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Functional and Field Performance of Epoxy Asphalt Technology-State-of-the-Art

Abstract

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

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

1.Introduction

Demand for more durable and cost-effective paving materials is increasing, and there are now more key variables to consider when choosing appropriate paving materials than there have been in the past. Structural performance and durability used to be the dominant factors in pavement construction. In today's more advanced construction methods, however, environmental factors, albedo, energy consumption, and climate change are new variables to consider. To address the challenge of meeting the requirements of pavement engineers, environmental policymakers, urban designers, contractors, and public work authorities, asphalt material specialists have developed various technologies, materials, and methods. One such material is epoxy asphalt technology, which has attracted attention due to its superior structural performance. Epoxy asphalt mixture (EAM) has been used in various paving projects worldwide. Laboratory tests on rheological characteristics of epoxy asphalt binder (EAB) showed the higher complex shear modulus (G*), elongation, tensile strength and softening point than traditional binder and modified binders (Fuhaid *et al.* 2018, Dong and Li 2015, EI Rahman *et al.* 2012, Huang and Huang 2011, Yu *et al.* 2009a). The reason is a cross-linking network formed between the asphalt and the epoxy resin increases the stability of the resultant binder against high temperature deformation, thermal cracking, moisture, and resistance to solvents such as fuel (Alabaster *et al.* 2008, Chen, 2009, Cong *et al.* 2011, Mo *et al.* 2012, Sun *et al.* 2021). The cross-linking network also results in the higher viscosity and intermolecular forces (Jamshidi *et al.* 2021, Lu and Bors 2015Cong *et al.* 2010, 2019, Huang *et al.* 2010, Yu *et al.* 2009b). However, the higher viscosity of EAB may restrict paving time span due to thermosetting characteristic of epoxy materials. Changes in the viscosity of EAB depends on curing agent (type, content and chemical base), curing time (and method), temperature, humidity and base binder type (Xiang and Xiao 2020, Zhu 2013, Miller Bellinger 2003, Kim e*t al.* 2000).

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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 (Vyrozhemskyi 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.
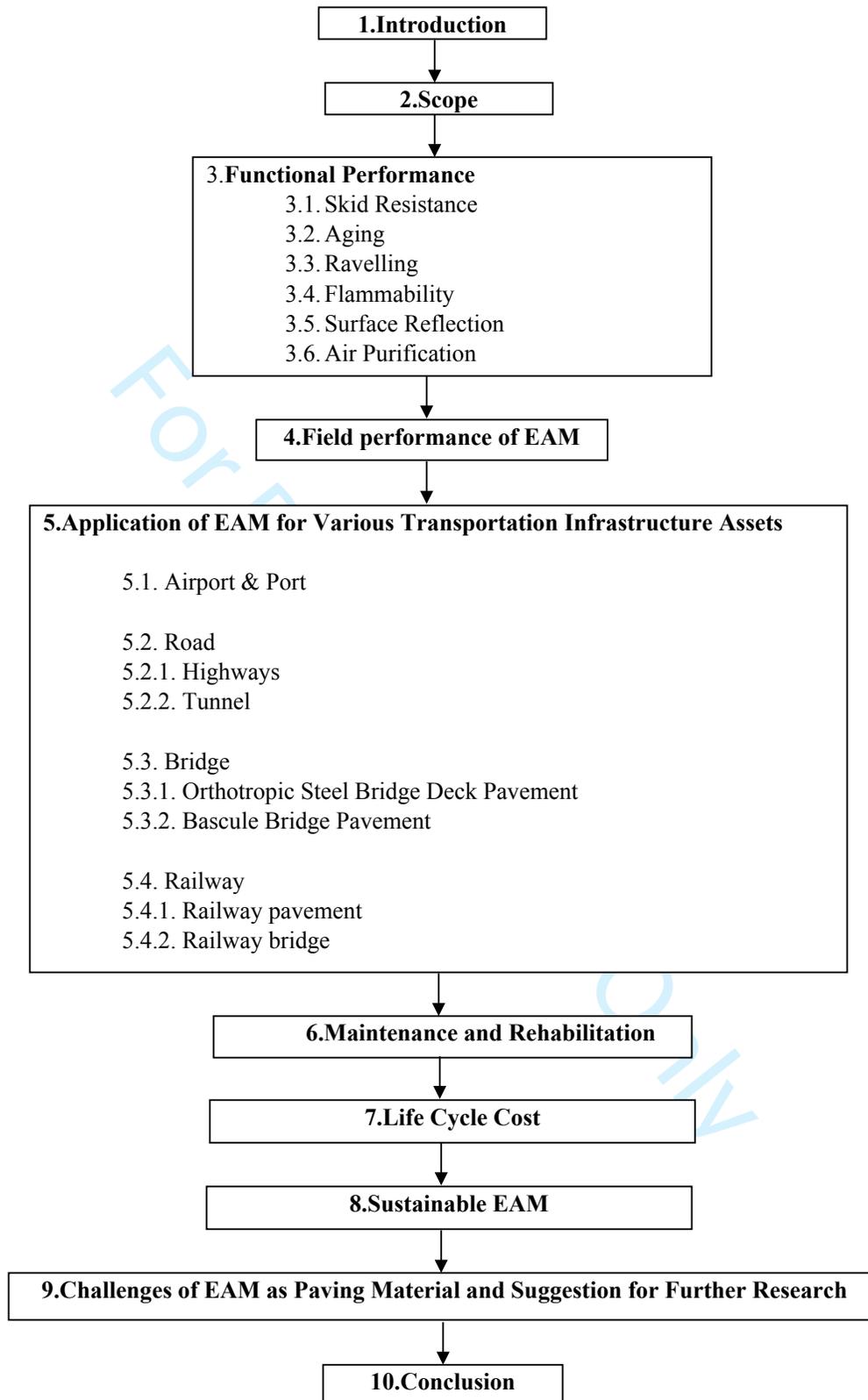
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1.Introduction

