Stiffening Thin Orthotropic Deck Structures with Thermoset Epoxy Asphalt for Improved Fatigue Resistance

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Abstract. Early fatigue cracking of the pavement was frequently observed on bridges with relatively thin decks of orthotropic design, particularly in hot climates. This study investigates the possible use of epoxy asphalt to stiffen a thin steel deck and mitigate flexural and fatigue failure. Three different epoxy asphalt binders were used and two pavement mix designs were employed. The binder and pavement mixture properties were evaluated with direct tensile test and pull-off strength test on the binder, Marshall and flexural fatigue tests on paving mixture with steel plates. Test results show that a relatively high modulus binder and a relatively stiff pavement can effectively reduce the composite's deflection and improve fatigue resistance. Binder adhesion to the aggregate in the composite seems to play a pivotal role and the strength of this bond may have a close relationship with the stiffness of the pavement.

1 Introduction

For more than 60 years, hundreds of orthotropic steel deck bridges have been successfully employed throughout the world. However, it is recognized that orthotropic bridges have not been problem-free historically. Pavement fatigue cracking has been observed frequently in such decks resulting from the complicated welded details combined with stresses that can be more difficult to quantify and, in particular, early designs which attempted to overly minimize plate thickness to reduce weight (FHWA 2012). Mainly because the inappropriate deflection-to-span requirement for early orthotropic bridge design, approximately 1/500, many bridge deck plates were designed only about 10–12 mm thick, while the stiffening rib spacing are 300 mm (AISC 1963). These may include the Auckland harbor bridge in New Zealand, Port Mann Bridge in Canada, Severin Bridge in England and many else. With rapid increase of vehicle weight and traffic volume nowadays, deflection of these thin deck bridges become higher and flexural fatigue cracking can easily occur on bridge pavement and even influence steel deck and leads to the fatigue of metal (FHWA 2012; Murakoshi et al. 2012). The purpose of this study is to find out the best bridge pavement material

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that can be used for the rehabilitation of thin deck orthotropic bridges and mitigate fatigue crack failure.

Bridge pavement design for orthotropic steel deck has followed divergent approaches. Guss asphalt system generally are multi-layer structures often in excess of 76 mm thickness using conventional or polymer-modified asphalt binder. The multi-layer structure can hardly meet the weight and density requirement for such older orthotropic bridges, take in account the dead and live load capacity of thin steel deck. America's epoxy asphalt material, on the other approach, is used in this study and the bridge pavement thickness can be designed to about 40 mm or less. Most epoxy asphalt pavement installations have exhibited excellent performance, after years of field performance survey and monitoring (Gaul 1996; Lu and Luo 2010; Jia et al. 2016).

Epoxy asphalt is thermoset, which means that it does not melt at high temperatures. Epoxy asphalt comprises two parts. Part A is epoxy resin and Part B contains asphalt, curing agent and suitable additives. After Part A and Part B are mixed according to a stoichiometric ratio to initiate the chemical reaction which ultimately leads to a cross-linked polymer structure, which can provide high stiffness, strength and adhesion in the composite. The encapsulated asphalt in the polymer structure act as an extender and possibly contributes to the flexibility of the viscoelastic structure. The material not only being used for bridge pavement, modified epoxy asphalt has also been used for pervious pavement, chip seal and other applications (OECD 2017; Alabaster et al. 2008, 2012; Wu et al. 2017).

2 Test Methodology

To the pavement technologist, orthotropic steel decks with their inherent flexibility present a particular challenge. The design of the wearing surface must take into account the flexibility of the deck, pavement mixture stability, density and weight, fatigue under heavy traffic load, as well as the skid characteristics. The following laboratory test methods were used to evaluate the epoxy asphalt and mixture properties:

- Binder direct tensile test, which gives the mechanical characterization of binder in tension.
- Marshall stability test, which is can assess the stability of the pavement immediately after placement and upon full cure.
- Flexural beam fatigue test, measures the effects of repetitive loading on the steel plate and the pavement.
- Pull-off test, measures the binder bond strength to the steel plate and gives an indirect indication to the strength of the bond to the aggregate.

