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Laboratory investigation and numerical simulation of the rutting performance of double-layer surfacing structure for steel bridge decks

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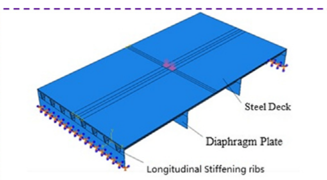
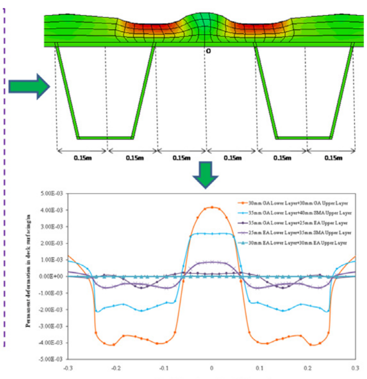
HIGHLIGHTS

- The rheological characteristics of three mixes were obtained by a repeated simple shear test.
- Creep parameters of three mixes were estimated based on the Bailey-Norton creep model.
- In a two-layer structure consisting of a single mix, rutting mainly occurs in the surface course.

GRAPHICAL ABSTRACT



Mixes	Temperature (°C)	Nonlinear Creep Model Parameters		
		A	m	n
GA	60	3.26×10^{-9}	1.064	-0.713
EA		3.00×10^{-5}	0.026	-0.815
SMA		2.51×10^{-10}	1.132	-0.763



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ABSTRACT

To optimize the surfacing structures for steel deck bridges, this study proposed new pavement structures combining two types of common surfacing mixtures, and evaluated their rutting resistance performance. A total of five pavement structures from different combinations of gussasphalt, epoxy asphalt, and stone mastic asphalt mixtures were analyzed. First the rheological characteristics of the three mixtures were obtained through a repeated simple shear test at constant height (RSST-CH). Creep parameters of the three materials were then estimated through nonlinear multiple regression analysis based on the Bailey-Norton creep model. With the estimated creep parameters, finite element models of orthotropic steel deck pavements were built to simulate permanent deformation of deck pavements at 60 °C. The simulation results were then verified by a wheel track rutting test. The study shows that in a two-layer deck pavement structure consisting of the same layer material, rutting failure mainly occurs in the surface layer. Findings from this study may be used in the design of steel deck pavement materials and structures for improved high-temperature performance.

1. Introduction

Surfacing for steel deck bridges, particularly long-span bridges, has remained a challenge in China for two decades. With a significant amount of research and practice effort devoted to this topic, a few asphalt paving materials have been selected and applied on long-span steel deck bridges in China, with both success and failure. Three of the main paving materials are Gussasphalt, epoxy asphalt, and stone mastic asphalt mixtures.

Gussasphalt (GA) is a type of asphalt mixture that is placed at high temperatures (200–240 °C) without roller compaction since

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it can automatically level into shape. It features near zero air-void content (impermeability), good corrosion resistance, high deformability, and superior cracking resistance. However, it is prone to permanent deformation at high temperatures. For example, the dynamic stability of GA is typically around 400 cycles/mm at 60 °C [1–4].

Epoxy asphalt (EA) is another type of asphalt mixture in which asphalt binder is modified with epoxy resin. It possesses good properties such as high strength, excellent rutting and fatigue resistance, and high stiffness at high temperatures due to the thermosetting nature of epoxy resin in the binder. Compared to GA, EA has lower deformation ability to match the deformation of steel deck. When used as the steel deck surfacing material, EA provides excellent cracking resistance. Top-down cracking, however, may still appear due to overloading of trucks, which is a common phenomenon in China, and propagate quickly downwards to the steel deck surface. Through cracks in steel deck pavements will significantly increase the corrosion potential of the steel deck, which will jeopardize the bridge structural integrity, and so should be prevented.

Stone mastic asphalt (SMA) is a gap-graded asphalt mixture and commonly used for highway pavements. In China, SMA containing modified asphalt has also been used for paving steel bridge decks. Its high-temperature stability and low-temperature cracking resistance are generally between those of GA and EA. Compared to EA, SMA is less resistant to rutting and fatigue cracking, but easier to maintain or rehabilitate due to its thermoplastic nature. Compared to GA and EA, SMA has high skid resistance due to the gap gradation of its aggregates.

