLIGHTS

- The cold-mixed epoxy asphalts are prepared.
- Compared with ESA, EA shows better processability at ambient temperature.
- EA is thermal stable due to 3D networks and high thermal stability of asphalt.
- EA shows high mechanical property due to 3D networks and good compatibility.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 January 2018
Received in revised form 16 April 2018
Accepted 5 May 2018

Keywords:
Cold-mixed epoxy asphalt
Curing rheology
Thermal properties
Mechanical properties

ABSTRACT

The research evaluated the properties of cold-mixed epoxy asphalt (EA) and cold-mixed epoxy styrene–butadiene–styrene (SBS)-modified asphalt (ESA) for paving steel-deck bridges. Compared with ESA, EA showed longer pot life and better processability at ambient temperature, as revealed by curing rheology analysis. The cured EA showed higher glass-transition temperature, superior thermal stability, tensile strength and elongation at breaking than ESA. These may be as a result of: (i) the high thermal stability of asphalt, (ii) the formation of a cross-linking network in the cured material, and (iii) the good compatibility between the epoxy resin and the asphalt.

1. Introduction

Epoxy asphalts are thermosetting materials that have attracted increasing attention due to their excellent performance as paving materials on orthotropic steel deck bridges [1–4]. In this sense, epoxy asphalts have been used to pave the Westgate (Australia), Erskine (Scotland), and Humber (England) bridges [1]. Epoxy asphalts were introduced in China at the end of the 20th century and first used on the Nanjing Second Yangtze River bridge [5–7]. The epoxy asphalt pavement layer used on this bridge exhibited superior performance and durability. Epoxy asphalt-related technologies have been intensively studied, and this material has become one of the most popular asphalt pavings for steel-deck bridges and roadways [1,2,8–10].

Epoxy asphalts usually consist of two components namely: A (mainly epoxy resin, ER) and B (comprised of asphalt, curing agent, and other additives such as diluent, flexibilizer, coupling reagents,

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https://doi.org/10.1016/j.conbuildmat.2018.05.035
0950-0618/

among others) [11,12]. Once components A and B are mixed, the resultant mixture is cured and three-dimensional (3D) networks is formed as a result. The presence of curing networks provides the cured epoxy asphalt with excellent mechanical, thermal, and aging resistance properties [13–15].

Epoxy asphalts are usually hot-mixed, and must be used and cured at high temperature (>170 °C) [16]. However, the utilization of high curing temperatures causes numerous drawbacks while using epoxy asphalts. First, special equipment is required to prepare, transport, and pave the epoxy asphalt mixture. Second, the overall consumption of energy increases during the application of epoxy asphalts. Most importantly, toxic fumes are released from the epoxy asphalt at high temperature, which are harmful to the environment and construction workers [17].

Thus, decreasing the construction temperature of the epoxy asphalt is effective in saving energy and protecting the environment and construction workers. Compared to traditional hot-mixed epoxy asphalts, warm- and cold-mixed epoxy asphalts (EAs) are emerging technologies. Warm-mixed epoxy asphalts can save energy by reducing the construction temperature by 30–50 °C [18]. Foaming technologies have been effective for decreasing the construction temperature of asphalt to prepare warm-mixed asphalt [19–22]. The same is true for foamed asphalt where foaming technology was used for preparing warm-mixed epoxy asphalt [18]. Recently, the research group of the authors has developed a foamed epoxy asphalt and investigated the influence of the foaming water content on the epoxy asphalt rheological properties and microstructure [17]. Then the construction temperature was further decreased to obtain EA that was used and cured at ambient temperature. EAs are green materials for paving steel-deck bridges, which combined the excellent thermal and mechanical performance of hot-mixed epoxy asphalts with unique characteristics such as convenience, energy conservation, and environmental protection.

As a kind of thermoplastic/thermosetting polymer blend, the construction process, thermal stability, and mechanical properties of cured epoxy asphalts depend on the curing behaviors of epoxy asphalt blends. These characteristics of hot- and warm-mixed epoxy asphalts have been studied and developed [13,23–26]. In order to accelerate the post-curing of epoxy asphalt composites (EACs), 2,4,6-tris(dimethylaminomethyl)phenol (DMP-30) was encapsulated into EACs, and the laboratory effects on accelerated post-curing of EACs were investigated systematically by Song *et al.* [25]. Ai *et al.* [26] studied the possibility of using microwave heating for epoxy asphalt curing, and investigated the effects of microwave heating on chemical and physical properties of epoxy asphalt.

