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# 1 **Functional and Field Performance of Epoxy Asphalt Technology-** 2 **State-of-the-Art**

## 4 **Abstract**

5 There is an increasing demand for high strength and more durable materials in the asphalt technology  
6 market. In response to the demand, epoxy asphalt mixture (EAM) is one relatively new technology for  
7 use as a paving material in flexible pavements. There are various research works carried out on  
8 laboratory and field performance of EAM. However, comprehensive research covering functional and  
9 field (F&F) performance of EAM is lacking. The main purpose of this review is to bridge this gap via  
10 the analysis of the functional properties of EAM, including surfacing aging, skid resistance, raveling  
11 resistance, flammability, and surface reflectance. Consequently, the field performance of EAM in  
12 different case studies is reviewed and the serviceability of EAM in various transportation  
13 infrastructure assets such as, airports, ports, roads, bridges, tunnels and railroad is investigated. This  
14 paper also reviews the life cycle cost and maintenance of EAM. The major findings indicate that  
15 EAM shows superior F&F performance compared to the traditional hot and warm asphalt mixture.  
16 Additionally, the use of EAM is beneficial in the structure of pavements in tunnels and on bridge  
17 decks. **However, recyclability, initial, maintenance and rehabilitation costs are matters of concern in**  
18 **the life cycle of EAM.** In conclusion, the higher F&F performance of EAM supports the development  
19 of better performing pavements for various applications.

20 **Keywords:** Epoxy modified Asphalt, Pavement, Rutting, Fatigue, Sustainability, Airport, Port,  
21 Highway, Railroad, Life cycle cost, and sustainable asphalt.

## 22 **1.Introduction**

23 Demand for more durable and cost-effective paving materials is increasing, and there are now more  
24 key variables to consider when choosing appropriate paving materials than there have been in the  
25 past. Structural performance and durability used to be the dominant factors in pavement construction.  
26 In today's more advanced construction methods, however, environmental factors, albedo, energy  
27 consumption, and climate change are new variables to consider. To address the challenge of meeting  
28 the requirements of pavement engineers, environmental policymakers, urban designers, contractors,  
29 and public work authorities, asphalt material specialists have developed various technologies,  
30 materials, and methods. One such material is epoxy asphalt technology, which has attracted attention  
31 due to its superior structural performance. Epoxy asphalt mixture (EAM) has been used in various  
32 paving projects worldwide. Laboratory tests on rheological characteristics of epoxy asphalt binder  
33 (EAB) showed the higher complex shear modulus ( $G^*$ ), elongation, tensile strength and softening  
34 point than traditional binder and modified binders (Fuhaid *et al.* 2018, Dong and Li 2015, EI Rahman  
35 *et al.* 2012, Huang and Huang 2011, Yu *et al.* 2009a). The reason is a cross-linking network formed  
36 between the asphalt and the epoxy resin increases the stability of the resultant binder against high  
37 temperature deformation, thermal cracking, moisture, and resistance to solvents such as fuel  
38 (Alabaster *et al.* 2008, Chen, 2009, Cong *et al.* 2011, Mo *et al.* 2012, Sun *et al.* 2021). The cross-  
39 linking network also results in the higher viscosity and intermolecular forces (Jamshidi *et al.* 2021, Lu  
40 and Bors 2015, Cong *et al.* 2010, 2019, Huang *et al.* 2010, Yu *et al.* 2009b). However, the higher  
41 viscosity of EAB may restrict paving time span due to thermosetting characteristic of epoxy materials.  
42 Changes in the viscosity of EAB depends on curing agent (type, content and chemical base), curing  
43 time (and method), temperature, humidity and base binder type (Xiang and Xiao 2020, Zhu 2013,  
44 Miller Bellinger 2003, Kim *et al.* 2000).

Laboratory studies on structural performance of EAM showed that the greater Marshall Stability than the traditional hot mixtures (Cong 2009). The results also indicated that the method for curing and preparation of EAB can affect Marshall Stability, flow number and volumetric properties of EAM. The higher stiffness of EAM also resulted in lower depth rut in the wheel tracking test (Vyrozhemskiy *et al.* 2017). Xue and Qian (2016) found that incorporation of mineral fibers decreases rut depth in EAM. Laboratory results showed that EAM has a higher stiffness in terms of indirect tensile strength compared with the other modified mixtures (Zhu *et al.* 2004, Apostolidis *et al.* 2019). It should be noted that aggregate type, gradation, epoxy content and binder performance grade play pivotal role in crack resistance of EAM (Bahmani *et al.* 2021, Li *et al.* 2022a). Cong *et al.* (2015) and Nguyen and Tran (2021) carried out research on the fatigue behavior of EAM. The outputs indicated that the effect of temperature on the fatigue life of EAM significantly depends on the stress level and epoxy content. Furthermore, Min *et al.* (2019) reported the flexural strength of EAM is almost three times higher than those of polymer-modified asphalt mixtures, which is consistent with results reported by Zhao *et al.* (2019). The similar trend was observed in flexural strength of EAM compared to SBS-modified asphalt mixtures (Wang *et al.* 2021).

Although laboratory tests have shown promising results regarding the rheological characteristics of epoxy asphalt binders and the laboratory structural performance of EAM, functional and field (F&F) performance of EAM remain a matter of concern. Since there is neither established database nor comprehensive report that collect the F&F performance data of EAM in various countries, it is necessary to evaluate technical notes, research papers, and conference proceedings. In addition, evaluation of F&F performance provides enough information for better judgment of its EAM properties compared to alternative asphalt mixtures. This state-of-the-art paper provides a detailed literature review with the goal of filling the research gaps and raising awareness of the F&F performance of pavements under various conditions. The paper also critically discusses the performance of EAM in various transportation infrastructure using different case studies, such as roads, tunnels, bridges and railway. Furthermore, the maintenance, rehabilitation, and life cycle costs of EAM are evaluated, thus helping engineers who may be dealing with pavement management service advisory. It should also be noted that pavements are no longer a simple structural system for withstanding traffic loads.

## 2. Scope

This paper primarily focused on F&F performance of EAM. Therefore, the chemical structure of epoxy materials is out of scope. The authors tried to draw a general trend of F&F performance in different paving projects and transportation infrastructure. However, the authors benefited from laboratory research to characterize the F&F behavior. In addition, effect of curing agent, curing method, and type were out of scope too. Figure 1 illustrates the flowchart of discussion in this paper.

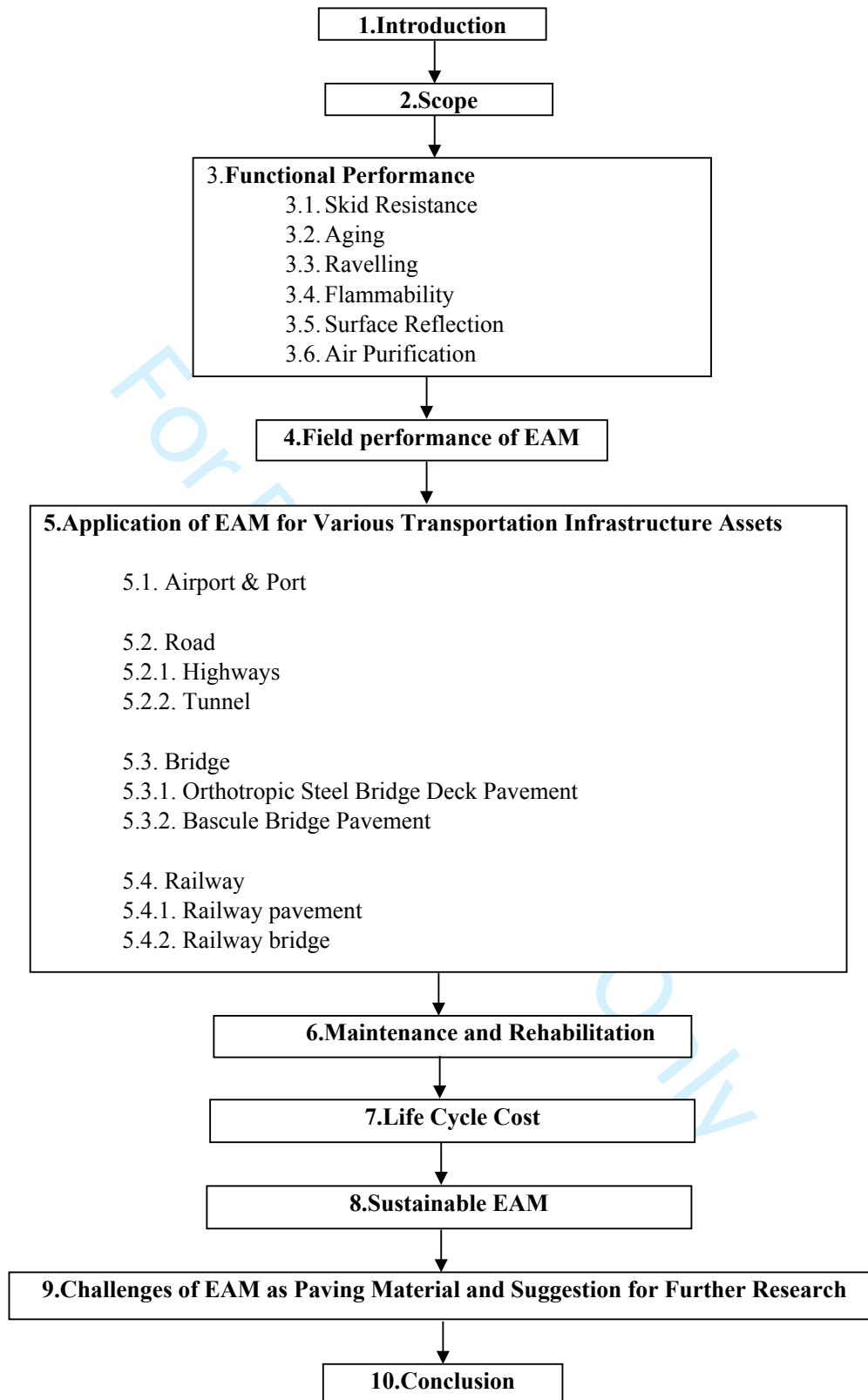


Figure 1 : Schematic illustration of the study structure.

### 3. Functional Performance

From a pavement users' perspective, the most important functions of pavements are related to the surface, including smoothness, brightness, safety, vibration, and noise. In this section, some functional aspects of EAM are discussed. More research is necessary to better understand noise generation and vibration and the smoothness of EAM, although these are usually determined by the size and gradation of the mixture, rather than the binder.

#### 3.1. Skid Resistance

Skid resistance of the pavement surface should be evaluated to meet safety requirements. In this regard, the surface texture and the friction coefficient of pavement could be indicative of skid resistance. Skid-resistance layers are being developed in different countries based on local requirements, materials, and technologies. For instance, in Belgium, Germany, the Netherlands, and Spain, POSSEHL antiskid resistance layers are widely used on runway surfaces because of good adhesion and fuel resistance characteristics (Xiao *et al.* 2012). For further information, POSSEHL consists of a thin layer of epoxy material and binding agent, e.g. asphalt, which is then coated with a basalt/high-grade grit mixture (Possehl Spezialbau, 2022). Following, the surface is compacted by roller and brooming extra aggregate materials. Then another protective binding layer is sprayed on top in order to improve the micro and macro texture.

The skid resistance primarily depends on aggregate gradation, binder content, air void percentage, and aging. Therefore, it is necessary to evaluate and characterize the surface texture and friction of EAM to make sure the level of safety is satisfied. For instance, Zhong *et al.* (2017) evaluated the surface depth of EAM using a laser texture scanner. The results indicated that the average profile and texture depths were 0.35 and 0.43 mm, respectively, while the depth profile of conventional asphalt mix and porous asphalt mixes were approximately 1 mm and 3 mm, respectively (Flintsch *et al.* 2003, Gendy and Salaby 2007). In another study, a texture depth equal to or greater than 1.30 mm is recommended for the runways in the Netherlands (Toan 2005, Nicholas 2009, CROW 2011). In Australia, the value is 1 mm or a groove on the runway pavement, which is mandatory (White 2017). However, the average friction coefficient of EAM was approximately 80%, which is close to the conventional hot mix asphalt (HMA) (Asi 2007). It is also double the friction coefficient recommended for the pavement laid on the deck of steel bridge deck.

Friction is not a constant value, but it depends on the speed of vehicles, especially the dynamic friction (Oden and Martin 1985, Wang *et al.* 2010). Analysis of the trends showed that a significant drop in dynamic friction occurred at speeds above 80 km/hr, meaning that the pavement surface may have no safe skid resistance above 80 km/hr. Therefore, the speed limit is recommended for the safe transportation on EAM pavements at certain speeds, depending on the dynamic friction results.

In another study, Hu *et al.* (2019a) evaluated the skid resistance of EAM prepared with emulsion asphalt compared with sand fog seal. Figure 2 shows the friction loss percentage at various temperatures. From the figure, the friction loss of EAM fluctuates 20.6% over the temperature range, while that of the fog seal increases linearly. Therefore, the friction loss in the fog seal is temperature sensitive, but the EAM is not sensitive due to thermosetting characteristics.

The friction of pavement surface can be characterized through different parameters, depending on practice code and standards adopted for the evaluation of functional performance. One of the parameters is Side-way Force Coefficient (SFC), which indicates the ratio of the force developed at right angles to the plane of the axis of the wheel to the load on the wheel. The vehicle for the test is driven at 5+4 km/hr. The higher SFC means the greater friction and skid resistance (Wu *et al.* 2020). Jia *et al.* (2016) compared the skid resistant of double EAM with mixture containing one layer of stone matrix asphalt (SMA) with gussasphalt (GA) in terms of SFC. The results of SFC tests showed that SFC of EAM is somewhat lower than SMA/GA mixture. In other words, it can be concluded that EAM shows lower skid resistance, which is inconsistent with other results discussed previously. It should be noted that the result of friction depends on testing procedure and mix properties mentioned

138 above. Therefore, there is no specific test procedure developed for EAM. It is recommended choosing  
 139 appropriate testing procedure that meet requirements of realistic conditions.

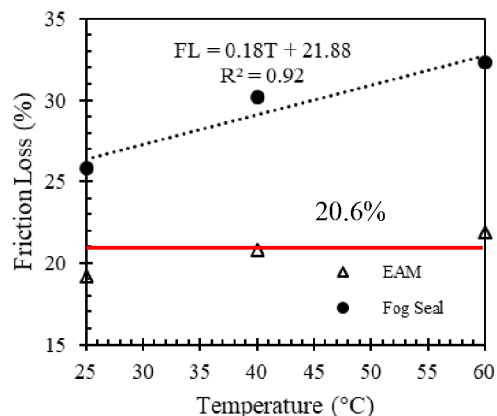


Figure 2 : Trend of friction loss as a function of temperature; plotted based on data outlined by Hu et al. (2016).