3 Experimentation and Analysis

Asphalt binders do not have a tensile strength in the conventional sense because they are viscous and are in semi-liquid state even in room temperature. Epoxy asphalts become thermoset when the binder is fully cured and the polymer structure is built up. The typical laboratory process to reach full cured condition for epoxy asphalt is at 121 °C for 4 h. At room temperature, it usually takes up to 60–90 days to reach a similar physical condition in the field. Direct tensile strength test—ASTM D 412 usually used in elastomer and rubber were adopted to use in here. Figure 1 shows the full cured epoxy asphalt binder under direct tension at the testing speed of 50 mm/min. Three types of epoxy asphalt binders were used and 6–9 samples were tested for each binder type. Table 1 shows the tensile strength properties of the three epoxy asphalt binders in full cured condition.

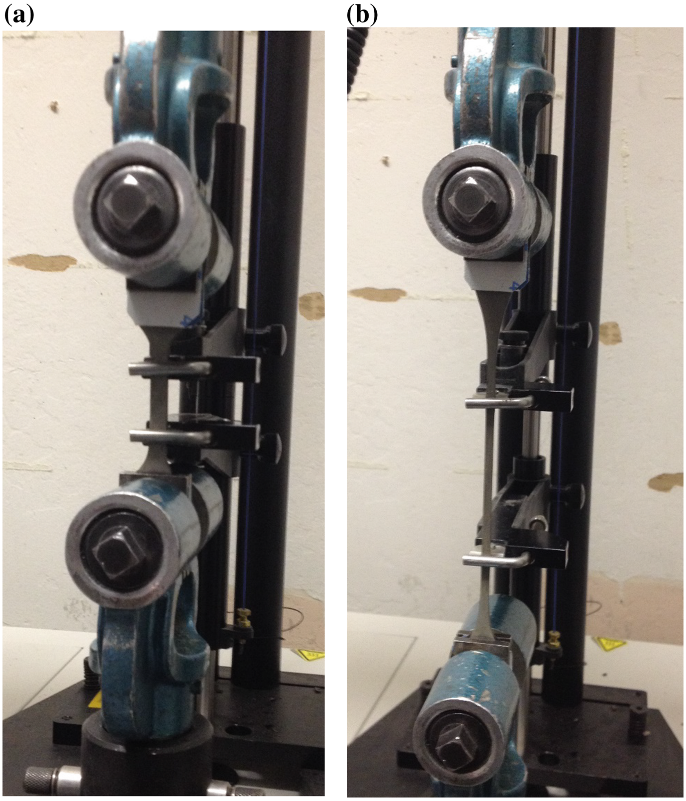

Fig. 1. Rubber and elastomer tensile strength test-ASTM D412 for full-cured epoxy asphalt binder **a** before the tensile test; **b** during the tensile test before rupture

As can be seen, Type A epoxy asphalt is a softer binder with lowest modulus, while Type C binder is much stiffer and higher in molecular weight. However, all three types of epoxy asphalts give similar elongation before rupture under direct tension, which means that although Type B and C binders are much stiffer, they do not lose much flexibility or ductility. Modulus above 100% elongation is not considered, because it is more likely in nonlinear stress-strain relationship and greater strain above 100% probably cannot be accommodated in the mixture under real load condition. All testing

Table 1. Tensile properties of epoxy asphalt in full cured condition

	Type A	Type B	Type C
Tensile strength (MPa)	7.1	10.3	19.4
% Elongation	228.5	248.5	238.5
Modulus @100% elongation (MPa)	1.42	2.98	4.33
Viscosity increase to 1000 cps @ 121 °C (mins)	32	41	54

was conducted at room temperature—23 °C. Time to 1000 cps is the viscosity condition of the epoxy asphalt after mixing and is an indicator of a recommended time length that the epoxy asphalt mixture should be delivered and placed on the bridge deck after production. A shorter time to 1000 cps viscosity usually means a shorter operational time for epoxy asphalt, and above a certain operational window, material could become too cured and harder to work with.