For EAs, the curing time should be adequate and the dynamic viscosity should be below 3 Pa · s to agree with the construction process at ambient temperature [27]. In order to obtain low-viscosity EA and ESA mixture (during laying and compaction) at ambient temperatures, reactive diluents for epoxy resin and asphalt were used. The diluents may take part in the curing process of EA and ESA to form the 3D network of the cured EA and ESA. In addition, the ER is polar material with epoxy group, and the asphalt is non-polar material, the compatibility between them is relatively poor, especially the EA blends at ambient temperature. This may result in decreased mechanical properties in epoxy asphalt pavement [16,28]. Therefore, it is necessary to research curing behavior and compatibility of EA blends at ambient temperature, and thermal stabilities and mechanical properties of cured EAs.

In this paper, EA that was cured at ambient temperature was obtained, and was compared with the cold-mixed epoxy styrene–butadiene–styrene (SBS)–modified asphalt (ESA). The curing rheology, thermal, mechanical, and micro-morphology properties of EA were investigated and compared with those of ESA to assess the effects of asphalts on the performance of EAs. This study attempted to promote understanding of the relationship between structure and performance of EAs, which will promote the development and wider application of EAs in paving steel-deck bridges and roadways.

2. Materials and methods

2.1. Materials

Base (70#) and SBS-modified asphalts were supplied by Tongsha, China. The properties of the base and SBS-modified asphalts are listed in Tables 1 and 2, respectively. E-51 epoxy was supplied by Wuxi Resin (Wuxi, China). The diluter for component B and a polyamide curing agent were prepared in the laboratory. The epoxidized soybean oil (Chemical pure) and γ-(2,3-epoxypropoxy) propyl trimethoxysilane (97% pure) were purchased from Aladdin Industrial Corp. (USA), and were used as received.

2.2. Preparation of the epoxy asphalt

The EA or ESA was composed of components A and B, the former comprised of epoxy E-51. Component B was prepared by mixing the asphalt or SBS-modified asphalt, curing agent, and other additives. The asphalt was heated to 120 °C for more than 30 min until it was sufficiently fluidized, and subsequently poured into a 250 mL three-necked flask. The diluter was subsequently added, and the mixture was stirred and refluxed at 120 °C for 1 h. The mixture in the flask was allowed to cool below 40 °C, after which the curing agent, the epoxidized soybean oil, and γ-(2,3-epoxypropoxy) propyl trimethoxysilane were added and the mixture stirred for 1 h at ambient temperature to finally obtain component B. Components A and B were subsequently stored and sealed for curing and further testing. An ER consisting of E-51 and a curing agent were also prepared and cured for the sake of comparison.

2.3. Preparation of cured epoxy asphalt

Cured ER, EA, and ESA were prepared for testing thermal and mechanical properties. Both the components A and B are liquid at ambient temperature, which show the viscosity of 0.725 Pa · s and 2.030 Pa · s, respectively. Components A and B were weighed and blended in a round bottom flask, and quickly agitated for 3 min until blended well. The mixture was subsequently poured into a dumbbell mold, and placed on platform for 24 h at ambient temperature. The mold with the mixture was subsequently put into an electric heat oven, and the mixture was cured for 48 h at 60 °C. Dumbbell-type specimens were demolded and stored for tensile testing. The specimens after tensile testing were used to characterize thermal and dynamic mechanical properties.

2.4. Characterization

2.4.1. Rotational viscosity test

Viscosity is an important property for evaluating the processability of epoxy asphalts. Thus, a proper viscosity is required for epoxy asphalts during the application process. Brookfield viscometer (DV-II, Brookfield Engineering Inc., USA) was used to measure the viscosity of ER, EA, and ESA materials [29]. Brookfield viscometer tests were performed at 25 °C according to the American Association of State Highway and Transportation Officials Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer (AASHTO T 316:2004).

The viscosity was measured as follows. First, components A and B were blended and quickly agitated for 3 min to obtain the EA and ESA mixtures. Second, the mixtures were immediately poured into a container at 25 °C. The viscosity data were subsequently recorded every 5 min for 120 min.

Table 1
Properties of the base asphalt.

Property	Data	Method
Density (15 °C, $g \cdot cm^{-3}$)	1.032	ASTM D 70
Penetration (25 °C, 0.1 mm)	63.2	ASTM D 5
Softening point (°C)	47.8	ASTM D 36
Ductibility (15 °C, cm)	>100	ASTM D 113
Solubility (trichloroethylene, %)	99.8	ASTM D 2042
Performance grade (PG)	PG64-22	ASTM D 946