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141 The friction decreases over time due to the traffic load, surface moisture, freezing and thawing, and  
 142 ambient environment conditions polishing the road's surface (Qian et al. 2016). Therefore, it is vital  
 143 to analyze the trend of skid-resistance attenuation of EAM in the long term. To develop an accurate  
 144 predicting model, Zheng et al. (2018) used genetic algorithm-back propagation neural network. The  
 145 training function and sensitivity analysis of various parameters indicated that the bulk specific gravity  
 146 of mix is the most important EAM property, followed by binder content and air-void percentage, in  
 147 skid resistance. In general, the antiskid resistance layer using EAM has good adhesive strength at the  
 148 interface between the antiskid resistance layer and underlying surface (Xiao et al. 2013).

149 **A skeleton-dense asphalt mix has been used to improve the short and long-term skid resistance of the**  
 150 **asphalt pavement (Xiaoning et al. 2012, Moriyoshi et al. 2014). Analysis of the skeleton-dense EAM**  
 151 **showed less skid-resistance attenuation compared to the conventional EAM and SMA mixtures (Xiaoning**  
 152 **et al. 2012). However, the trend in the friction of ice-covered skeleton-dense EAM, conventional EAM,**  
 153 **and SMA was almost identical (**

154

155 **Figure 3).** From the figure, the friction trend consists of three different phases: (1) the friction  
 156 decreases when the surface is fully covered by ice. The thickness of the ice can be important because  
 157 a thin layer of ice can be shattered due to the wheel load. (2) The friction remains constant during the  
 158 partial ice-cover phase. (3) The friction increases after the ice melts and eventually reaches a plateau.  
 159 The EAM may contain snow-melting agents that decrease ice adhesion (Min et al. 2017). Such snow-  
 160 melting agents improve safety in the winters. However, the optimum percentage of the agents and  
 161 their long-term performance needs further field investigations.

162 **It should be noted that SMA was developed in Germany in 1960s. High strength in rutting or a high**  
 163 **resistance to plastic deformation from heavy vehicle loads at elevated temperatures, simple**  
 164 **technology for production, satisfying skid resistance and high durability at low temperatures make**  
 165 **SMA as a great option for heavy duty asphalt pavements (Blazejowski, 2016, Devulapalli et al. 2021,**  
 166 **Ismael et al. 2022, Miao et al. 2022, Saed et al. 2022). Furthermore, the higher performance of SMA**  
 167 **decreases the costs of maintenance and rehabilitation of the pavement, which increases both durability**  
 168 **and sustainability of SMA. Therefore, comparable surface friction of EAM with SMA shows high**  
 169 **performance of EAM.**

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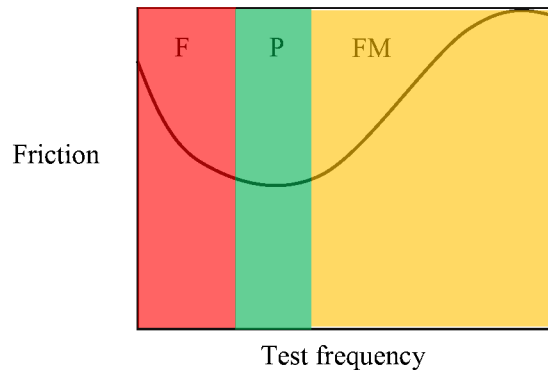


Figure 3: Trend of friction test over the test; F: fully covered (phase 1); P: Partial covered (phase 2); and FM: fully melted ice (phase 3), adopted based on the data reported by Xiaoning *et al.* (2012).

### 172 3.2. Aging

173 Short-term aging of asphalt binder is a physicochemical reaction that occurs during the mixing of  
 174 aggregate particles and hot asphalt binder in the mixing facilities (SP-1 2001). The long-term aging of  
 175 the binder begins after mix placement. The mechanism and trend of aging depend on many variables,  
 176 such as aggregate type, gradation, binder content, type or (performance grade), filler type,  
 177 construction temperature/technology, rejuvenator type/content, and binder extender type/content.  
 178 Aging can result in functional failures, which can eventually lead to structural deficiency. However,  
 179 the stiffening effects of aging in the asphalt mix increases the load-bearing capacity of the mix and  
 180 decreases the temperature susceptibility. Consequently, if the aging level is within allowable ranges, it  
 181 can be useful. Therefore, aging is a key characteristic of asphalt surfaces.

182 There are various procedures for laboratory aging of asphalt binders and mixtures. For example,  
 183 ASTM D 2872 and D 6521 procedures are used to simulate short term aging of binder, by means of  
 184 rolling thin film oven (RTFO), and long-term aging, using pressure aging vessel (PAV), respectively.  
 185 To simulate short-term aging of the mix, the samples are conditioned for 2 h at the compaction  
 186 temperature (SP-2 2000). According to AASHTO PP2, the samples can be conditioned at 80 °C for  
 187 120 h for long-term laboratory aging. In addition, there are recently developed methodologies to  
 188 simulate field aging, which resulted in more realistic outputs. Mirwald *et al.* (2020) proposed a new  
 189 methodology, called Viennese Binder Aging (VBA), for conditioning long-term aging in laboratory.  
 190 This methodology considers reactive oxygen species (ROS), such as O<sub>3</sub> and NO<sub>x</sub>, in aging process,  
 191 which is neglected in PAV. It should be noted that the surface of the pavement exposes to air  
 192 containing ROS, especially in cities. The results of laboratory tests and field investigations showed  
 193 that VBA can reach and even surpass level of aging by means of RTFO plus PAV within three days at  
 194 80°C. Therefore, VBA can provide more realistic understanding of the phenomenon of aging  
 195 compared with commonly used methodologies such as PAV and RTFO. Furthermore, Steiner *et al.*  
 196 (2016) developed a laboratory aging procedure, called Viennese Aging Procedure (VAPro), which  
 197 can be used for conditioning compacted samples. VAPro enable researches and engineers to simulate  
 198 short term and in-service aging through triaxial cell with forced flow of a gaseous oxidant agent  
 199 through the compacted asphalt mixture. The results of conditioned recovered binder showed VAPro  
 200 can simulate long term aging state at moderate temperatures (+60°C) and within 4 days and a flow  
 201 rate of 1 l/min.

202 Also, Crucho *et al.* (2020) developed an accelerated methodology of aging for compacted asphalt  
 203 mixtures specimens in the laboratory, called Técnico accelerated AGEing (TEAGE). The samples of  
 204 asphalt mixtures were tested for stiffness and fatigue under unaged and aged conditions by TEAGE.

1  
2  
3 205 The result of initial studies showed that TEAGE has potential to simulate accurate field aging  
4 206 condition. It worth mentioning that Aging Index significantly depends on the types of parameters  
5 207 adopted for analysis of the ageing phenomenon (Jamshidi et al., 2012 and Hamzah et al., 2012).  
6 208 Therefore, it may not be as accurate as the other consecutive reaction model developed based on  
7 209 chemical reactions. For example, The Zero-order model was suitable to describe the long-term aging  
8 210 reaction kinetics of bitumen based on the oxygen-containing functional groups with the reaction rate  
9 211 constants in  $0.7\text{--}3.3 \times 10^{-4}$  ( $\text{mol L}^{-1} \cdot \text{h}^{-1}$ ), while the most optimum kinetics model for aromatic  
10 212 fraction was the Third-order reaction model and the corresponding reaction kinetics constant ( $k_1$ ) was  
11 213  $0.02$  ( $\text{mol} \cdot \text{L}^{-1}$ ) $^{-2}(\text{h})^{-1}$  by means of Saturate, Aromatic, Resin and Asphaltene (SARA) test (Ren et  
12 214 al., 2020). Elwardany et al. (2017) reported that loose mix aging in an oven resulted in a promising  
13 215 laboratory long-term aging procedure to produce mixture for performance testing in terms of various  
14 216 factors such as efficiency, specimen integrity, and versatility. It is also a cost-effective methodology,  
15 217 which can be readily used for various mixture types. However, it should be noted that the  
16 218 methodologies mentioned above have not been standardized. It is essential to standardize and develop  
17 219 laboratory protocols to use in the pavement industry.

18 220 The effects of aging on the mix properties can be evaluated by the aging index based on the target  
19 221 engineering property, such as resilient modulus, ITS, and  $E^*$ . It is necessary that the effects of aging  
20 222 on EAM are characterized; however, the difference between aging and curing in EAM must be  
21 223 recognized. The aging increases the binder stiffness due to the evaporation of oil and the  
22 224 transformation of resins into long chains of asphaltenes, while curing has a stiffening effect due to the  
23 225 chemical reaction between the epoxy and the curing agent in epoxy asphalt binder (EAB). Therefore,  
24 226 aging and curing in EAM or EAB must not be used interchangeably. In HMA and warm mix asphalt  
25 227 (WMA), curing and aging are almost identical. Furthermore, there is no laboratory-based  
26 228 methodology or parameters developed exclusively for EAM/EAB. The same procedures used for  
27 229 traditional asphalt mixtures are deployed for EAM.

28 230 Long-term aging can occur when the majority of the curing (over 70%) is achieved. Therefore, aging  
29 231 and curing are parallel reactions in EAM, which makes a stiffer mixture compared with the traditional  
30 232 asphalt concrete. There is a lack of fundamental research on the synergistic effects of aging and curing  
31 233 in EAB as well as the effects of different curing agents and binder types.

32 234 In a laboratory study, Widyatmoko et al. (2006a) evaluated the effects of aging on hot-rolled (HR)  
33 235 and SMA epoxy asphalt. Figure 4 shows the effects of aging based ITS results. It can be seen that  
34 236 aged ITS of HR-EAB was much higher than the control counterpart, in which such high stiffness is  
35 237 due to synergistic effects of curing and aging (Figure 4(a)). However, unaged ITS of HR-EAM  
36 238 beyond  $20^\circ\text{C}$  is slightly less than that of unaged HR. This lack of strength can be compensated by the  
37 239 stiffening effects of aging or further curing.

38 240 Figure 4(b) reveals the results of aging in SMA. The difference between the aged and unaged ITS of  
39 241 SMA is not significant because of the dense matrix of the mixture. Furthermore, ITS of unaged SMA-  
40 242 EAM is less than that of the control sample up to  $20^\circ\text{C}$ . Beyond  $20^\circ\text{C}$ , the ITSs are almost identical  
41 243 for the unaged sample. In SMA, the lack of ITS strength is compensated by aging. Hence, irrespective  
42 244 of mix type, the lack of initial strength in both mixes can be balanced by the stiffening effects of  
43 245 aging.

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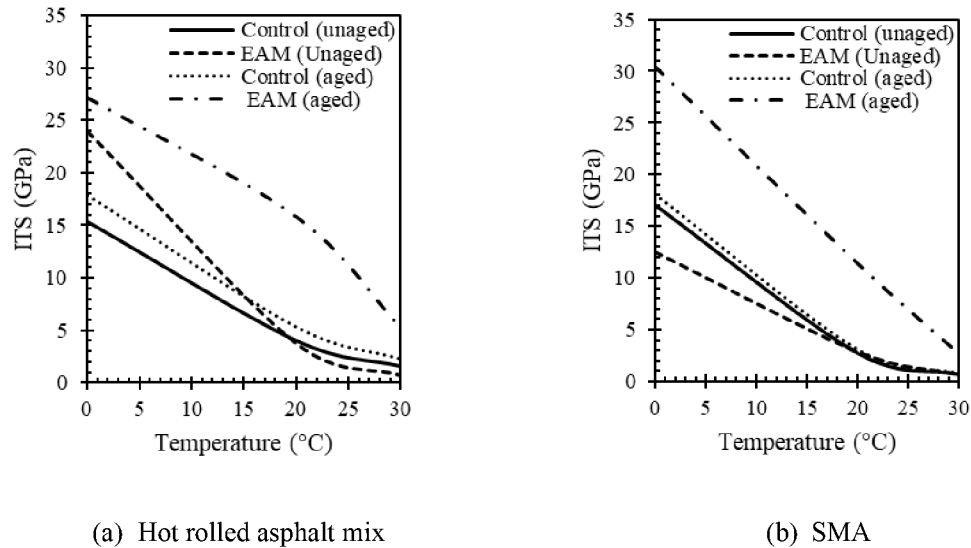


Figure 4: Effects of aging on various mix types of EAM; plotted based on data outlined by Widyatmoko *et al.* (2006a).

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248 Additionally, Widyatmoko *et al.* (2006a, b) showed that the stiffening effects of aging reduced rutting  
 249 depth and plastic strain in HR and SMA-EAM. Although the higher stiffness due to aging and  
 250 progressive curing improved the structural capacity of EAM, it may have an adverse effect on the  
 251 fatigue and low-temperature performance. One approach to avoid fatigue cracking is to increase the  
 252 flexible pavement thickness. A thick, well-designed flexible pavement has high-bending rigidity so  
 253 the fatigue – cracking decreases from the bottom up. Instead, surface and rutting cracking are the only  
 254 distresses expected (Nunn *et al.* 1997). Due to its high stiffness, EAM may behave as a fully elastic  
 255 material at low temperatures (Yao *et al.* 2016).

256 The use of a thicker EAM may not be a practical measure due to the costs of materials. The thicker  
 257 EAM increases the dead load of the bridge deck, which is problematic. Moreover, the rate of curing  
 258 and aging of thickened EAM may change. Therefore, it is necessary to build a balance between the  
 259 stiffening effect of aging and curing, as well as the structural performance of EAM. I

### 260 3.3. Raveling

261 Raveling (disintegration of mixture components into the aggregate particles) is a functional failure  
 262 which results in severe structural distresses. It is due to stress concentration at the reduced aggregate  
 263 contact area and aging of asphalt binders (Qian and Lu 2015). Raveling decreases quality of riding  
 264 because the surface of pavement become uneven due to disintegrated aggregate particles from the  
 265 surface. In addition, the sharp disintegrated aggregates can be dislodged and made airborne by  
 266 moving tyres, which can damage cars, or injure pedestrians and bicycle riders. Therefore, raveling  
 267 decreases the level of safety for pavement users. As raveling is not rehabilitated, it may result in  
 268 structural distresses. Thus, it is necessary to evaluate the performance of EAM in terms of raveling.