Mix design were attempted for both dense graded (DSG) mix and stone mastic asphalt (SMA) mix with 9.5 mm (3/8-in.) maximum size aggregate, that is, 100% passes the 12.5 mm (1/2 in.) sieve. Aggregate size distribution for the two designs are shown in Fig. 2. It is noted that the DSG gradation is very close and parallel to the maximum density line, while the SMA aggregates have a larger percentage retained on 4.75 mm (#4) sieve. The DSG uses 100% high quality basalt aggregates from China, while the SMA mixture contains 23% lightweight slate crushed fines. The philosophy of SMA is to use high quality coarse aggregates with stone-to-stone contact. However, lightweight aggregates were introduced in this mix to help reduce the density and weight of bridge pavement, and coarse stone mastic structure can provide a rougher surface texture and better skid resistance at the same time. The Marshall Method of Mix Design is used for stability, flow and void analysis for the two types of mixtures, and the optimum binder content were determined based on the lowest air voids of com-

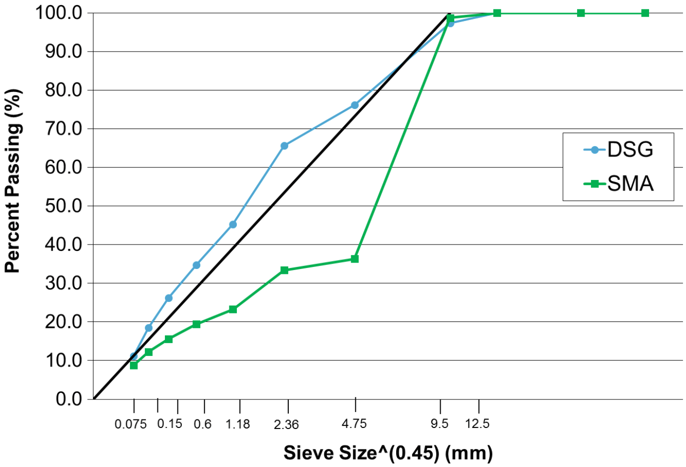

Fig. 2. Aggregate size distribution for dense grade and stone mastic mixture

pacted samples. The optimum binder content for DSG mixture is 6.1% by weight of mix, and SMA is designed rich in binder with 7.5% binder content.

Marshall stability for uncured epoxy asphalt mixture is generally used to estimate when the bridge pavement can be open for traffic and a minimum 8.0 KN is required for uncured Marshall stability according to the MS-2 handbook (Asphalt Institute 1979). As can be seen in Table 2, both mixtures with the three types of binders all meet the stability requirement and the bridge pavement can open to traffic in 12 h after paving. Full cured Marshall stability (with an additional 4 h conditioning in the oven at 121 °C) were not tested, because full cured mixture with Type C binder may easily exceed the stability ring measurement capacity at 90 KN. A minimum of 3 Marshall samples were made, and the density of the DSG samples are around 2.60 g/cm^3 and it is about 2.27 g/cm^3 for SMA with lightweight aggregates added. Both mixtures give air void content less than 3%, in which water permeability and moisture damage do not need to be considered. The density of SMA is about 13% lighter than the DSG and can reduce the deadweight by 13 kg/m^2 based on 40 mm lift thickness of the wearing surface.

Table 2. Marshall values of uncured epoxy asphalt mixtures

		Type A binder	Type B binder	Type C binder
Dense graded mixture	Density (g/cm^3)	2.608	2.593	2.590
	Stability (KN)	11.7	13.1	13.9
Stone mastic mixture	Density (g/cm^3)	2.285	2.275	2.280
	Stability (KN)	8.4	9.8	12.1