2.Scope

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10.Conclusion

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

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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.
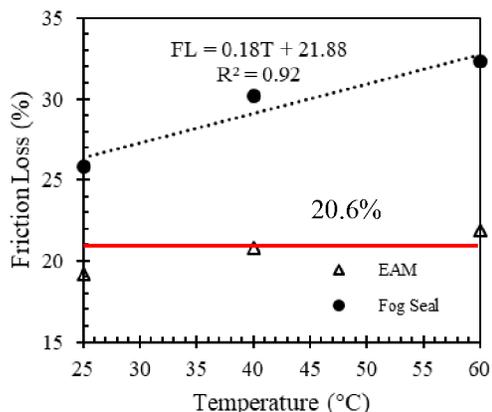

Figure 2 : Trend of friction loss as a function of temperature; plotted based on data outlined by Hu et al. (2016).

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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 (**

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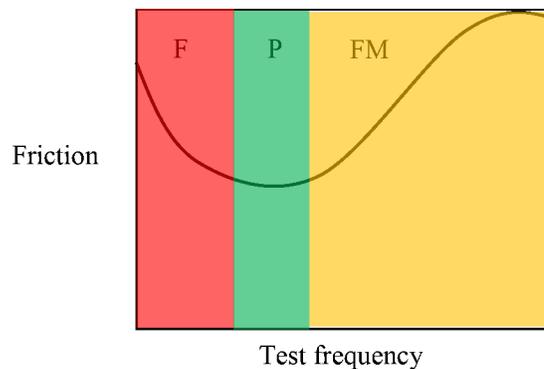169   performance of EAM.
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Figure 3: Trend of friction test over the test; F: fully covered (phase 1); P: Partial covered (phase 2); and FM: fully melted ice (phase 3), adopted based on the data reported by Xiaoning et al. (2012).

3.2. Aging

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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 O3 and NOX, 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 pf 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 TEcnico accelerated AGEing (TEAGE). The samples of
204   asphalt mixtures were tested for stiffness and fatigue under unaged and aged conditions by TEAGE.