269 Although Sang *et al.* (2012) reported raveling on the surface of EAM samples, Qian and Lu (2015)  
 270 found porous EAM shows satisfying results in Cantabro raveling test.

271 It should be noted that use of the higher viscous binder improves the raveling resistance in the  
 272 mixture. For example, Hu *et al.* (2019b) indicated that raveling resistance increases as the thickness of  
 273 asphalt film increases to 14  $\mu\text{m}$  and the viscosity of asphalt increases to 35,000 Pa.s. In other words,  
 274 the high viscosity of EAB and high binding result in excellent adhesion and cohesion in the mixture.  
 275 The reason why the high viscosity binder decreases raveling can be justified through activation energy

( $E_a$ ) of binder. As a fluid flows, the layers of the fluid molecules slide over each other, while intermolecular forces resist the motion, causing resistance to flow (Haider *et al.* 2011). Therefore, for fluid to begin flowing or any deformation and disintegration, energy is required that must be higher than the intermolecular forces, and this energy is called  $E_a$ . The higher  $E_a$  indicates that more energy is required to cause flow, deformation and disintegration. The higher viscosity due to incorporation of new additives and waste materials such as recovered binder and nanomaterials increases  $E_a$ , which results in the higher structural adequacy in terms of higher dynamic modulus of mixture and complex shear modulus ( $G^*$ ) of modified binder (Jamshidi *et al.* 2019 and Jamshidi *et al.* 2015). Therefore, the higher viscosity increases the activation energy of EAB (Figure 5). In other words, a crosslinking network formed in EAB increases intermolecular forces. Therefore, more energy is required to overcome the force or  $E_a$ . From the Figure, there is a relatively linear relationship between the  $E_a$  and epoxy content. It can be seen that adding unit epoxy material (1%) improves  $E_a$  by 1.45 mJ/mol. As a result, more energy is required to disintegrate components of EAM, which results in the higher raveling resistance.

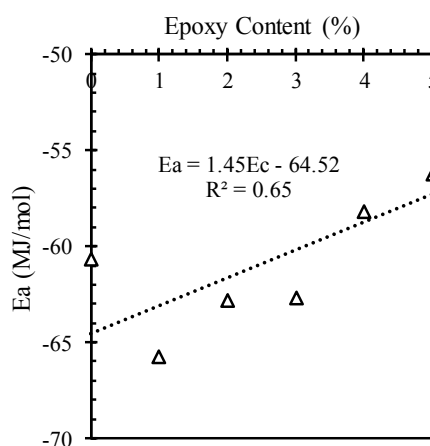


Figure 5: Effect of epoxy content on the activation energy of EAB, plotted based on data reported by Cubuk *et al.*, (2009).

In addition, Wang and Zhang (2019) studied the effect of glass fiber on the raveling of EAM. The results indicated the glass fiber generally increases the raveling resistance; however, the optimum fiber content should be chosen based on fiber size. However, it is recommended for further research on raveling of EAM.

### 3.4. Flammability

Since EAM can be used for different infrastructure types, the safety of the pavement is a matter of concern because epoxy resins and asphalt binders are combustible and emit smoke and toxic substances (Pack 2015). Consequently, retardants added to the asphalt binder should meet the standard requirements. Inorganic flame retardants are commonly used in the asphalt pavements (Bonati *et al.* 2012, Xu *et al.* 2011, Wan *et al.* 2015, Zhang *et al.* 2015). Additionally, one of the widely used flame retardants is a brominated flame in the asphalt concrete (Cong *et al.* 2008, Yu *et al.* 2009b). Because of concerns about the persistence, bioaccumulation, and toxic materials, some brominated flaming agents, such as brominated diphenyl ethers and polybrominated biphenyl halogenated flame retardants have not been allowed (Mitchel 2014). Instead of brominated flaming retardants, halogen-free flame retardants are used (Zhang *et al.* 2016a). Among the halogen-free

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3 308 materials, mineral fillers, such as aluminum trihydrate and magnesium hydroxide are increasingly  
4 309 used in asphalt binders (Barral *et al.* 2012, Ren *et al.* 2013, Bonati *et al.* 2013, Šušteršič *et al.* 2014).  
5 310 Therefore, it is necessary to find the most appropriate flame retardant materials for EAM, depending  
6 311 on the epoxy resin, curing agent, asphalt modifier, and additive type. In this regard, Chen *et al.*  
7 312 (2018c) carried out a laboratory study on the synergistic effects of aluminum trihydrate and zinc  
8 313 borate on the flammability of EAB. The results showed that the limited oxygen index of EAM  
9 314 containing 20% of aluminum trihydrate and zinc borate are the highest compared to control EAB  
10 315 (without flammability retardant) and samples containing aluminum trihydrate or zinc borate. The  
11 316 results indicated that incorporation of aluminum trihydrate and zinc borate had the best flame  
12 317 retardancy in this study because aluminum trihydrate decomposes in  $Al_2O_3$  and creates strong  
13 318 endothermic reactions when heating the flame-retardant polymeric material, which leads to an  
14 319 incremental ignition time. Moreover, the porous, ceramic-like structure of char of boric oxide and  
15 320 alumina produced at high temperatures ( $>600$  °C) performs as an insulating material or thermal shield  
16 321 for the underlying, unburned polymeric material. Decomposition of zinc borate also releases water  
17 322 that decreases the polymer's surface temperature (Bourbigot *et al.* 1999, Weil and Levchik, 2016).  
18 323 Chen *et al.* (2021a) also proposed to use reactive polymeric flame retardant in the binder which is  
19 324 composed of a reactive polymeric brominated epoxy oligomer and antimony oxide. The results  
20 325 showed that level of limited oxygen index (LOI) improved, which increased flame retardant loading  
21 326 of EAB.

22  
23 327 Additionally, a combination of aluminum trihydrate and zinc borate increases the thermal stability of  
24 328 EAM. The mechanism of flaming of EAB, resulting in thermal degradation, should be well-  
25 329 understood. The mechanism consists of two steps as follow (Zhang *et al.* 2014b):

- 26 330
- 27 331 • Step one: Poor chemical bonding of asphalt and unreacted epoxy resin are failed at the
  - 28 332 temperatures ranging from 200 to 350 °C.
  - 29 333 • Step two: the larger molecules of asphalt binders are degraded into smaller molecules and
  - 30 334 epoxy crosslinking networks are degraded from 350 to 500 °C.
- 31 335

32  
33 336 The high thermal degradation of aluminum trihydrate and zinc borate delay these two steps in EAM.  
34 337 Therefore, the interaction of two or more flammable retardants could be more efficient. However, it  
35 338 may have negative effects on the other properties of EAB and EAM. For instance, the incorporation  
36 339 of aluminum trihydrate and zinc borate increased the EAM viscosity (Chen *et al.* 2018c), thereby  
37 340 decreasing EAM workability and potentially reducing the EAM resistance to fatigue and cold  
38 341 fracture.

### 342 3.5. Surface Reflectance

343 Urban heat islands threaten ecological health, particularly in densely populated areas. Additionally,  
344 urban sprawl increases hard surfaces, which results in flooding. Therefore, pavement networks are  
345 considered as multi-role infrastructure assets. It means that they should not only provide a safe surface  
346 for the transportation of passengers and goods but also drain run-off and reduce heat-island effects  
347 (Jamshidi *et al.* 2019). As such, the solar reflectance (albedo) or retroreflective characteristics of  
348 pavement surfaces should be improved via various strategies based on the principles of cool pavement  
349 design (Rossi *et al.* 2016). Some commonly used methods include planting trees or shrubs to shade  
350 the pavement surface and constructing asphalt pavements with a thin layer of highly reflective  
351 material (Li, 2012 and Anupam *et al.* 2021).

352 There are different procedures to evaluate thermal emission paving materials and pavement surfaces,  
353 such as ASTM C1371, C 1549 and E 1918. The brightness and thermal emissions of pavements  
354 depend on the angle of the sunrays, time of measurement and the pavement material type.  
355 Furthermore, when the pavement is new, the concrete pavement shows a higher albedo due to its  
356 bright surface in comparison with the asphalt pavement (Jamshidi *et al.* 2017), even though the albedo

357 levels of concrete and asphalt pavement are almost identical after approximately 7 years (Cambridge  
358 Systematic 2005).

359 The use of synthetic binder and epoxy materials is an efficient strategy to improve the reflectance of  
360 asphalt pavement (Tran *et al.* 2009). The use of a transparent binder (resin binder) increases the  
361 brightness of the pavement surface, which improves the reflection of the pavement surface (Figure 6).  
362 The retroreflection of EAM can also be improved by adding waste glass to the mix (Min *et al.* 2019).  
363 The higher retroreflection of EAM improves the safety of the pavement surface during nighttime.  
364 Additionally, the brighter texture of the pavement not only increases reflectance during the night and  
365 rainy or foggy weather, but also can result in energy savings for highways and airports lighting. As  
366 result, improved sustainability of EAM and safety of road users increase eco-friendly characteristics  
367 and social acceptance.



Figure 6: Use of resin as a transparent binder.

370

### 371 3.6. Air purification

372 Surface of EAM pavement can degrade hazardous gases via using titanium dioxide ( $\text{TiO}_2$ ). The  
373 mechanism is that hydrogen carbon (HC), nitric oxide (NO) and carbon monoxide (CO) compounds  
374 due to fuel burning can be degraded into salt and water by nano- $\text{TiO}_2$  under photocatalysis that is an  
375 irradiation by a light source with a wavelength less than 387.5 nm (Liu *et al.* 2015, Wang *et al.* 2016,  
376 Toro *et al.* 2016, Tang *et al.* 2016, Leng and Yu, 2016, Jin *et al.* 2018). In a laboratory study, Huang  
377 and Wen (2019) evaluated effect of size and content of nano- $\text{TiO}_2$  on the degradation performance of  
378 emulsified EAM. Results indicated that EAM containing 5nm  $\text{TiO}_2$  increases degradation of CO, HC,  
379  $\text{CO}_2$ , and NO by 46%, 48%, 21%, and 60% respectively, compared to those of 10 nm. Therefore, 5nm  
380 can be chosen as optimum size of nano  $\text{TiO}_2$ . In addition, general trend is that higher contents of  $\text{TiO}_2$   
381 in the EAM increases degradation of hazardous materials.  $\text{TiO}_2$  can be sprayed on the surface of  
382 pavement, however long-term durability is cause of concern. As a result, air purification in EAM  
383 leads to the health of pavement users and residents. In other words, the pavements as multi-role  
384 infrastructure assets can create better environment in the cities.

## 385 4. Field Performance of EAM

386 Field investigations show the structural and functional performance of pavements constructed using  
387 EAM under realistic conditions. Therefore, successful field performance can be used to provide  
388 confidence in other EAM projects worldwide. It should be noted that the results of field investigation  
389 can be used to propose new test protocols and experimental procedures for accurate simulation of  
390 realistic condition of EAM.

391 The results of the field investigation of EAM showed that the pavement could be opened to the traffic  
 392 within 2 hours of paving (Dubowick and Ross 2001, Alabaster and Herrington 2008, Apostolidis *et al.*  
 393 2018), which significantly decreases paving time. In this regard, Yao *et al.* (2019) showed that certain  
 394 amounts of SBS in EAB increase adhesive characteristics. This will have the effect of shortening the  
 395 amount of time needed for initial curing before the site will be ready to receive traffic. Field  
 396 investigations of porous EAM in New Zealand showed lower rutting for EAM than for the control  
 397 mix (Herrington 2010). However, some raveling was reported. To achieve the better durability,  
 398 stability, and strength without much loss of permeability, Lu *et al.* (2021) recommended the smaller  
 399 nominal maximum aggregate size in the porous EAM. Furthermore, the noise level increased after the  
 400 first year of evaluation. The reason is that hardening and aging of EAM increases over time. There is  
 401 a linear relationship between the pavement age and noise for passenger cars and multi-axle, heavy  
 402 vehicles (Bendtsen *et al.* 2010, Lu *et al.* 2009). In contrast, the analysis of noise emissions showed  
 403 that the level of noise of porous EAM is comparable with the noise emissions from porous-control  
 404 asphalt (Figure 7). However, the 30% epoxy slightly increases the noise level due to the pick-up of  
 405 aggregate materials during compaction and early traffic loading, which results in a rough  
 406 macrostructure of the pavement surface.

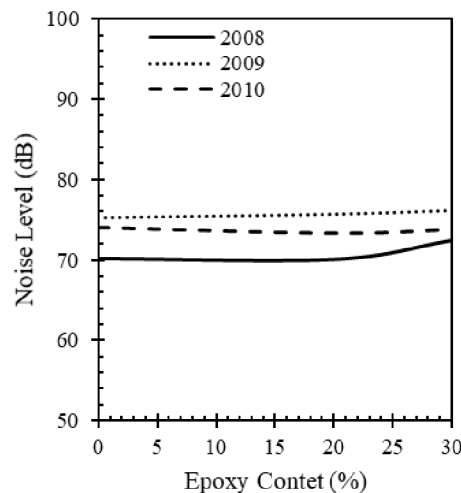


Figure 7: Noise level of EAM, plotted based on data reported by Herrington (2010).

407 Neither material exhibited abnormal fuming or smell during construction and use (Herrington 2010).  
 408 Zegard *et al.* (2019) also reported neither fume nor smell were detected in their field study in the  
 409 Province of Northern Holland in the Netherlands. In addition, they reported the rate of curing of EAM  
 410 was slower than the samples prepared in the laboratory. However, the lower rate of curing did not lead  
 411 to any lack of strength gaining in the field. It should be noted that the lack of strength gaining may  
 412 result in delayed opening of the road to traffic and premature structural and functional failures.

413 There are different applications of EAM based on current challenges in field. For example, in the  
 414 Netherlands, the use of coal tar for runways has been forbidden since 2010 due to the toxic  
 415 components and carcinogenic effects (Van Leest *et al.* 2005). In this regard, some alternative binders  
 416 with sufficient fuel-resistant properties were developed, although the performance, in terms of anti-  
 417 skid resistance, was lower than for coal tar (Put 2006, Rooijen 2004). Therefore, EAM has been used  
 418 as an alternative material for runways and roads.