Experimentation with the interaction of composite wearing surface and steel deck structure is the most important test content. According to the finite element analysis performed by Seim and Ingham (2004), the curvature of the bridge deck is greater transversely than longitudinally under loading, and stresses are also higher in this direction. Both peak compressive stress and tensile stress would occur on the top fiber of the wearing surface, directly under the load. The peak shear stress is also directly under the load, on the bottom fiber where the wearing surface is bonded to the deck plate. The stress distributions are illustrated in Fig. 3a, b, adopted from Seim and Ingham (2004). To best simulate the stiffener-to-stiffener deflection of real bridge deck plate and wearing surface under load, a simplified small-scale experiment model was designed. A steel plate in 380 mm long by 100 mm wide size and 11 mm thick was fabricated, two stiffeners were welded on each end of the plate and extend out about 40 mm, so that the composite beam can be placed on the test machine firmly. Steel plate span/spacing between two stiffeners are 300 mm long. The schematic of the testing steel plate is shown in Fig. 3c. Composite beam samples were made in three steps: bond coat material was spread on steel plate first, then, hot epoxy asphalt mix were placed onto the bond coat, compacted in a mold and then fully-cured in the oven at 121 °C for 5 h. Finally, extrude the composite beam specimen out of the mold, and ready for the beam fatigue test. Thickness of the mixtures are all 40 mm (±1 mm), and

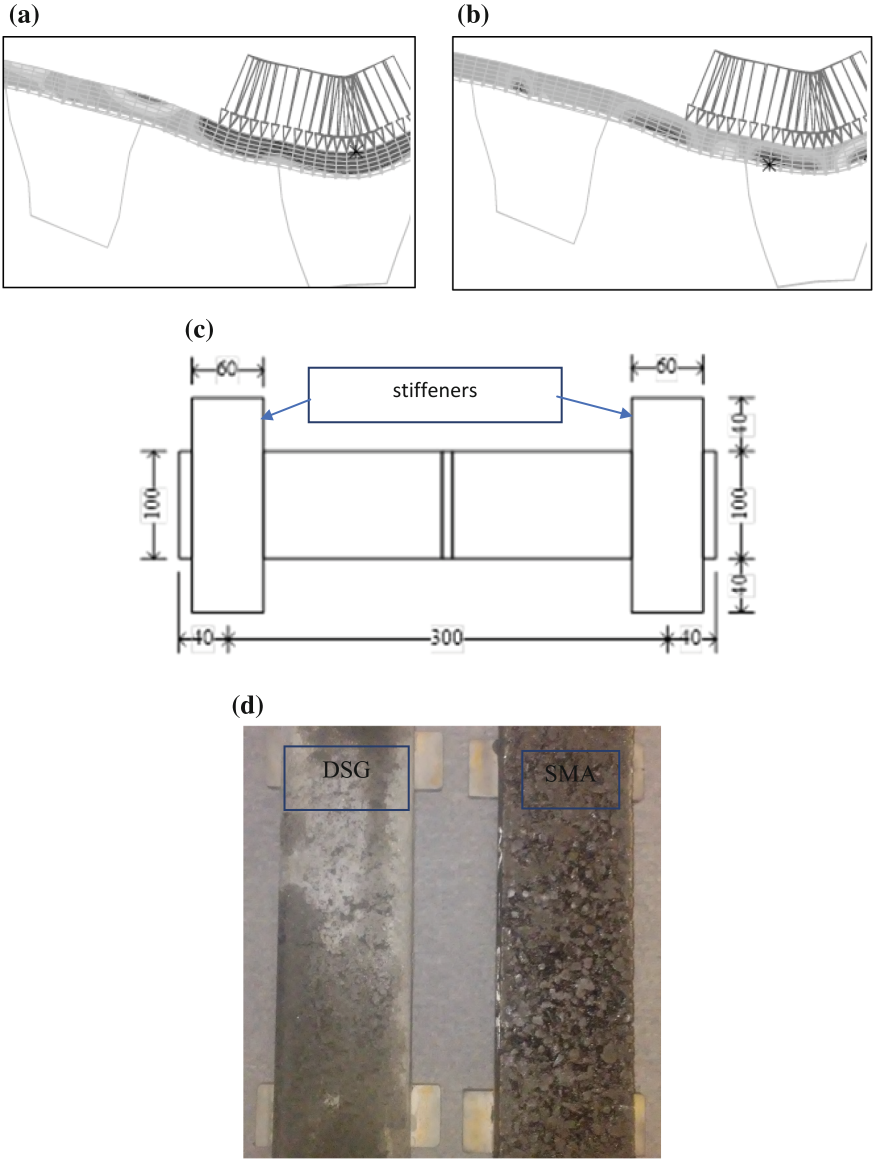

Fig. 3. Composite action of wearing surface and steel deck plate: **a** tensile and compressive stress distribution, **b** shear stress distribution **c** schematic of steel plate for testing, **d** completed composite beam specimen **e** beam flexural fatigue test equipment