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205   The result of initial studies showed that TEAGE has potential to simulate accurate field aging
206   condition. It worth mentioning that Aging Index significantly depends on the types of parameters
207   adopted for analysis of the ageing phenomenon (Jamshidi et al., 2012 and Hamzah et al., 2012).
208   Therefore, it may not be as accurate as the other consecutive reaction model developed based on
209   chemical reactions. For example, The Zero-order model was suitable to describe the long-term aging
210   reaction kinetics of bitumen based on the oxygen-containing functional groups with the reaction rate
211   constants in $0.7–3.3x10{-4}$ (mol $L{-1}·h{-1}$), while the most optimum kinetics model for aromatic
212   fraction was the Third-order reaction model and the corresponding reaction kinetics constant (k1) was
213   0.02 (mol·L−1)−2(h)−1 by means of Saturate, Aromatic, Resin and Asphaltene (SARA) test (Ren et
214   al., 2020). Elwardany et al. (2017) reported that loose mix aging in an oven resulted in a promising
215   laboratory long-term aging procedure to produce mixture for performance testing in terms of various
216   factors such as efficiency, specimen integrity, and versatility. It is also a cost-effective methodology,
217   which can be readily used for various mixture types. However, it should be noted that the
218   methodologies mentioned above have not been standardized. It is essential to standardize and develop
219   laboratory protocols to use in the pavement industry.
220   The effects of aging on the mix properties can be evaluated by the aging index based on the target
221   engineering property, such as resilient modulus, ITS, and E*. It is necessary that the effects of aging
222   on EAM are characterized; however, the difference between aging and curing in EAM must be
223   recognized. The aging increases the binder stiffness due to the evaporation of oil and the
224   transformation of resins into long chains of asphaltenes, while curing has a stiffening effect due to the
225   chemical reaction between the epoxy and the curing agent in epoxy asphalt binder (EAB). Therefore,
226   aging and curing in EAM or EAB must not be used interchangeably. In HMA and warm mix asphalt
227   (WMA), curing and aging are almost identical. Furthermore, there is no laboratory-based
228   methodology or parameters developed exclusively for EAM/EAB. The same procedures used for
229   traditional asphalt mixtures are deployed for EAM.
230   Long-term aging can occur when the majority of the curing (over 70%) is achieved. Therefore, aging
231   and curing are parallel reactions in EAM, which makes a stiffer mixture compared with the traditional
232   asphalt concrete. There is a lack of fundamental research on the synergistic effects of aging and curing
233   in EAB as well as the effects of different curing agents and binder types.
234   In a laboratory study, Widyatmoko et al. (2006a) evaluated the effects of aging on hot-rolled (HR)
235   and SMA epoxy asphalt. Figure 4 shows the effects of aging based ITS results. It can be seen that
236   aged ITS of HR-EAB was much higher than the control counterpart, in which such high stiffness is
237   due to synergistic effects of curing and aging (Figure 4(a)). However, unaged ITS of HR-EAM
238   beyond 20 °C is slightly less than that of unaged HR. This lack of strength can be compensated by the
239   stiffening effects of aging or further curing.
240   Figure 4(b) reveals the results of aging in SMA. The difference between the aged and unaged ITS of
241   SMA is not significant because of the dense matrix of the mixture. Furthermore, ITS of unaged SMA-
242   EAM is less than that of the control sample up to 20 °C. Beyond 20 °C, the ITSs are almost identical
243   for the unaged sample. In SMA, the lack of ITS strength is compensated by aging. Hence, irrespective
244   of mix type, the lack of initial strength in both mixes can be balanced by the stiffening effects of
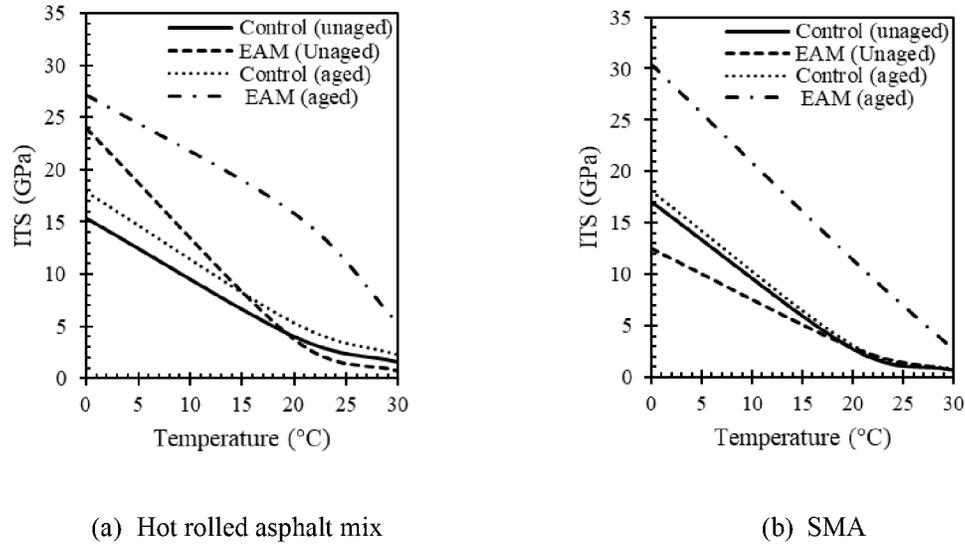245   aging.
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(a) Hot rolled asphalt mix   (b) SMA