419 There is a substantial long-term performance of EAM in different countries. For example, EAM was  
 420 used on the San Mateo-Hayward Bridge and has been in service since 1967 and was only recently  
 421 replaced (Chen *et al.* 2018a). The EAM used on Fremont Bridge in Portland, Oregon lasted for 40  
 422 years before being replaced with new EAM (Hicks *et al.* 2012, Maggenti and Shatnawi 2017). In

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2  
3 423 Australia, EAM on the Westgate Bridge in Melbourne lasted for 14 years (Rebbechi and Lancaster  
4 424 1994). The Erskine, Humber, Lions Golden Gate, and Golden Gate Bridges in Scotland, the UK,  
5 425 Canada, and the USA are successful applications of EAM as a paving system (Cluett 1996, Forrest  
6 426 2002, EAPA 2013, Laxdal 2013). However, some EAM projects could not satisfy expectations, such  
7 427 as the San Diego-Coronado, Old McDonald, Runyang Yangtze River, and Ulsan Bridges in the USA,  
8 428 Canada, China, and the South Korea, respectively (Bocchi and Canestrari 2012, Zhu 2013, Chen *et al.*  
9 429 2018a). The probable reason was the lack of experience in design and construction with EAM,  
10 430 especially for the curing process, the wet deck of the bridge, poor bonding between the aggregate and  
11 431 the epoxy binder, lack of bonding between the EAM and the deck, and high level of uncertainty in the  
12 432 analysis of service conditions (Chen *et al.* 2021b, Xu *et al.* 2021, Lu and Bors 2015). However, there  
13 433 are simple strategies to improve the performance of EMA. For example, Chen *et al.* (2018a)  
14 434 recommended that a high polymer epoxy asphalt mixture product containing low oil content can be  
15 435 used on extremely thin steel deck plate (11 mm or even less), to help stiffen the deck plate, mitigate  
16 436 fatigue problems on bridge pavement.

## 19 437 **5. Application of EAM for Various Transportation Infrastructure** 20 **Assets**

21 438  
22 439 EAM can be used for different transportation infrastructure assets due to its structural performance  
23 440 and high durability that are explained in the following sections.

### 25 441 **5.1. Airports and Ports**

26 442 EAM technology was introduced airport pavements in the 1950s (Jet Age). Conceptual airplanes,  
27 443 such as the B747, the Concorde, and the C 130 (Hercules), were designed during this age. Therefore,  
28 444 it was necessary to build the infrastructure to support the new air fleets. The fast operation, ever-  
29 445 increasing wheel load, tire pressure, and complex landing gear led to many structural failures in the  
30 446 airport concrete and asphalt pavements during the Jet Age. It was necessary to develop a durable  
31 447 binder against erosive jet blast (Ke 2008). Shell Oil Company developed the first generation of EAM,  
32 448 under the trademark of AEAPON, to address the structural failures. The higher structural performance  
33 449 and lower vulnerability to fuel spillage and hot gasses emitted from the jets encourage the airport  
34 450 pavement technologists to develop EAM. For example, the US Air Force tested the durability of EAM  
35 451 against the exhaust by an F-86 (Saber) fighter jet on a stand for 60 seconds, and no failures were  
36 452 reported (Simpson *et al.* 1960, Joseph 1965). EAM has been used in civilian and military airports  
37 453 since the 1960s, including Los Angeles International Airport, Berry Field Airport in Nashville,  
38 454 Tennessee, and Bunker Hill Airport in Indiana (Joseph 1965). However, EAB use remains limited  
39 455 with most airports using polymer-modified binder instead. With the success of EAM in these  
40 456 example airports, pavement engineers have since developed EAM for other transportation  
41 457 infrastructure applications (Balala 1969, Rebbechi 1980, Gaul 1996).

42 458 The high structural consistency and less vulnerability against chemical solvents and mineral salts  
43 459 made EAM a promising material for paving in the ports and stacking containers yards. The heavy  
44 460 point loads of the container studs and various modes of loading, such as forklifts, transtainers, straddle  
45 461 carriers, and tractors, result in a combination of static and dynamic loading. Thus, EAM is resistant to  
46 462 a wide variety of loadings compared with highways and airports. In the late 1970s, EAM was used to  
47 463 pave the stacking container yard of Royal Seaforth Dock in the UK (Lu 1994, Lu and Bors 2015).

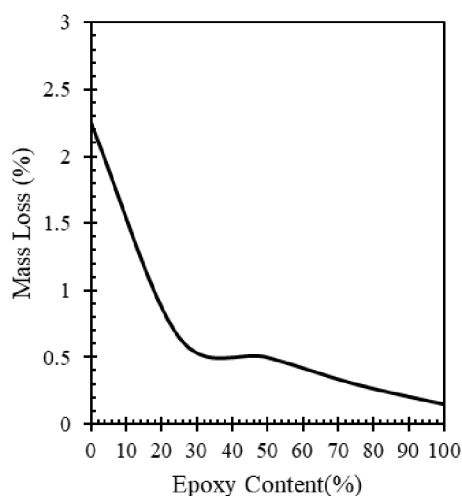
### 51 464 **5.2. Roads**

#### 53 465 **5.2.1. Highways**

54 466 The first application of EAM or AEAPON was in 1960 in the USA (Hicks 2000). The superior  
55 467 performance of the EAM encouraged pavement engineers to perform further research. Eventually, in

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3 468 1986, a full-scale road trial of EAM showed promising results in Staffordshire, UK (Read *et al.* 2016).  
4 469 In China, the first EAM was used as a road pavement in Shanghai in the 1990s (Lu *et al.* 1996, Lu and  
5 470 Bors 2015). The application of EAM was developed for several road infrastructures. For example,  
6 471 porous EAM was used to pave a section of road in Christchurch, New Zealand (Herrington 2010). In  
7 472 Japan, EAM was used as a surface for intersections because of its high durability, which resulted in a  
8 473 satisfactory performance (DRI 2005). However, there is still a lack of detail on EAM for roads under  
9 474 different service conditions.

10 475 Porous asphalt is another paving system that has been used for the construction of roads and parking  
11 476 lots. Porous asphalt is a multi-role infrastructure that improves the landscape and urban design.  
12 477 Porous asphalt pavements have high air voids contents (around 20%) compared with the dense asphalt  
13 478 pavement (around 4% to 6%). Due to the high porosity, the binder drain-down results in clogging.  
14 479 Various methods are used to evaluate the drain-down process, such as the Caltran (Test Method 368),  
15 480 the Pyrex plate method (GDT 2011), the metal wire basket method standardized by ASTM D 7064,  
16 481 and the Schellenberg binder drainage test (BSI 2004). However, clogging in the pavement is complex.  
17 482 A solution to reduce binder drain-down is to use a polymer-modified asphalt binder (Ongel *et al.*  
18 483 2008). EAB can be an appropriate binder to avoid binder creep and drain down due to its high  
19 484 viscosity. Additionally, the porous asphalt pavement's service life is relatively short, around 8 to 12  
20 485 years. EAB can also extend the pavement's life due to its high stiffness (Kandhal *et al.* 1998, Bennert  
21 486 and Cooley 2014). For example, porous EAM showed the higher fatigue resistance compared with  
22 487 porous mixtures produced using high viscosity binder (Li *et al.* 2022b). However, the use of porous  
23 488 EAM is not new. It was first used in San Francisco-Oakland in 1969 (Brewer 1970). High-quality  
24 489 epoxy resin and other advanced materials have resulted in a more efficient porous EAM. For example,  
25 490 Cantabro test results clearly showed that the Cantabro losses of porous EAM were 76% and 60%  
26 491 lower than traditional porous pavements for the unaged and aged states, respectively (Lu *et al.* 2015).  
27 492 The Cantabro test shows the potential of raveling in the porous pavement. Therefore, the less mass  
28 493 loss, the less prone to the raveling. Also, oxidation decreases the loss modulus of porous EAM, based  
29 494 on the Cantabro test (Herrington and Alabaster 2008). Figure 8 shows that the mass loss of porous  
30 495 EAM decreased as epoxy content increased. However, the binder type played a significant role in the  
31 496 mass loss of EAM (Holleran *et al.* 2017).  
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53 Figure 8: Trend of the mass loss as a function of epoxy content; plotted based on data reported by  
54 *Wu et al.* (2017).

55 498 The sound absorption coefficient of porous EAM fluctuates between 0.35 to 0.45, while the  
56 499 coefficient of traditional porous asphalt varies from 0.15 to 0.65, indicating a more efficient noise

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3 500 reduction of associated with EAM (Luo *et al.* 2015). The noise emissions can be reduced more via the  
4 501 use of crumb rubber in the porous pavement. For example, in Japan, a new type of porous mix  
5 502 containing crumb rubber was developed, referred to as PERS (Kubo 2011a). Analysis of road  
6 503 acoustics showed that the noise level could be decrease by around 20% according to the Japan Road  
7 504 Association (2006, 2009). Use of crumb rubber may decrease the surface friction (Kawakami and  
8 505 Kubo 2008, Kubo *et al.* 2011a, b), but the use of sand in PERS improves the friction.

9 506 The performance of porous EAM in rutting and fatigue was superior to traditional samples. Visual  
10 507 inspection of rutted samples showed that the rutting was primarily by crushing and loosening of  
11 508 aggregate particles under the vehicles' wheels instead of deforming due to shear stresses (Luo *et al.*  
12 509 2015). The oxidation of EAB results in loss of surface material (Herrington and Alabaster, 2008).  
13 510 Furthermore, the pores of the porous EAM are filled with worn tires from a wheel tracking test. The  
14 511 rutting in the porous pavement can decrease over time. However, the early-life rutting of porous EAM  
15 512 is not likely to be greater than that of the traditional porous asphalt pavement (Alabaster *et al.* 2008).  
16 513 However, Holleran *et al.* (2017) found the dynamic modulus and fatigue life of the porous EAM  
17 514 containing 25% epoxy are lower than the figures for the polymer-modified porous mixes.  
18 515 Furthermore, the use of a small aggregate size can improve the performance of porous EAM in terms  
19 516 of friction, moisture resistance, and high and low-temperature stability (Qian and Lu, 2014, 2015).

### 21 22 517 5.2.2. Tunnel Pavement

23 518 Structural performance and high visibility are key factors for pavement in tunnels. The pavement in  
24 519 tunnels is less prone to rutting and aging, due to the tunnels' lower temperatures. For better visibility  
25 520 of the pavement surface, the tunnels are usually equipped with a lighting system, which is costly and  
26 521 not an environmental-friendly approach. Signs are also used to reflect the vehicles' light more  
27 522 effectively. However, it is necessary that the signs are periodically washed, which enhances  
28 523 maintenance costs. Another solution is the use of waste glass in the asphalt mixes to increase  
29 524 pavement albedo (Jamshidi *et al.* 2016). In Japan, brightly colored EAM is used to improve the  
30 525 visibility in the pavement tunnels. For example, a layer of the brightly colored EAM was overlaid on  
31 526 the old concrete pavement in the tunnel. After 10 years, the EAM was evaluated based on the normal  
32 527 serviceability prescribed by the Japan Road Association. The results indicated neither cracks nor a  
33 528 change in the density of mix (Takahashi *et al.* 2004). The level of visibility of EAM was also higher  
34 529 than the concrete pavement, which increases the safety of road traffic.

35 530 Additionally, survey results show that the first maintenance was 30 years after the evaluation.  
36 531 Therefore, the life cycle of the overlay is 40 years because the first survey was 10 years after the first  
37 532 construction. The life cost analysis using the Taniguchi methodology (Taniguchi 2003), standardized  
38 533 by Japan Society Civil Engineering, showed that the total costs of brightly colored EAM are 80% and  
39 534 73% of the concrete pavement and polymer-modified asphalt pavement, respectively. Therefore, the  
40 535 use of EAM overlay not only improved the safety and structural performance of the pavement but also  
41 536 decreases the costs of the pavement management system.

### 42 43 44 45 537 5.3. Bridge

46 538 Traditionally, SMA, the polymer-modified, and GA mixes have been used to pave bridge decks.  
47 539 Although these mixes can meet the requirements, they are vulnerable to the heavy-duty loading by  
48 540 trucks and high deck temperatures. Maintenance and rehabilitation of the bridge pavement is not an  
49 541 easy task due to a short window of work. Additionally, overlaying increases the total bridge dead  
50 542 loads that changes the seismic response of the structure. Therefore, it is necessary to use mixes with  
51 543 the highest available performance. One of the alternatives is the use of EAM. For example, However,  
52 544 Nie *et al.* (2022) found that the fatigue endurance limit strain level of EAM ( $600 \mu\epsilon$ ) was higher than  
53 545 that of the steel bridge deck pavement ( $<300 \mu\epsilon$ ), indicating that the EAM has better flexibility and  
54 546 can achieve a longer service life.



547 The structural response of the bridge depends on the interaction between bridge and pavement system,  
 548 bridge type, and traffic loading. EAM has been used for various bridge types. The performance of  
 549 bridges paved with EAM was studied based on structure type and is discussed in the following  
 550 section. Table 1 shows summaries of details of bridges paved with EAM worldwide.