the density of the beam is close to that of Marshall compacted samples. Figure 3d shows the completed composite beam specimens for both DSG and SMA epoxy asphalt mix as well as the surface texture for the two types of mix. A 3 KN load at the midpoint was given for the preconditioning and residual stress relieve purpose in the

(e)

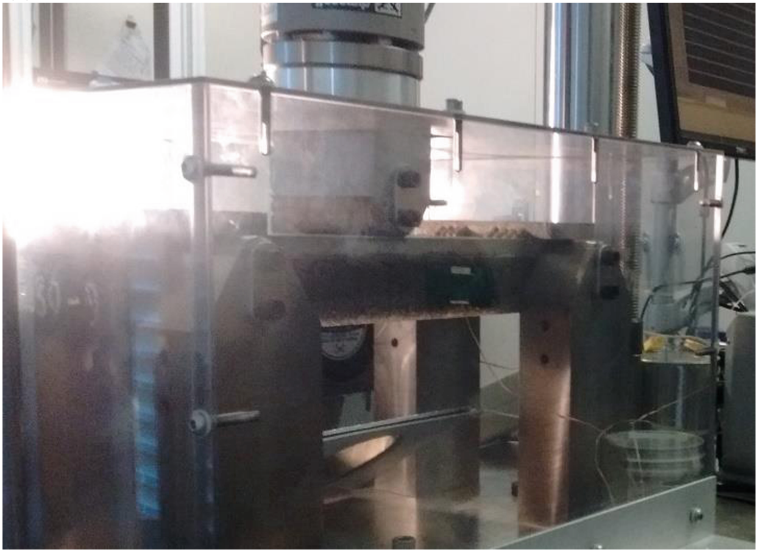

Fig. 3. (*continued*)

first 50,000 cycles. Then a 5 KN load and 10 Hz frequency were used to test the beam until it fails or passes 12 million cycles. Figure 3e shows the composite beam test specimen and test equipment. Composite beam was tested in a temperature controlled chamber at 23 °C. Load force was applied to the steel plate directly, which is upside-down comparing to real vehicle load. Both the steel plate and epoxy asphalt mix deflect and recover together as elastically to withstand the given loading energy and also distribute the energy to adjust two stiffeners. Deflection values in Table 3 were recorded at around 300,000 cycles, by the time, deflection become fairly constant and before fatigue failure start to set in.

Table 3. Results for beam flexural fatigue test in full cured condition

	Type A binder	Type B binder	Type C binder
Dense graded mix			
Initial flexural stiffness (N/mm)	12,575.8	22,701.7	25,991.5
Final flexural stiffness (N/mm)	Failed	18,787.0	21,349.0
Fatigue performance (cycles)	2.0 million	12 million	12 million
Beam deflection (mm)	0.138	0.116	0.098
Stone mastic mixture			
Initial flexural stiffness (N/mm)	12,671.7	20,816.4	24,738.8
Final flexural stiffness (N/mm)	Failed	15,624.4	19,280.1
Fatigue performance (cycles)	0.8 million	12 million	12 million
Beam deflection (mm)	0.160	0.122	0.112

The factors of temperature and pavement thickness are not considered. The composite effect has been analyzed on two different steel plate thicknesses (11 and 16 mm) and pavement layer thicknesses is 40 mm.