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

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

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

3.3. Raveling

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

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

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

276 (E_a) of binder. As a fluid flows, the layers of the fluid molecules slide over each other, while
277 intermolecular forces resist the motion, causing resistance to flow (Haider *et al.* 2011). Therefore, for
278 fluid to begin flowing or any deformation and disintegration, energy is required that must be higher
279 than the intermolecular forces, and this energy is called E_a. The higher E_a indicates that more energy is
280 required to cause flow, deformation and disintegration. The higher viscosity due to incorporation of
281 new additives and waste materials such as recovered binder and nanomaterials increases E_a, which
282 results in the higher structural adequacy in terms of higher dynamic modulus of mixture and complex
283 shear modulus (G^*) of modified binder (Jamshidi *et al.* 2019 and Jamshidi *et al.* 2015). Therefore, the
284 higher viscosity increases the activation energy of EAB (Figure 5). In other words, a crosslinking
285 network formed in EAB increases intermolecular forces. Therefore, more energy is required to
286 overcome the force or E_a. From the Figure, there is a relatively linear relationship between the Ea and
287 epoxy content. It can be seen that adding unit epoxy material (1%) improves Ea by 1.45 mJ/mol. As a
288 result, more energy is required to disintegrate components of EAM, which results in the higher
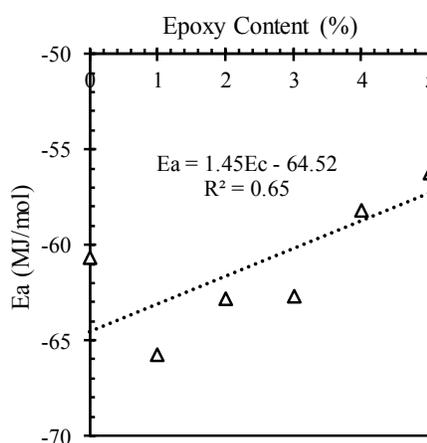289 raveling resistance.
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Figure 5: Effect of epoxy content on the activation energy of EAB, plotted based on data reported
by Cubuk *et al.*, (2009).

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

298 Since EAM can be used for different infrastructure types, the safety of the pavement is a matter of
299 concern because epoxy resins and asphalt binders are combustible and emit smoke and toxic
300 substances (Pack 2015). Consequently, retardants added to the asphalt binder should meet the
301 standard requirements. Inorganic flame retardants are commonly used in the asphalt pavements
302 (Bonati *et al.* 2012, Xu *et al.* 2011, Wan *et al.* 2015, Zhang *et al.* 2015). Additionally, one of the
303 widely used flame retardants is a brominated flame in the asphalt concrete (Cong *et al.* 2008, Yu *et al.*
304 2009b). Because of concerns about the persistence, bioaccumulation, and toxic materials, some
305 brominated flaming agents, such as brominated diphenyl ethers and polybrominated biphenyl
306 halogenated flame retardants have not been allowed (Mitchel 2014). Instead of brominated flaming
307 retardants, halogen-free flame retardants are used (Zhang *et al.* 2016a). Among the halogen-free

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

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

336   The high thermal degradation of aluminum trihydrate and zinc borate delay these two steps in EAM.
337   Therefore, the interaction of two or more flammable retardants could be more efficient. However, it
338   may have negative effects on the other properties of EAB and EAM. For instance, the incorporation
339   of aluminum trihydrate and zinc borate increased the EAM viscosity (Chen *et al.* 2018c), thereby
340   decreasing EAM workability and potentially reducing the EAM resistance to fatigue and cold
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 acceptation.
368
369

Figure 6: Use of resin as a transparent binder.

370

3.6. Air purification

372 Surface of EAM pavement can degrade hazardous gases via using titanium dioxide (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-TiO2 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-TiO_2 on the degradation performance of
378 emulsified EAM. Results indicated that EAM containing 5nm TiO_2 increases degradation of CO, HC,
379 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 TiO_2. In addition, general trend is that higher contents of TiO_2
381 in the EAM increases degradation of hazardous materials. 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.

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
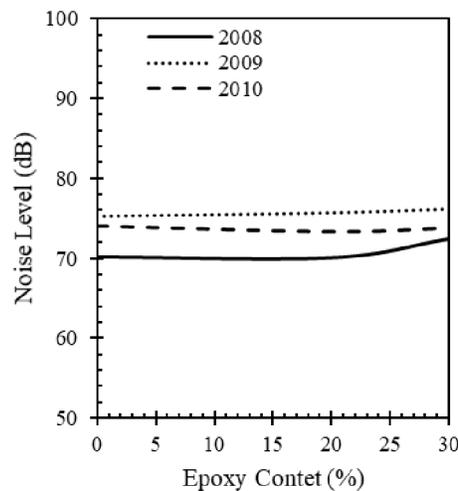406　macrostructure of the pavement surface.