551

552 Table 1: Specifications of bridges paved with EAM in different countries, based on data reported by

553

Chaohui et al. (2018)

Bridge name	Country	Year of construction	Structure of bridge	EAM thickness (mm)
Verrazano	USA	1964	Steel truss girder	50 (single layer)
San-Mateo Hayward	USA	1967	Steel truss girder	50 (double layer)
San Diego Coronado	USA	1969	Steel truss girder	50 (double layer)
San Francisco Oakland Bay	USA	1969	Pre-stress concrete beam bridge	13 (single layer)
Queensway	USA	1970	Steel truss girder	50 (double layer)
Mckay	Canada	1970	Steel truss girder	50 (double layer)
Angus Lewis Macdonald	Canada	1971	Concrete	38 (single layer)
Evergreen Point Floating	USA	1972	Concrete	13 (single layer)
Sellwood	USA	1973	Concrete	22 (single layer)
Merce	Canada	1974	Steel truss girder	38 (single layer)
Costa De Silva	Brazil	1974	Pre-stress concrete beam bridge	50 (double layer)
Lions Gate	Canada	1975	Steel truss girder	35 (single layer)
West Gate	Australia	1976	Steel box girder	50 (double layer)
Fremont	USA	1980	Concrete	50 (double layer)
Hale Boggess	USA	1983	Concrete	63.5 (double layer)
Kuandu	China	1983	Steel box girder	50 (double layer)
Lu Ling	USA	1984	Steel truss girder	57 (double layer)
Ben Franklin	USA	1986	Steel truss girder	42 (double layer)
Golden Gate	USA	1986	Steel truss girder	50 (double layer)
Champlain	USA	1993	Concrete	10 (single layer)
Maritime Off-Ramp	Canada	1996	Steel truss girder	76 (double layer)
The Second Nanjing Yangtze	China	2000	Steel box girder	50 (double layer)
Yanjiang Highway	China	2004	Steel box girder	40 EAM+40 SMA
Tianjin Dagu	China	2005	Steel box girder	50 (double layer)
North Branch Bridge of Runyang Yangtze River	China	2005	Steel box girder	55 (double layer)
South Branch Bridge of Runyang Yangtze River	China	2005	Steel box girder	55 (double layer)
Connecting Line of Runyang Yangtze River	China	2005	Steel box girder	55 (double layer)
The Third Nanjing Yangtze River	China	2005	Steel box girder	50 (double layer)
Zhoushan Taoyaomen	China	2006	Steel box girder	85 EAM+ 25 HMA
Zhanjiang	China	2006	Steel box girder	50 (double layer)
Guangdong Pingsheng	China	2006	Steel box girder	50 (double layer)
Beijing Changping	China	2006	Steel box girder	50 (double layer)

1					
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3	Tianjin Jinbu	China	2007	Steel box girder	50 (double layer)
4	XiamenWushi	China	2007	Steel box girder	60 (double layer)
5	Wuhan Yangluo Chang-jiang	China	2007	Steel box girder	60 (double layer)
6					
7	Shenzhen Houhai	China	2007	Steel box girder	60 (double layer)
8	The Second Shenzhen Houhai	China	2007	Steel box girder	60 (double layer)
9					
10	Tianjin Fumin	China	2008	Steel box girder	65 (single layer)
11	Nanjing Xuanwu Huayuan	China	2008	Concrete	30 EAM+40 SMA
12	Zhoushan Xihoumen	China	2008	Steel box girder	55 (double layer)
13	Nanjing Cupinggang	China	2008	Concrete	30 EAM+40 SMA
14	Shanghai Yunzaobin	China	2008	Concrete	40 EAM+40 SMA
15	Guangzhou Dongsha	China	2008	Steel box girder	10 (single layer)
16	Zhujiang Huangpu	China	2008	Steel box girder	60 (double layer)
17	Sutong Yangtze River	China	2008	Steel box girder	55 (double layer)
18	The Third Ji'nan Yellow River	China	2008	Steel box girder	50 (double layer)
19					
20	Wuhan Tianxingzhou	China	2009	Steel box girder	60 (double layer)
21	Nanjing Binjiang Road Xiaguan	China	2009	Steel box girder	70 (double layer)
22					
23	Chongqing Fish Mouth Yangtze River	China	2009	Steel box girder	55 (double layer)
24					
25	Shanghai Min Pu	China	2009	Steel box girder	55 (double layer)
26	Guizhou Baling	China	2009	Steel box girder	55 (double layer)
27	Humen	China	2009	Steel box girder	70 (double layer)
28	Jiangyin Sanjiang	China	2009	Steel box girder	50 (double layer)
29	Wuhan Baishazhou	China	2009	Steel box girder	50 (double layer)
30	Shanghai Yangtz	China	2009	Steel box girder	55 (double layer)
31	Shanghai Longhua	China	2010	Steel box girder	80 (double layer)
32	Huzhou Xindatong	China	2010	Steel box girder	55 (double layer)
33					
34	Shanghai Ji Chang East Road	China	2010	Steel box girder	95 EAM+ 40 SMA
35					
36	Tianjin Guotai	China	2011	Steel box girder	55 (double layer)
37	Chongqi	China	2011	Steel box girder	55 (double layer)
38	Guangdong Mafang	China	2011	Steel box girder	55 (double layer)
39	Tianjin Binhai	China	2012	Concrete	75 (double layer)
40	Taizhou Yangtze River	China	2012	Steel box girder	80 (double layer)
41					
42	Wuxi Wuyue	China	2012	Steel box girder	50 EAM+ 40 HMA
43					
44	Nanjing Shuanglong	China	2012	Steel box girder	60 (double layer)
45	Beijing Hangzhou Grand Canal	China	2012	Concrete	75 (double layer)
46					
47	The Second Ningbo Daxie	China	2013	Steel box girder	55 (double layer)
48					
49	Gaokan	China	2013	Steel box girder	55 (double layer)
50	Jiangshun	China	2013	Steel box girder	55 (double layer)
51	Li Shunchen	Korea	2013	Concrete	50 (double layer)
52					
53	Xiamen Fenhe	China	2014	Pre-stressed concrete box girder	70 (double layer)
54	Panjin Neihu	China	2016	Steel box girder	60 (double layer)
55	Fanli	China	2016	Steel box girder	80 (double layer)
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### 5.3.1. Orthotropic Steel Bridge Deck Pavement

Construction of the orthotropic steel bridge decks (OSBD) is becoming popular owing to lower costs, rapid assembly, and relatively easy maintenance and rehabilitation. OSBD were first introduced in Germany and have since been built in different countries, such as the United States, China, Japan, and Australia (Touran and Okereke 1991, Hulsey *et al.* 1999, Mangus 2000, Seim and Ingham 2004, Austroad 2018). The term “orthotropic” is used for such bridges because of the use of stiffening ribs at a right angle (orthogonal) to the floor beam, which results in an anisotropic characteristic of the deck. Moreover, the bridges are not homogenous structures because of different construction materials with various properties. For example, the elastic modulus of the steel deck is 210 GPa, but the dynamic modulus of the EAM is 12 GPa (Wang and Zhang 2018). Furthermore, the utility condition of asphalt surface course on OSBD is vastly different from the other pavements as follows:

- The wearing course is placed directly on top of OSBD steel. Therefore, the maximum stress/strain and deflection usually happens on the top of the wearing course (Huang 2015), while the maximum stress/strain occurs on the bottom of the traditional highway and airport pavement. For example, Matsukawa *et al.* (1983) analyzed the top and bottom of EAM in summer and spring and found that the maximum stress happened on the surface of EAM on the main girder of the bridge.
- The wearing course is more prone to thermal stresses rather than the traditional pavement because of the high thermal conductivity of steel. The high temperature in the steel structure of the bridge increases the thermal stresses in the surface course. Therefore, expansion and contraction of the bridge can result in failures in the asphalt due to different thermal conductivity. For instance, Iwasaki (1997) analyzed the thermal stress generated in the structure of the Nagoya Expressway Bridge in Japan. The results showed that the thermal stresses produced in the steel plates proportionally increased by the temperatures of pavement surface.
- As OSBDs are three-dimensional structures, the structure of the bridge can be deformed due to dynamic loads stemming from the wind. The deformed structure (i.e., deflection, bending, and torsion) impose internal strain/strains and deflection in the surface course throughout the service life. Therefore, it is necessary the asphalt pavement deforms with the steel deck synchronously.

One of the materials that can be used as a surface course on OSBD is EAM because the ductility and damping characteristics of EAM can be advantageous for paving the OCBD. Figure 9 shows the elongation and tensile strength of EAB. As shown in the figure, the elongation decreases slightly, while the tensile strength increases. Consequently, the epoxy network in the structure of the binder improves the strength modulus of the mixture, which is less prone to deformation owing to expansion and contraction. From the figure, the elongation and toughness modulus of EAB can be selected to design a synchronized EAM with the bridge decks.

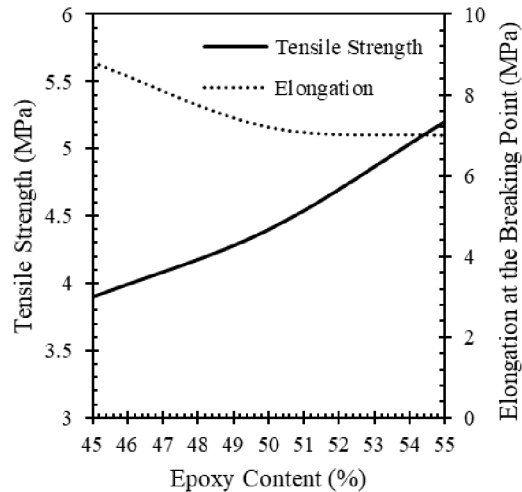


Figure 9: Effect of epoxy content on the tensile strength and elongation; plotted based on data reported by Yin *et al.* (2015).

In an analogous study, the tensile adhesive strength of EAM was two times higher than the values prescribed by the Japan Road Association (Katagiri *et al.* 2010), indicating good bond with the steel plates in the OSBD. The utility condition of OSBD, air temperature, moisture content, traffic loading, and aggressive chemical materials (e.g., mineral salts) is another variable. For example, interaction between heavy traffic loading and temperature variations significantly increases fatigue failures in the long span steel bridges (Xu *et al.* 2019). Also, the critical points of deck pavement in OSBD, in terms of strain and displacement, can change due to temperature variations (Kim *et al.* 2014). It is therefore necessary to collect various input data, including environment, climatological, raw material, and traffic loading characteristics. In this regard, Huang (2015) developed a five-step strategy as an integrated system for the design of EAM and OSBD:

- Step 1: Data collection and preparation.
- Step 2: EAB and EAM design.
- Step 3: Structural design of OSBD.
- Step 4: Tolerance determination of bridge.
- Step 5: Empirical validation.

Reportedly, this methodology was tested for the second bridge connecting the two banks of the Nanjing Yangtze River in China. Since the completion of the bridge in 2001, EAM designed by the proposed strategy is in a satisfactory service condition.

To reduce tensile stress/strain, one strategy is the use of thicker steel plates for the deck, or a thicker EAM layer (Seim and Ingram 2004, Bocci and Canestrari, 2012, Yao *et al.* 2013b, Chen *et al.* 2018a), which both increase the total dead load of the bridge structure. It is clear that less dead load results in a more cost-effective design. In this regard, Hu *et al.* (2016) suggested replacing the aggregate with the lightweight aggregates. The results showed that the maximum indirect tensile strength (ITS) could be achieved for the EAM containing 5% epoxy. However, fracture energy and bending modulus decreased as lightweight aggregate content increased.

Moreover, the EAM may crack after 5 to 10 years (Li *et al.* 2010, Han *et al.* 2010). Since the cracks are so narrow, the crack sealing materials should be viscous enough to penetrate and fill throughout the openings. The sealing materials should gain strength at an appropriate time. Furthermore, the rapid cooling rate of the EAM can result in cracking due to residual thermal stress. Therefore, the selection of a suitable base binder, curing agent, ambient temperature, and the temperature gap of the upper and

627 lower surface plates used in the bridge is vital. Otherwise, traditional crack sealing materials cannot  
628 be used efficiently. A comparative study carried out by [Yin et al. \(2016\)](#) showed that epoxy sealing  
629 materials could show higher penetration, bonding strength, and shorter curing time. The epoxy resin  
630 materials can therefore be used for the efficient maintenance and rehabilitation of the pavement. It is  
631 also necessary to understand EAM cracking via advanced methods ([Qian et al. 2014](#)). Additionally,  
632 based on viscosity and tensile strength, [Gong et al. \(2019\)](#) recommended warm-EAB containing 1.9%  
633 weight ethylene-vinyl acetate copolymer as an optimum binder blend for use on the bridge.  
634 Consequently, the structural requirements of EAM for bridge deck wearing course can be met via the  
635 appropriate selection of additive contents and binder types. Furthermore, development of predictive  
636 models based on rheological characteristics of EAB and engineering properties of EAM can be  
637 considered as a useful tool to structural performance of pavement on the bridge. For example, [Huang  
638 et al. \(2019\)](#) recommended to use the modified second-order extensive rheological Kelvin model for  
639 predicting stresses in EAM.

640 Durability of pavement structure on the bridge is another challenge which requires further attentions.  
641 For example, blistering decreases durability of the bridge pavement. This often takes place as the  
642 bond between the waterproofing membrane and the substrate layers disintegrates. The mechanism of  
643 blistering can be divided into three stages ([Zhang et al. 2016b](#)): (1) initiation, (2) stale; and (3)  
644 unstable propagation. It should be noted that the most important factor on the growth of blistering is  
645 temperature and blistering reaches to its limit within 30min to 90 during curing period of EAM ([Lia  
646 and Luo, 2022](#)). Therefore, it is difficult to detect blistering growth at low temperatures. The ability of  
647 EAM to resist deformation of blistering phenomenon positively correlates with curing time ([Lia and  
648 Luo, 2022](#)).

649 There are different strategies to improve the durability using epoxy asphalt technology. As an  
650 instance, [Huang et al. \(2020\)](#) proposes epoxy asphalt rubber with silane coupling agent for the as tack  
651 coat on orthotropic steel bridge decks. Such tack coats showed improved mechanical properties and  
652 performance in freeze-thaw cycles compared to traditional tack coats. However, further laboratory  
653 studies and field investigations are required to understand blistering and the other phenomena impact  
654 on the durability of EAM used on the bridge.