Previously surfacing steel deck bridges with GA, EA, or SMA commonly adopted a single layer structure of the selected paving mixture, either placed in one lift (for GA) or two lifts (for EA and SMA). After observing examples of failure in some bridge paving projects with these materials, it came to the mind of some researchers, including the authors, to design a two-layer paving structure that can combine the advantages of two mixtures and alleviate each other's weakness. Initial designs were developed and tried on some bridges, such as the Dongqing experimental bridge for the Runyang Yangtze River Bridge, the JiangyinYangtze River Bridge, and the Taizhou Yangtze River Bridge. Considering the relatively low rutting resistance of GA and SMA at high temperatures, one of the key design objectives of the two-layer structure is to optimize its high-temperature stability with the inclusion of an EA layer. To this end, this study was carried out to gain insights into the permanent deformation characteristics of various two-layer surfacing structures. Specifically, the following five two-layer surfacing structures, which had been tried on long-span bridges in China, were included in the study:

1. 30 mm GA as the lower layer and 30 mm GA as the upper layer (30 mm GA + 30 mm GA) (placed on the Jiangyin Yangtze River Bridge in 1999).
2. 35 mm GA as the lower layer and 40 mm SMA as the upper layer (35 mm GA + 40 mm SMA) (placed on the Anqing Yangtze River Bridge in 2004, on the Chongqing Chaotianmen Yangtze River Bridge in 2009, and on the Shanghai Minpu Second Bridge in 2010).
3. 35 mm GA as the lower layer and 25 mm EA as the upper layer (35 mm GA + 25 mm EA) (placed on the Dongqing experimental bridge for the Runyang Yangtze River Bridge in 2002 and on the Taizhou Yangtze River Bridge in 2012).
4. 25 mm EA as the lower layer and 35 mm SMA as the upper layer (25 mm EA + 35 mm SMA) (placed on the Liujiaxia Bridge in Gansu province in 2013 and on the Tiexin Bridge in 2015).
5. 30 mm EA as the lower layer and 30 mm EA as the upper layer (30 mm EA + 30 mm EA) (placed on the Huangpu Bridge in 2008 and on the Dongsha Bridge in 2010).

The first and last structures are essentially the one layer structures (paved in two lifts) used previously. They are included for comparison purposes.

The study mainly involved the following procedures. First the rheological characteristics of the GA, EA, and SMA materials were investigated using a repeated simple shear test at constant height (RSST-CH). Creep parameters of the three materials were then estimated through nonlinear multiple regression analysis based on a time hardening model. With the estimated creep parameters, finite element models of orthotropic steel deck pavement were built to simulate permanent deformation of deck pavement at high temperatures under both conditions of standard loading and overloading. The simulation results were then verified through a composite structure rutting test. It is expected that findings from this study may provide theoretical and technical supports for design of steel deck pavement materials and structures for improved high-temperature performance.

2. Study of high-temperature creep parameters of pavement materials

To provide permanent deformation parameters of the three asphalt mixtures (GA, EA, and SMA) as inputs for finite element analysis, laboratory shear testing was first conducted under various stress conditions.

2.1. Materials and mix design

One EA mixture with a nominal maximum aggregate size (NMAS) of 9.5 mm (labelled as ED95), one GA mixture with a NMAS of 9.5 mm (labelled as GA95), and one SMA mixture with a NMAS of 9.5 mm (labelled as SMA10) are included in the study. Their aggregate gradations are shown in Table 1. One basalt aggregate type was used for all mixtures.

The EA binder is a two-phase system in which the continuous phase is a thermosetting epoxy resin and the discontinuous phase is asphalt and curing agent. The basic properties of the three components (Pen 60/80 asphalt, epoxy resin, and curing agent) and the fully cured EA binder are shown in Table 2. The GA binder is a mix of a Pen 20/40 asphalt (i.e., the asphalt penetration is 20–40 dmm) and a Trinidad Lake asphalt (TLA), blended at a mass ratio of 7 (No. 30 asphalt) to 3 (TLA). The basic properties of the GA binder are

Table 1
Aggregate gradations used in the study.

Mix ID	ED95	GA95	SMA10
	Epoxy DGAC-9.5	Gussasphaltmix-9.5	SMA-10 using highly-elastic binder
Sieve size (mm)	Percentage passing (%)		
16.0	100.0	100.0	100.0
13.2	100.0	100.0	100.0
9.5	99.0	99.6	96.7
4.75	77.6	70.5	37.8
2.36	62.3	59.1	25.9
1.18	49.1	49.3	20.8
0.6	37.8	43.0	18.6
0.3	24.6	36.7	15.2
0.15	18.0	33.2	13.6
0.075	11.4	25.9	11.3
Binder Content (%)	6.5	8.5	6.0