The fatigue resistance seems to be related to stiffness, as can be seen in Table 3. The better performing of mixtures for fatigue resistance all have extremely high stiffness, which may come from the higher stiffness binder used (binder B and C) as well as the dense and stable mixture structure. Mixture is considered extremely good in fatigue resistance if the beam can pass 12 million cycles without reducing 50% of initial flexural stiffness. Final flexural stiffness was also recorded, as can be seen, none of them is reduced to 50% or less. Fatigue failure is defined as 0.5 mm midpoint deflection is reached and visible cracking can be seen often. Although Type A binder has good elasticity, this softer binder does not give enough fatigue resistance and suffered higher deflection. The similar phenomenon—stiffer epoxy asphalt mixture lead to lower steel deck deflection was also observed in other studies using various testing temperature, test frequency and wearing surface thickness (Seim and Ingham 2004; Yao et al. 2013). It can be seen that the deflection-to-span ratio ranges from 0.0004 to 0.0005 for Binder B and C beam samples. The value is lower than the 1/1200 (0.0008) deflection-to-span ratio specified in the new version of AASHTO bridge design specification (AASHTO 2010). This may indicates that it is practical to stiffen the steel deck and improve bridge pavement performance by using extreme high strength epoxy asphalt material.

The result—stiffer binder can provide better fatigue resistance is more or less contradictory to many previous studies that as the asphalt become oxidized and stiffer, the visco-elastic properties and fatigue resistance would greatly reduce (Islam and Tarefder 2015; Tang et al. 2015). This may be mainly due to the loss of adhesion and gain of rigidity after oxidation for conventional asphalt binder. To make it clear, the words "rigid" and "stiff" reflect different meaning and physical characteristics in this study. The cured epoxy asphalt binders with a 3 dimensional and continuous polymer structure become very stiff and greatly resistant to deformation; while aged asphalt binders become brittle and rigid, undergo no deformation and easier to crack under force.

Binder adhesion test was also conducted in this study. Direct measurement of binder and aggregate adhesion is difficult, mainly because of the aggregate's irregular shape and different sizes. Two types of pull-off test were done following a modified ASTM D 4541 method. In the first test, binder was sandwiched in between two pull-off steel tabs in 20 mm diameter (see Fig. 4a). In the second test, the pull-off tab was bonded on smooth cement mortar substrate, which is made of standard-graded Ottawa sand and Portland cement mix (Fig. 4b). To avoid neat epoxy asphalt binder flow out before hardening, samples were conditioned in a lower oven temperature at 60 °C for three days to reach full cured condition. Pull off tests were performed in room temperature (23 °C) and the test speed is 1.27 mm/min. Table 4 shows the pull-off bond strength for the three types of binders, and the pull-off bond strength is commonly referred to as "adhesion". Obviously, epoxy materials have the best adhesion to the steel as shown in Table 4. The binders also give good adhesion to cement mortar. The adhesion to cement mortar provides us an indirect indication of the binder bond strength to the aggregates as well. Studies in the University of Wisconsin-Madison

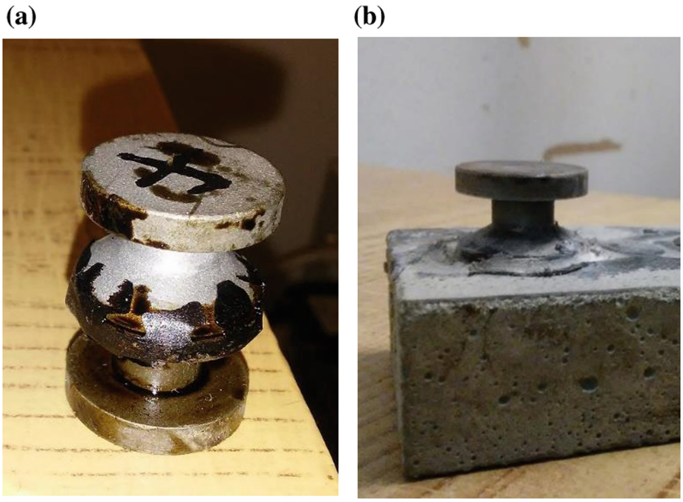

Fig. 4. Pull-off test samples for full cured epoxy asphalt: **a** steel to steel adhesion, **b** steel to cement mortar adhesion

Table 4. Pull-off bond strength test for epoxy asphalt in full cured condition

	Type A	Type B	Type C
Steel to steel (MPa)	4.88	8.77	9.55
Steel to cement mortar substrate (MPa)	1.75	5.19	6.03

show that, conventional asphalt binder and polymer-modified asphalt usually have an adhesive strength in between 1.5 and 2.5 MPa on limestone aggregates tested by Bituminous Bond Strength Test machine (Bahia et al. 2012), and the crumb rubber modified asphalt usually has an even lower adhesive strength (Bahia et al. 2012; Huang et al. 2016), as the crumb rubber is not an adhesive material and can hardly depolymerize homogenously in base asphalt.