### 655 5.3.2. Bascule Bridge Pavement

656 In a similar study, [Qian et al. \(2011\)](#) replaced the traditional aggregate with a lightweight aggregate of  
657 EAM up to 70% for the pavement of the Bascule Bridge. The main reason for the use of the  
658 lightweight aggregate was the reduction of dead load in the design and construction of the bridge.  
659 Figure 10 shows the effect of the lightweight aggregate content on the engineering properties of  
660 EAM. **Figure 10 (a) shows Marshall Stability and Flow of the mix. From the figure, the lightweight  
661 aggregate has no significant effect on Stability, while it decreased the Flow of the mix. Figure 10(b)  
662 shows the OBC increased as the lightweight aggregate percentage increased. The reason is that the  
663 high porosity of the lightweight aggregate absorbs more asphalt binder, which increases the asphalt  
664 binder requirement. Figure 10(c) shows the dynamic stability of the EAM increased by increasing the  
665 lightweight content because of higher binder content. Additionally, incorporation of lightweight  
666 aggregate improves the bending beam strength of the EAM (Figure 10(d)).**

667

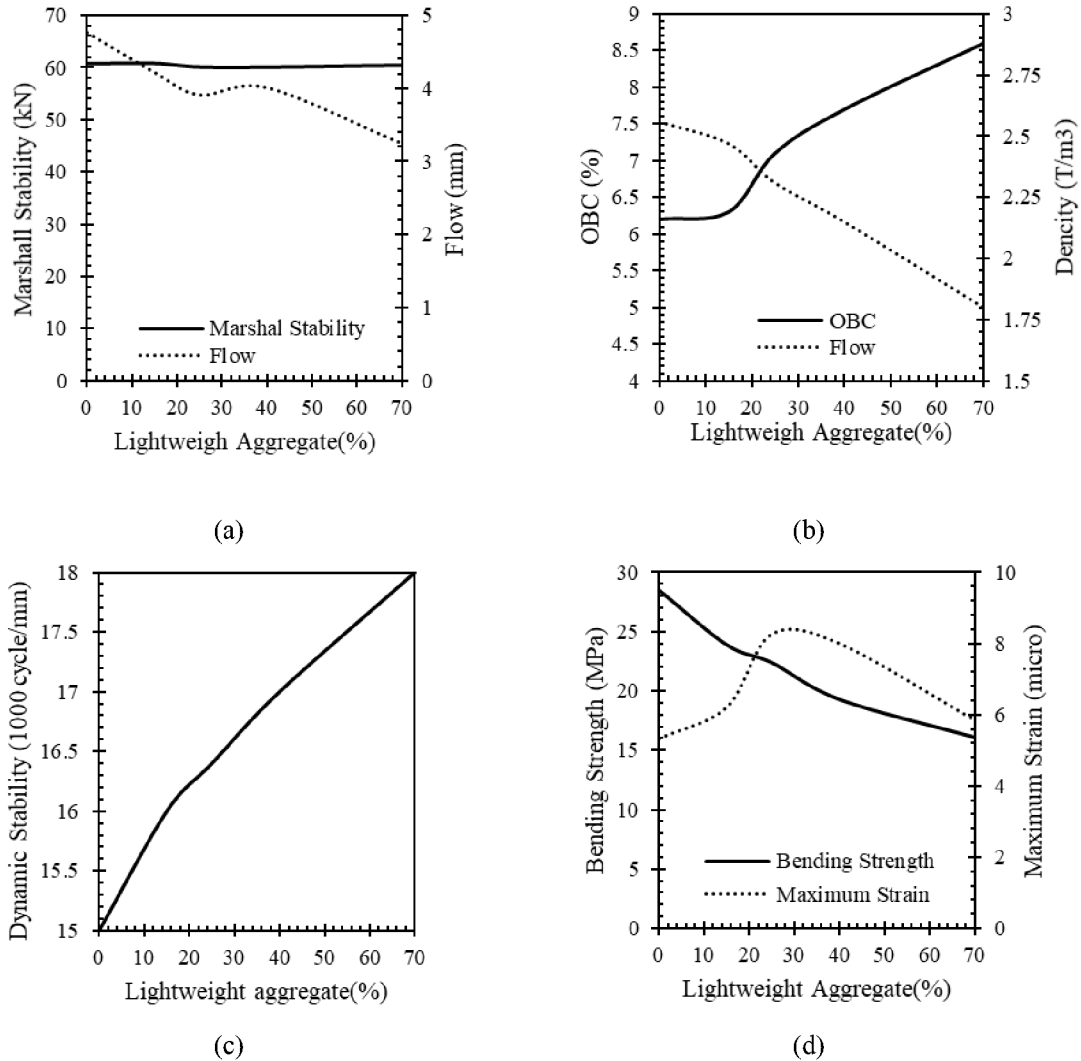


Figure 10 : Effects of the lightweight aggregate on the engineering properties of EAM; plotted based on data reported by [Qian et al. \(2011\)](#).

668

669 The aggregate shape is another property of the lightweight aggregate that influences the engineering  
 670 properties of EAM. Figure 11 shows the effect of two shapes of lightweight aggregates on different  
 671 engineering properties. From Figure 11(a), the rounded aggregate content had no effect on the  
 672 Marshall Stability of EAM, while the higher percentages of the granular aggregate decrease. Both  
 673 aggregate shapes decreased the Flow of EAM, which means the mix may become more brittle.

674 Figure 11(b) shows that incorporation of the lightweight aggregate increases optimum binder content  
 675 (OBC) because the lightweight aggregate particles are more porous, thereby absorbing more asphalt  
 676 binder. Additionally, a higher percentage of lightweight aggregate increases mix voids. To fill the  
 677 voids, more OBC is required. The use of the lightweight EAM prepared with high binder content  
 678 reduced the dead load by 13–15% ([Chen et al. 2018a](#)).

679 From Figure 11(c), the dynamic stability of EAM containing the lightweight aggregate increased;  
 680 however, the dynamic stability of EAM prepared by granular aggregate is even higher. For both  
 681 aggregate shapes, the maximum dynamic stability is for EAM containing 70% lightweight aggregate.  
 682 Due to the lower dead load, the outputs of finite element modeling of the bridge showed the  
 683 maximum shear strain of the bridge deck decreased ([Qian et al. 2011, 2013](#)).

684

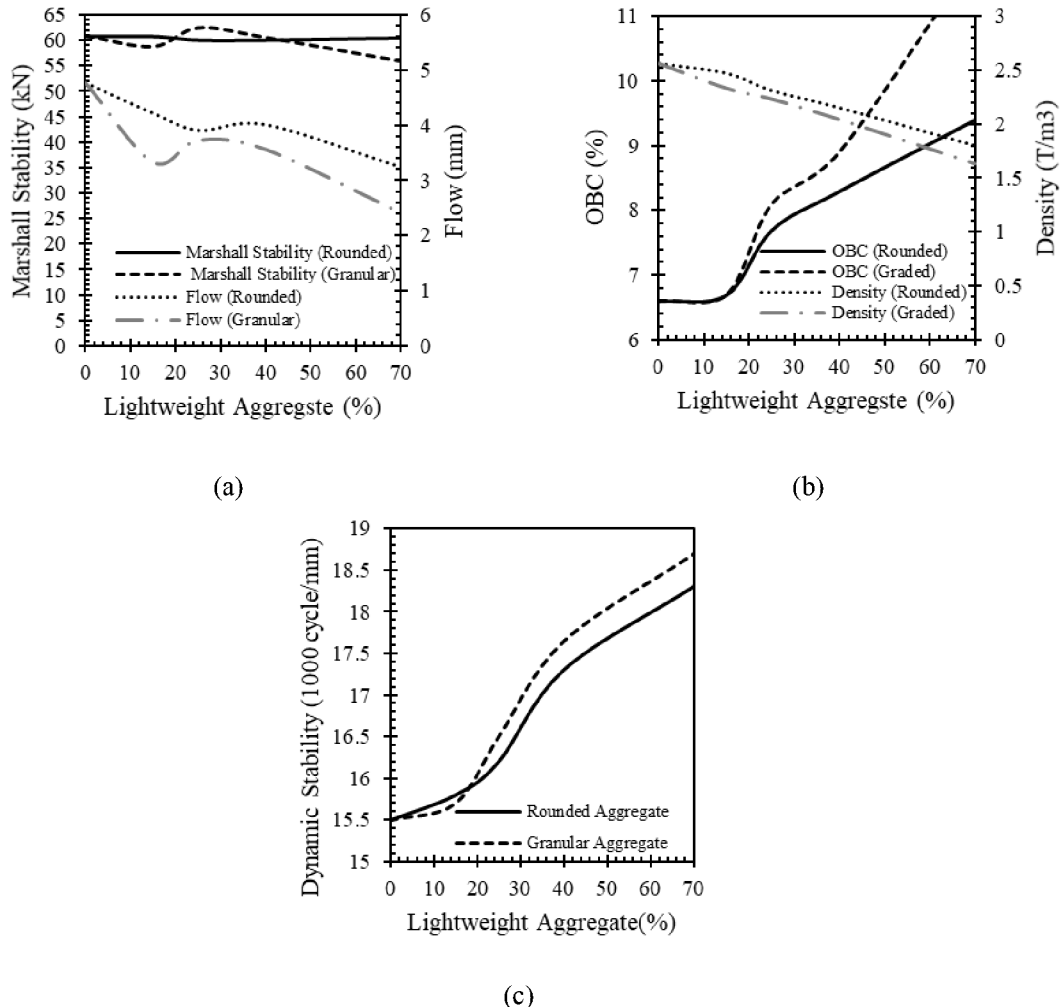


Figure 11: Effects of the lightweight aggregate shape on the engineering properties of EAM; plotted based on data reported by [Qian et al. \(2013\)](#).

## 685 5.4. Railroad

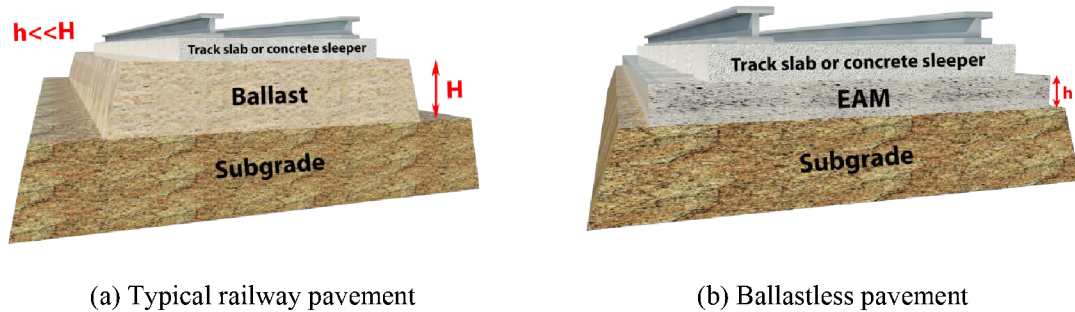
### 686 5.4.1. Railroad Pavement

687 Due to the rapid development of high-speed and heavy-load trains, a cost-effective and durable  
 688 railroad pavement system with high capacity for vibration attenuation is necessary. For example,  
 689 Japan and China have invested significant financial resources on the development of the most recent  
 690 generation of bullet trains, related infrastructure assets, and materials.

691 The current concrete substructures of railroads are prone to cracking, and access for maintenance is  
 692 becoming exceedingly difficult ([Al-Qadi et al. 2010](#), [Lee et al. 2015](#), [Li et al. 2016](#)). There are  
 693 different solutions and alternative railroad pavement materials to address this challenge. One practical  
 694 solution is to use asphaltic materials in the construction in the substructure of the railroad. For  
 695 example, in Japan, the Japan Railroad (JR) provided technical documents to use an asphalt pavement  
 696 layer with crushed concrete to improve the structural stability of the track-bed in the ballasted railroad  
 697 pavement ([Momoya and Sekine 2004](#)). However, the first use of asphaltic material in the railroad  
 698 pavement system dates back to the 19<sup>th</sup> century in the United States ([Read et al. 2016](#)).

699 Furthermore, there is a ballastless railroad pavement that consists of a relatively thick asphalt slab  
 700 between subgrade and concrete slab track. For the first time, the ballastless railroad pavement for the  
 701 high-speed trains, namely Getrack, was used in Germany ([Freudenstein 2005](#)). Since EAM has high

1  
2  
3 702 stiffness, high damping effect, anti-fatigue characteristics, and is less vulnerable to aging and  
4 703 chemical attacks, EAM can be proposed for the ballastless pavement system designed for high-speed  
5 704 trains (  
6 705 Figure 12). In this regard, *Liu et al. (2018b)* researched the performance of the three types of EAM as  
7 706 railway substructures in comparison with traditional concrete materials.  
8 707  
9 708



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19  
20 (a) Typical railway pavement (b) Ballastless pavement  
21  
22  
23 Figure 12: Schematic illustration of a typical cross-section of railway pavement structure with and  
24 without Ballast.  
25

26 709  
27 710 Figure 13 reveals the results of the compressive strength, ITS, bending strengths damping ratio (DR),  
28 711 and coefficient of thermal expansion (CTE) for various materials. The compressive strength of EAM  
29 712 is comparable to the concrete (Figure 13(a)). Although EAM is a viscoelastic material, the high  
30 713 stiffness of hardened EAM increased the compressive stiffness. Figure 13(b) shows that ITS of EAMs  
31 714 is almost two times that of concrete samples. The higher tensile strength of EAM provides improved  
32 715 resistance to cracking, which results in a longer service life of the substructure.  
33 716 Additionally, Figure 13(c) shows the bending resistance of EAMs is higher than that of concrete  
34 717 samples. This means that the deformability of EAM is more than for the traditional concrete  
35 718 substructure due to high ductility of EAM. That is an important factor because the cumulative  
36 719 stress/strain due to structural loading results in cracking in the substructure. The bending strength of  
37 720 the rubber EAM is the highest. The use of rubber can therefore improve the fatigue properties of the  
38 721 substructure. However, the rheological characteristics of the base binder and curing methods play a  
39 722 pivotal role. Figure 13(d) reveals that the CTE of EAM is superior to the concrete materials. This  
40 723 means that EAM is less prone to cracking from the thermal stresses induced by ambient temperatures  
41 724 and the magnetic properties of the high-speed trains because of the thermosetting characteristics of  
42 725 EAM. The higher damper ratios of EAM show a high potential in the vibration attenuation, which  
43 726 significantly increases comfortability for the passengers. It also generates a sense of reliability among  
44 727 the passengers because the high speed of the trains ( $\geq 300$  km/hr) may result in some psychological  
45 728 problems for users.  
46 729  
47 730



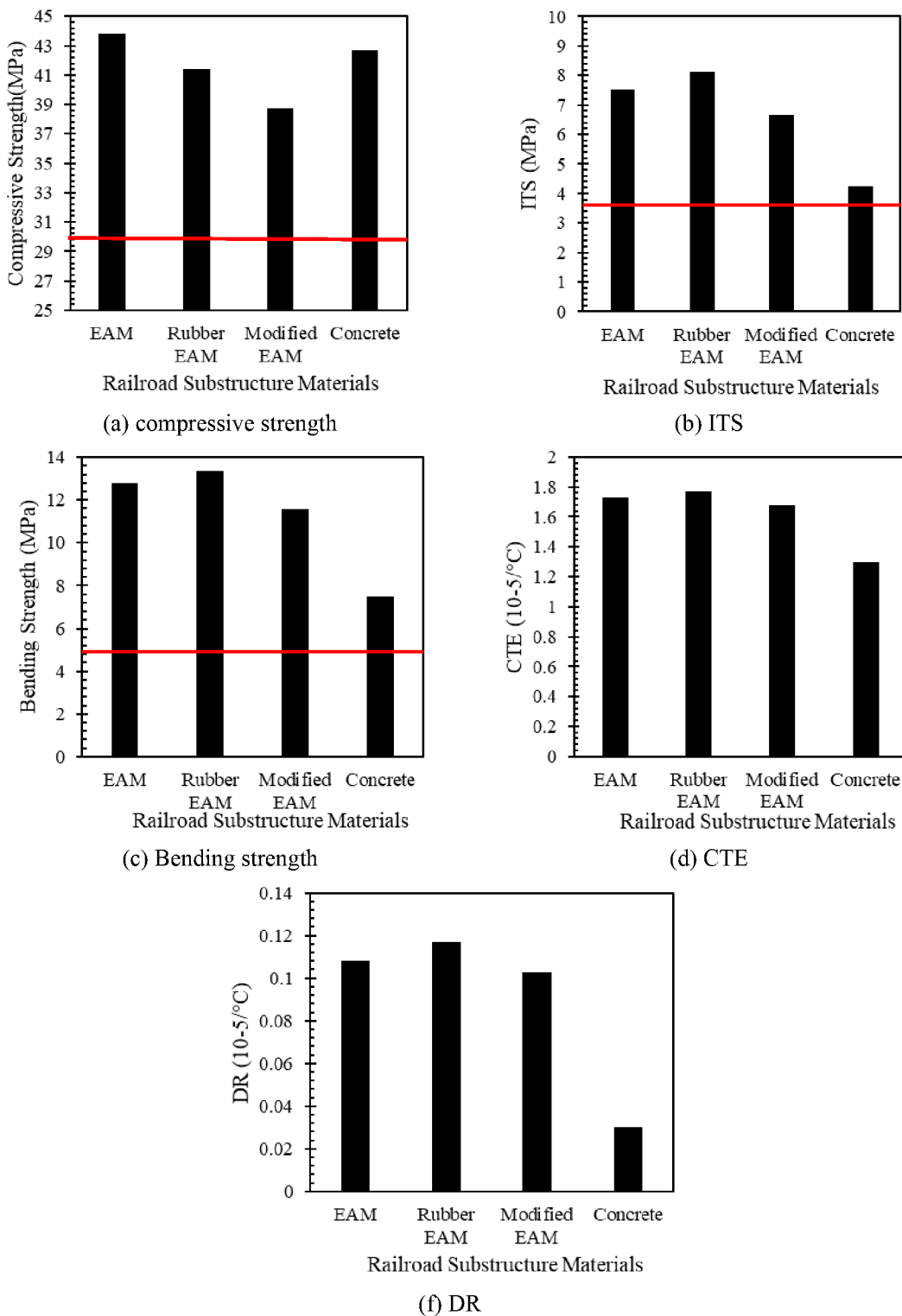


Figure 13: structural performance and durability of EAM as substructure materials in railroad pavement of high-speed train; plotted based data reported by Liu *et al.* (2018b).

Note: The allowable level is shown by the red line.

731

#### 5.4.2. Railroad Bridge

The structure of a railroad bridge is subjected to the severe combinations of dynamic loading, especially for bullet trains. The bridges constructed for the rapid bullet trains should be light and resistant enough to provide safe and cost-effective transportation.

In the railroad pavement, before laying the ballast, a protective course is constructed to protect the waterproof membrane against the sharp edges of the ballast aggregate. Both asphalt and concrete protective layers are used. However, the concrete protective layer is brittle, and concrete shrinkage can result in cracking. To achieve higher strength, [Chen et al. \(2013\)](#) proposed EAM as a protective layer for bridges serving the rapid bullet trains (Figure 14).

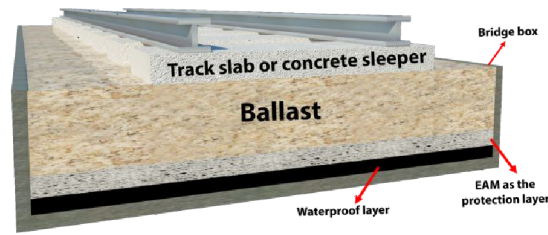


Figure 14: Schematic illustration of a typical cross-section of railway pavement structure on the bridge deck.

742

The performance of the EAM and cement concrete protective (CCP) layers were compared in terms of compressive strength, bending, and abrasion loss in Figure. Figure 15(a) shows that the compressive strength of CCP is higher than EAM samples. However, both samples meet compressive strength. Figure 15(b) and (c) indicated that the indirect tensile and bending strength of EAM is higher than CCP, which means that EAM is less prone to the tensile cracking. Therefore, the life span of EAM is expected to be longer than CCP.

The water can ingress through cracks into the waterproof layers, significantly decreasing the durability of the pavement structure. EAM can therefore be considered as a solution to decrease the water penetration in the railroad structure on steel bridges. Furthermore, EAM's strength against abrasion loads is 60% higher than for CCP. The higher abrasion strength also improves the durability of the pavement structure and costs of maintenance and rehabilitation. Therefore, the use of EAM can be proposed as a strategy to reduce the cost and time of maintenance. Additionally, numerical analysis of EAM and the steel structure of the bridges shows a satisfactory interaction. **However, EAM is vulnerable at the initial stage of paving under train-induced vibration, the process of breakdown rolling is essential after paving and the requirements of material should be improved properly in the design phase (Zhang et al. 2022). Moreover, the vibration of train may affect the curing of EAM. To tackle this problem, rapid-curing EAM is recommended.** Therefore, it is necessary to conduct research focused on the effects of vibration on the characteristics and long-term performance of EAM on rail bridges under realistic conditions.

762

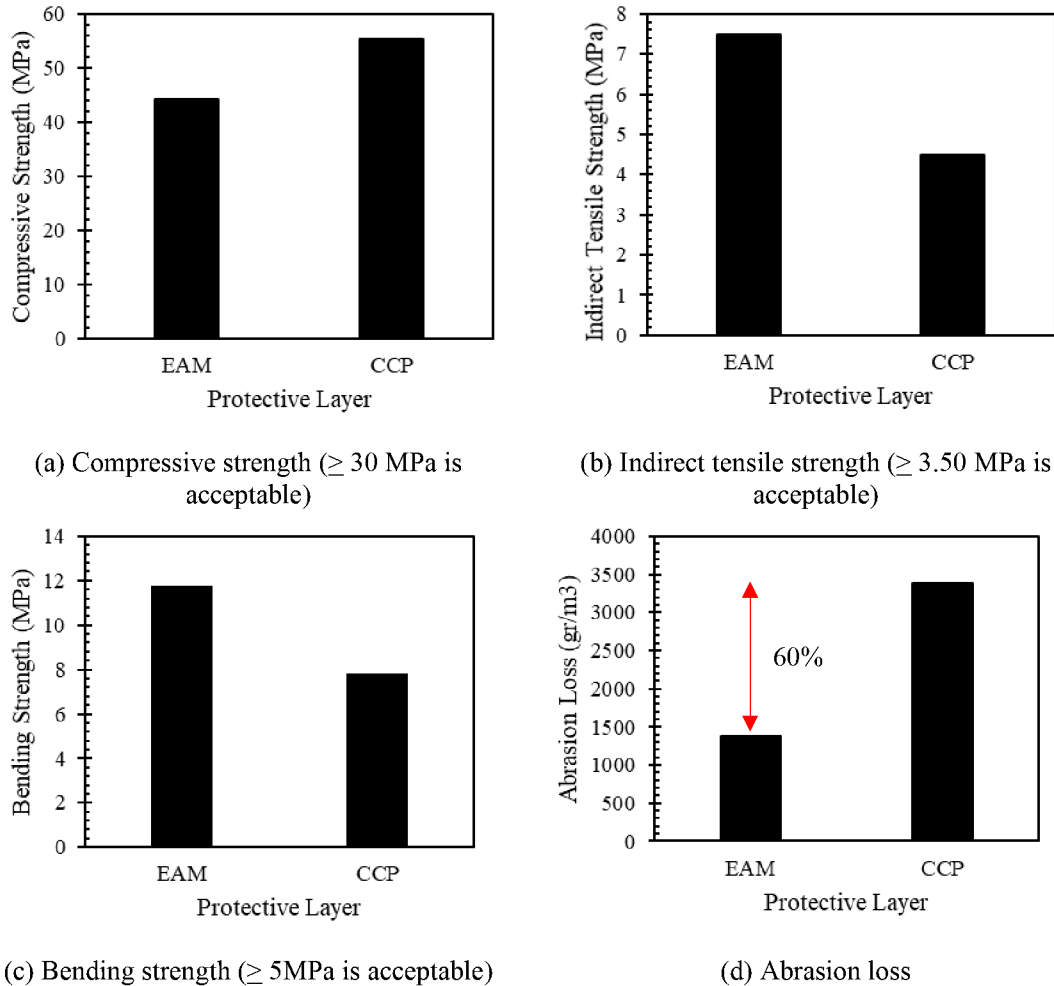


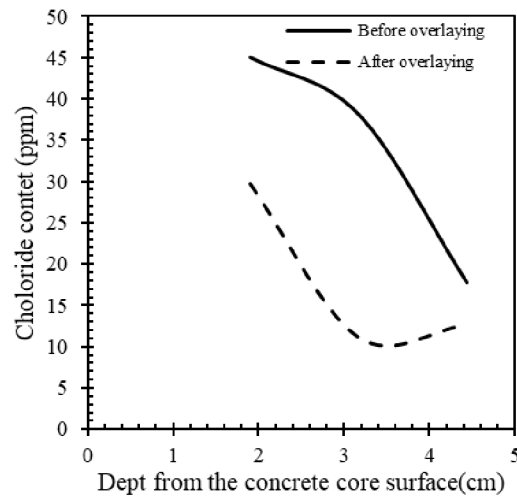
Figure 15: Comparison of different engineering properties of EAM and CCP; plotted based on data reported by [Chen et al. \(2013\)](#).

763

## 764 6. Maintenance and Rehabilitation

765 Pavements constructed using EAM require maintenance and rehabilitation. EAM can be used as an  
 766 overlay on the asphalt and concrete pavement surfaces. For example, 25,000 m<sup>2</sup> was overlaid using  
 767 EAM on the Evergreen Point Bridge in 1972 ([Luo et al. 2013](#)). Additionally, 11,000 m<sup>2</sup> of the  
 768 pavement of McDonald Bridge was overlaid in Halifax, Canada, in 1971. The San Francisco Bay  
 769 Bridge was also repaired using epoxy paving materials ([Seim 1979](#), [Luo et al. 2013](#)). Epoxy asphalt  
 770 can be also used as a tack coat layer to bond new overlay and the old pavement. The optimum content  
 771 of the epoxy resin and binder type should be chosen with care to achieve the maximum bonding  
 772 between the two layers. For example, [Zhang et al. \(2017\)](#) recommended 3% styrene-butadiene-rubber  
 773 with a water-born resin content of 3% as an optimum blend of water-born polymer-modified EAM.  
 774 The increase of the interlayer bonding is due to the two mechanisms working together. The first  
 775 mechanism is the increase in the amount of the asphalt binder absorbed by the aggregate particles and  
 776 an increase in film thickness coating the aggregate. The second mechanism is a crosslinking network  
 777 structure formed by the resin particles in the binder structure. Therefore, the interaction between  
 778 polymer material and epoxy resin play a vital role in the performance of EAM.

779 From Figure 16, analysis of the chloride content of the concrete on the bridge showed that as the  
 780 EAM-overlay containing anti-ice agent is reduced, the chloride content also decreases, which  
 781 improves the durability of pavement structure against corrosive ions.  
 782



783  
 784 Figure 16: Trend of chloride content with depth of before and after overlaying using EAM; plotted by  
 785 data reported by [Young et al. \(2012\)](#).  
 786

787 It is obvious that late maintenance increases the costs of pavement rehabilitation. For example, there  
 788 are microwave maintenance trucks for the maintenance of EAM in China ([Ai et al. 2016](#)). Therefore,  
 789 preventive maintenance can be an efficient strategy to reduce the costs of pavement utility ([Gingras et  
 790 al. 2005](#), [Khattak and Alrashidi 2013](#), [Mamlouk et al. 2014](#)).

791 Since the emission of toxic materials from EAM is an environmental concern, the use of a cold mix  
 792 can be recommended ([Si et al. 2018](#)). Furthermore, [Si et al. \(2022\)](#) recommends to use antioxidants or  
 793 choose asphalt with good anti-aging properties when preparing epoxy cold mix asphalt. Also, the  
 794 preventive maintenance using emulsion shows promising results. However, early-strength gain is  
 795 problematic ([Al Nageim et al. 2012](#)), as is the case for many asphaltic products.

796 Furthermore, field investigations on the EAM on the steel bridge show that different modes of failures  
 797 ([Chen et al. 2012b](#)). The methodology for repairing the failures is chosen based on different factories.  
 798 However, the interface between the new and existing materials is a matter of concern. For instance,  
 799 fine aggregate materials can be used in patching the EAM because the high surface area of the  
 800 aggregate increases bonding. For example, [Yang et al. \(2015\)](#) proposed a recipe of EAM using fine  
 801 aggregate, limestone, and a fast-curing epoxy binder for pothole patching. The results indicated that  
 802 the difference in viscoelastic properties of patching and the existing pavement is a problem which  
 803 results in poor stress distribution throughout the repair structure. Type of construction technology  
 804 adopted is another variable in maintenance and rehabilitation of EAM. For example, [Luo et al. \(2015\)](#)  
 805 recommended to use warm-EAM for construction of new pavement of bridge in arid climate, while  
 806 hot EAM is suitable as an overlay for high traffic bridges.

807 [Hu et al. \(2019a\)](#) also recommended EAM, containing an emulsion binder and a fine aggregate, as a  
 808 bond coat for preventive maintenance. Therefore, the aggregate particles are better coated, and the  
 809 high stiffness of mix increases the structural capacity of the paving system. Furthermore, more  
 810 waterborne epoxy resin increases the dynamic stability of the mix because of the higher viscosity of  
 811 the binder ([Zhang et al. 2018a](#), [Li et al. 2019](#)). However, more attention should be paid to the  
 812 selection of materials for maintenance and rehabilitation of pavements with EAM.