If we compare the testing values from Tables 1 and 3 with Table 4, it can be easily noticed that, the adhesion measured by pull-off strength test seems to have a considerable influence and linear relationship to the modulus of epoxy asphalt binder as well as the stiffness of the beam sample. The correlation charts were made in Fig. 5. It is highly possible that the fatigue resistance and durability come from the adhesion properties of epoxy asphalt binder. However, the mechanism is not fully understood and more tests will be conducted to confirm the correlation in the future. In addition, all three tests, including binder tensile strength test, beam flexural fatigue test and pull-off bond test, were conducted in same temperature and should be comparable with no bias. Figure 6 shows the failure pattern after pull-off test. The figures further illustrate that Type A epoxy asphalt, like most conventional and polymer-modified asphalt, would have the adhesion failure mainly occur inside the thin bond layer, while the Type C binder have an adhesion failure totally from the aggregate and cement substrate.

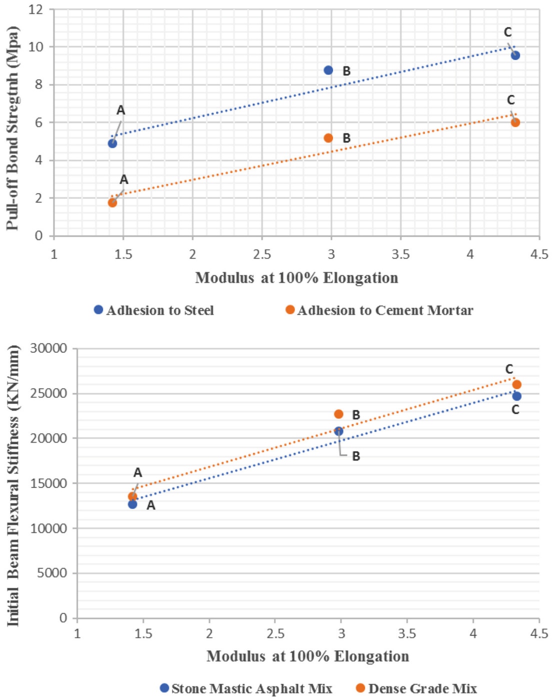

Fig. 5. Correlation among pull-off bond strength, binder modulus @ 100% elongation, and beam flexural stiffness

Fig. 6. Cement mortar substrate after pull-off test (left-Type A binder, middle-Type B binder, right-Type C binder)

4 Conclusions

Experimental results demonstrated good correlation of epoxy asphalt pavement on thin steel plates, particularly fatigue resistance, with specific physical bulk properties of the binder. Two major findings in this study are (1) Beam flexural fatigue tests show that a stiffer binder and mixture can effectively reduce deflection of the composite beam and improve the fatigue resistance of the bridge pavement without further increase pavement layer thickness and weight; (2) Binder adhesion to the aggregate matrix seems to play a pivotal role and the adhesive bond strength could have a close relationship with the beam flexural stiffness as well as the binder elastic modulus in low strain range.

The study also support that epoxy asphalt product can be used on extremely thin steel deck plate (11 mm or even less), to help stiffen the deck plate, mitigate fatigue problems on bridge pavement and steel deck. Type B epoxy asphalt seems to be the optimal binder for use in the job site, with an extended service time, which can give a longer time window for transportation and paving. Lightweight epoxy asphalt mixture with rich binder content were also developed that are good in fatigue resistance. This system can help reduce the dead weight by 13–15% and provide better skid resistance for bridge pavement.

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