813 **EAB does not melt at high temperatures ([Chen 2009](#)). Therefore, EAM is less prone to bleeding at the  
 814 elevated temperatures. Although the high stiffness of EAM improves rutting resistance of the  
 815 pavement, it can render the asphalt more brittle, which increases the risk of non-repaired brittle cracks**

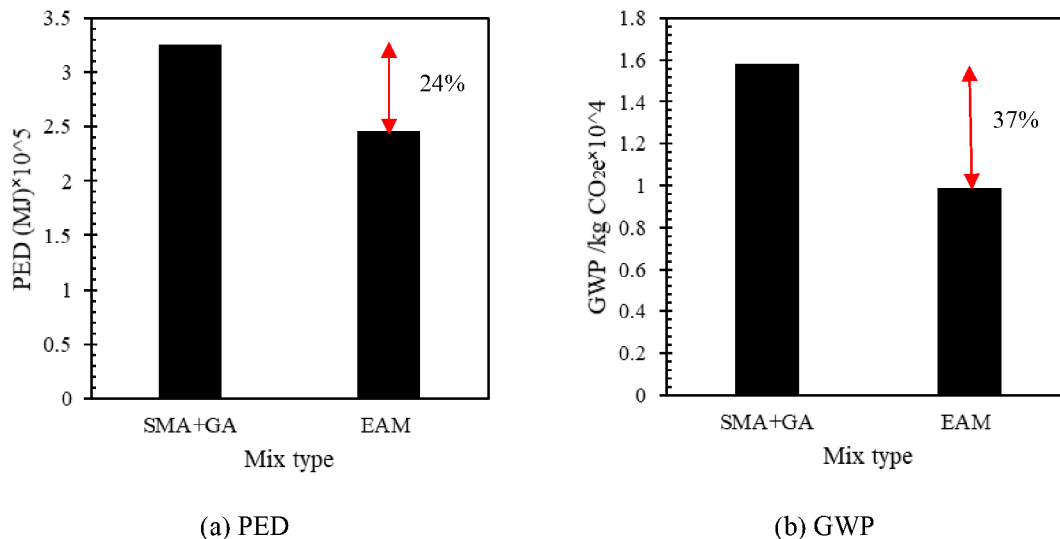
1  
2  
3 816 at low temperatures. To address the problem, the toughness modulus of the mixture can be improved  
4 817 by rubber, thermoplastic resins, polymers, nanomaterials, basalt and polyester fibers (Bucknall and  
5 818 Dumbleton 1987, Bucknall and Gilbert 1989, Aspler *et al.* 1992, Jackson *et al.* 1993, Morrison and  
6 819 Hesp 1995, Kim *et al.* 1996, Ni-sheng *et al.* 2006, Jamshidi *et al.* 2015, Sun *et al.* 2018, Chen *et al.*  
7 820 2019). Such materials can be used to modify the high toughness of EAM, which decreased the low  
8 821 temperature cracking. For example, Xu *et al.* (2016) proposed to use a hyperbranched polymer (HBP)  
9 822 in EAM. The results indicated that the optimum content of aromatic and aliphatic HBP into EAM  
10 823 reduces risk of low temperature cracking via improved binder elongation. However, hydroxyl end  
11 824 groups of HBP can accelerate the reaction rate of EAM (Xu *et al.* 2022), which may have a negative  
12 825 effect on the phase dispersion between the resin and asphalt binder. Therefore, hydroxyl end groups of  
13 826 HBP as inert alkyl end groups should be modified to avoid its rapid curing reaction with the epoxy  
14 827 resin (Xu *et al.* 2018). As such, further positive effects in HBP-EAM, including viscosity reduction  
15 828 and better compatibility, can be achieved. It should be noted that rapid curing can be an advantage in  
16 829 runway overlay and maintenance without interrupting traffic flow. To improve initial curing for such  
17 830 cases, a dense mix with chosen unit weight of 95%, coarse aggregate ratio of 40%, and fine aggregate  
18 831 coarse fraction of 35% is recommended for EAM (Min *et al.* 2020).

## 21 832 **7. Life Cycle Cost**

22 833 Life cycle cost (LCC) is one of the most important criteria to choose EAM as a choice for paving  
23 834 projects. LCC covers the entire costs of pavement from cradle to grave. Therefore, all the costs of  
24 835 material supply, design, construction, maintenance and even recycling should be not only considered  
25 836 in LCC, but also costs incurred due to environmental consequences are covered. The further details of  
26 837 each part of pavement life cycle, the more accurate outputs of LCC and the better engineering  
27 838 judgement. The main advantage of EAM is the higher structural capacity, which is reflected in high  
28 839 dynamic modulus and more fatigue strength compared with the other asphalt technologies. Thus, the  
29 840 higher load-bearing capacity of EAM results in then thinner asphalt, which leads to significant raw  
30 841 material saving. For example, 25 mm of EAM is comparable to 50 to 62 mm of tradition, dense  
31 842 asphalt mix (Simpson *et al.* 1960). Additionally, Herrington (2010) and Alabaster *et al.* (2016)  
32 843 concluded that porous EAM, even samples containing 25% epoxy, will have a long-life expectancy of  
33 844 around 40 years or more, based on the Cantabro results. Therefore, the costs and environmental  
34 845 burdens of raw, non-renewable natural resource extraction, processing, and transportation decrease.  
35 846 Moreover, the construction of long-life pavements reduces the costs of maintenance and  
36 847 rehabilitation. However, epoxy materials are very costly, which may increase the cost of initial  
37 848 pavement construction. Additionally, modification of mixing plants to produce EAM incurs extra  
38 849 costs for the asphalt industries. However, there are different approaches to reduce the initial costs of  
39 850 EAM. For instance, the use of modified binders decreases the cost of EAM (Zheng 2015) because of  
40 851 higher structural performance. The use of waste materials in EAM production is another strategy to  
41 852 decrease the initial costs of EAM. However, incorporation of the waste materials in the asphalt plant  
42 853 may require facilities, which incurs further costs. Furthermore, the incorporation of high percentage of  
43 854 waste materials may decrease resistance to fatigue and low temperature cracking (Yi *et al.* 2022).  
44 855 Therefore, the cost-savings due to the use of less material in EAM can be compensated by the higher  
45 856 price of EAM production. But the long life of pavements demonstrated by field investigation shows  
46 857 LCC of EAM can be less than traditional hot mix. Thus, it is expected that the asphalt industry pays  
47 858 more attention to EAM in the future, which could result in more cost-effective and high-quality epoxy  
48 859 materials. Although the use of cold EAM may decrease costs of finished product protection after  
49 860 placement (Shao & Zhou 2021), lack of strength compared to hot and warm EAM is matter of  
50 861 concern. The lower cost due to use of cold EMA may incur further costs in the life cycle.  
51 862

## 8. Sustainable EAM

Recycling of Epoxy reclaimed asphalt pavement (ERAP) can be challenging in future. In other words, EAM will be milled and recycled, which generates ERAP. ERAP not only contains aged asphalt binder, but also there fully cured epoxy materials, which significantly increases the stiffness of the reclaimed materials. Furthermore, milling and recycling ERAP may require further energy due to the higher stiffness compared with the traditional asphalt mixture. Therefore, the high stiffness of ERAP may limit its application in production of virgin mixture. However, the life cycle cost of EAM or any other types of mixture can be decreased through use of ERAP. To study recyclability of ERAP, *Alamri et al. (2020)* carried out a laboratory research on new mixtures containing various percentages of ERAP. The results indicated that that replacing the coarse aggregate particles in the fresh hot mixtures with ERAP up to 80% had no adverse effects on its Marshall stability, tensile strength, and moisture resistance. However, the plastic deformation restricted use of ERAP up to 40%. Use of such percentage of ERAP results in huge energy saving and lower environmental burdens. Therefore, epoxy asphalt recycling can be accredited as a closed-loop recycling method in the asphalt industry. Environmental burdens of EAM is one of key indicator to analyze sustainability of pavement. In this regard, *Zhang et al. (2018b)* developed a life cycle analysis model for characterization of the environmental burdens of EAM, SMA, and GA. SMA and GA were used together as a paving system. The environmental impacts were assessed in terms of primary energy demand (PED), global warming potential (GWP), acidification potential (AP), and respiratory in-organic (RI). Figure 17 shows the results of model.



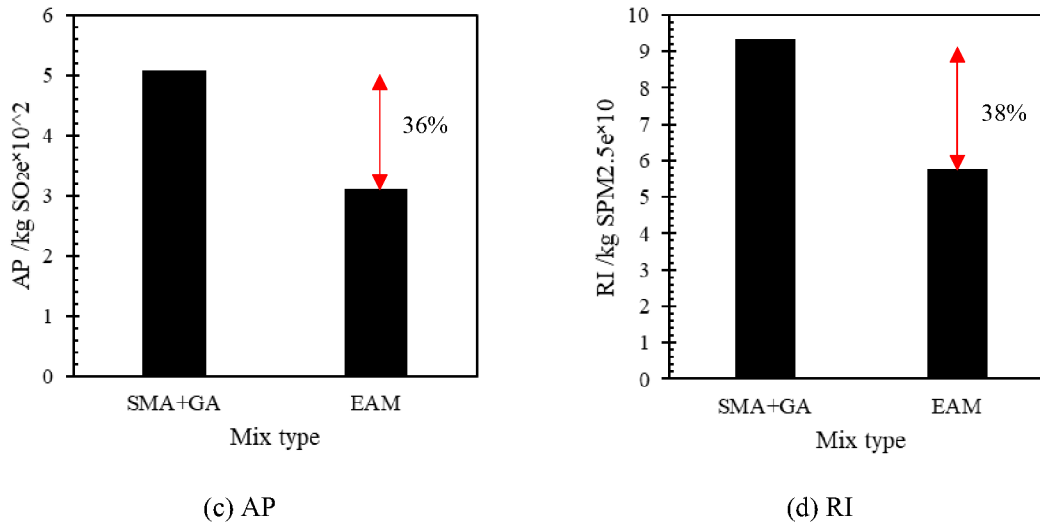


Figure 17: Results of the LCA model based on the selected environmental burdens, plotted based on data provided by Zhang *et al.* (2018b).

884

885 From the Figure, it can be seen that EAM showed the lower environmental burdens compared to the  
 886 other mixtures. For example, PED of EAM is 24 % lower than that of mixtures. The reason might be  
 887 lower raw materials used in the pavement due to less thickness. Also, GWP, AP, and RI of EAM are  
 888 almost 38% less than the other mixture. In other words, less raw materials are used for EAM which is  
 889 consistent with results obtained by Simpson *et al.* (1960). Furthermore, Zhang *et al.* (2018b) showed  
 890 that SMA+GA consumes 2.5 times of energy and produces 3.4 times of gas more than EAM in phase  
 891 of plant production. Also, SMA+GA produces 1.7 more environmental burdens than EAM phase of  
 892 on-site construction. However, the curing agent, type, local materials (e.g., aggregate type and  
 893 gradation, binder, type and content of waste materials, filler, rejuvenator, and modifier), availability of  
 894 production facilities, service condition, construction norms, regulations of environmental impact  
 895 assessments, recycling technology, and strategies of maintenance and rehabilitation can differ in  
 896 paving projects which results in different outputs of LCA of costs and environments. Therefore,  
 897 further research is necessary to develop models that considers all the variables of EAM technology.  
 898 Furthermore, such models should be validated through the field performance of EAM.

899

## 900 9. Challenges of EAM as Paving Material and Suggestion for 901 Further Research

902 One of most important challenges of EAM is the lack of a predictive structural/functional model of  
 903 EAM. The predictive models can provide useful information for maintenance and rehabilitation of the  
 904 pavement, which is necessary for pavement management service. There is also lack of analytical  
 905 models of carbon footprint to rate sustainability of EAM compared to the other alternative pavements.  
 906 In addition, LCA-based models are needed with considering social norms, functional/structural  
 907 criteria and cost of EAM. There is also a lack of micro models that characterize or predict friction loss  
 908 and skid resistance of EAM produced using various aggregate, binder and epoxy materials.

909 It should be noted that the use of ERAP can be problematic due to high stiffness. Therefore, it is  
 910 essential to use admixtures to improve the workability of HMA and WMA containing various  
 911 percentages of ERAP. Further research is necessary to determine the optimum content of ERAP for  
 912 various binder types and aggregate gradations. In addition, ERAP can be used as a base material in the  
 913 pavement structure. As a result, it is necessary to propose protocols and practice codes to use ERAP  
 914 as alternative granular materials in the base and subbase layer. Furthermore, the compatibility of

ERAP with the other waste materials are a matter of concern which should be addressed in laboratory tests and field investigations.

In the railroad pavement system and on the deck of bridges and airport pavements, the resonance of EAM may affect the models of the failures of pavement. It seems that there is a gap in research that addresses the effect of epoxy type, content and curing agent on the resonance characteristics of EAM utilized in the railroad and heavy-duty pavements.

There is another gap that the current fatigue and rutting criteria may not be applicable for structural design and functional assessment of asphalt pavements incorporating EAM. Therefore, it is essential the current methodologies for the structural design and functional assessment of EAM are evaluated and the norms and new criteria are proposed, as necessary. New design charts and construction standards may be developed, which can be used as a platform to develop application of EAM in various infrastructure assets. In addition, further research is required to study the effect of gas emission and fumes of burnt EAB and EAM on human health. The results of this research will be helpful for the risk assessment of paving sites, which improves the level of safety.

## 10. Conclusion

The functional performance of EAM was characterized based on skid resistance, aging, moisture sensitivity, flammability, and surface reflectance. The better macro texture of EAM results in higher skid resistance and safety level at different time and temperature. However, it seems that the trend of the dynamic friction coefficient changes at higher speeds. Therefore, the maximum allowable speed of traffic based on skid resistance property of EAM should be determined. EAM can also improve the reflectance of a pavement surface which results in lower heat-island effects in urban areas, and relatively low flammability of EAM improves the safety of EAM in the service conditions.

Also, various mix types, including SMA, porous, hot-rolled, traditional mix, can be produced using EAM, which results in the use of EAM in various transportation infrastructures. The findings of performance-related assessments showed that the complicated construction technology of EAM restricts its applications. In addition, results of field performance showed promising results in different countries. However, the construction technology and technical norms should be reset for EAM because of incorporation of waste materials and new modifiers.

The pavement material should be synchronized with steel bridges, and the materials should be durable against shear stresses of traffic loads and thermal stresses of a temperature gradient. To meet these requirements, EAM can be suggested as a premium surfacing material used for the construction of heavily trafficked pavements on the decks of different types of bridges for highways and railroads.

Although the cost of production EAM is higher than traditional asphalt mixtures, due to the high price of epoxy materials, the extra cost can be compensated by the considerable material and energy savings in the construction phase and less maintenance in the utility phase. However, the life cycle cost and environmental burdens of EAM in a paving project should be evaluated separately. High strength, excellent adhesion, high-temperature durability and flexibility are the main contributive factors result in the superior engineering characteristics of EAM. Such advantages make EAM as best mixture in the construction of heavy-duty pavements. However, the thermosetting characteristics of EAB, since it does not have reversible viscosity (i.e. EAB cannot be remelted) after curing, will render the EAM more sensitive to the skills of paving crews and workmanship. Therefore, any error cannot be rectified once the epoxy has cured. Another disadvantage of EAM is recyclability and carbon footprint emission which require further laboratory studies and field investigations. As a result, both advantages and disadvantages of EAM should be considered in the paving projects through a strong engineering judgement in terms of the material characterization, practical experiences, life cycle analysis, cost analysis, and environmental impact assessment.

Given that the evaluation of the field performance of EAM in various projects showed acceptable results and EAM is a relatively energy-efficient material, structural and environmental requirements



964 can be satisfied. Nevertheless, certain drawbacks continue to restrict the application of EAM. In  
965 conclusion, further research is required regarding the consideration of EAM as a potential option in  
966 pavement industry.  
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