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

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

5. Application of EAM for Various Transportation Infrastructure Assets

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

5.1. Airports and Ports

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

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

## 5.2. Roads

5.2.1. Highways

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

13

468 1986, a full-scale road trial of EAM showed promising results in Staffordshire, UK (Read *et al.* 2016).
469 In China, the first EAM was used as a road pavement in Shanghai in the 1990s (Lu *et al.* 1996, Lu and
470 Bors 2015). The application of EAM was developed for several road infrastructures. For example,
471 porous EAM was used to pave a section of road in Christchurch, New Zealand (Herrington 2010). In
472 Japan, EAM was used as a surface for intersections because of its high durability, which resulted in a
473 satisfactory performance (DRI 2005). However, there is still a lack of detail on EAM for roads under
474 different service conditions.
475 Porous asphalt is another paving system that has been used for the construction of roads and parking
476 lots. Porous asphalt is a multi-role infrastructure that improves the landscape and urban design.
477 Porous asphalt pavements have high air voids contents (around 20%) compared with the dense asphalt
478 pavement (around 4% to 6%). Due to the high porosity, the binder drain-down results in clogging.
479 Various methods are used to evaluate the drain-down process, such as the Caltran (Test Method 368),
480 the Pyrex plate method (GDT 2011), the metal wire basket method standardized by ASTM D 7064,
481 and the Schellenberg binder drainage test (BSI 2004). However, clogging in the pavement is complex.
482 A solution to reduce binder drain-down is to use a polymer-modified asphalt binder (Ongel *et al.*
483 2008). EAB can be an appropriate binder to avoid binder creep and drain down due to its high
484 viscosity. Additionally, the porous asphalt pavement's service life is relatively short, around 8 to 12
485 years. EAB can also extend the pavement's life due to its high stiffness (Kandhal *et al.* 1998, Bennert
486 and Cooley 2014). For example, porous EAM showed the higher fatigue resistance compared with
487 porous mixtures produced using high viscosity binder (Li *et al.* 2022b). However, the use of porous
488 EAM is not new. It was first used in San Francisco-Oakland in 1969 (Brewer 1970). High-quality
489 epoxy resin and other advanced materials have resulted in a more efficient porous EAM. For example,
490 Cantabro test results clearly showed that the Cantabro losses of porous EAM were 76% and 60%
491 lower than traditional porous pavements for the unaged and aged states, respectively (Lu *et al.* 2015).
492 The Cantabro test shows the potential of raveling in the porous pavement. Therefore, the less mass
493 loss, the less prone to the raveling. Also, oxidation decreases the loss modulus of porous EAM, based
494 on the Cantabro test (Herrington and Alabaster 2008). Figure 8 shows that the mass loss of porous
495 EAM decreased as epoxy content increased. However, the binder type played a significant role in the
496 mass loss of EAM (Holleran et al. 2017).
497
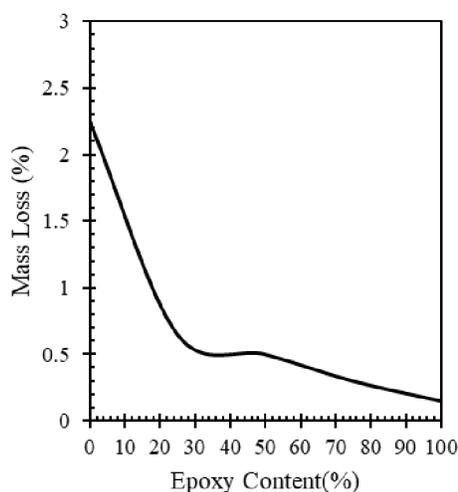
Figure 8: Trend of the mass loss as a function of epoxy content; plotted based on data reported by
Wu *et al.* (2017).

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

500   reduction of associated with EAM (Luo *et al.* 2015). The noise emissions can be reduced more via the
501   use of crumb rubber in the porous pavement. For example, in Japan, a new type of porous mix
502   containing crumb rubber was developed, referred to as PERS (Kubo 2011a). Analysis of road
503   acoustics showed that the noise level could be decrease by around 20% according to the Japan Road
504   Association (2006, 2009). Use of crumb rubber may decrease the surface friction (Kawakami and
505   Kubo 2008, Kubo *et al.* 2011a, b), but the use of sand in PERS improves the friction.
506   The performance of porous EAM in rutting and fatigue was superior to traditional samples. Visual
507   inspection of rutted samples showed that the rutting was primarily by crushing and loosening of
508   aggregate particles under the vehicles' wheels instead of deforming due to shear stresses (Luo *et al.*
509   2015). The oxidation of EAB results in loss of surface material (Herrington and Alabaster, 2008).
510   Furthermore, the pores of the porous EAM are filled with worn tires from a wheel tracking test. The
511   rutting in the porous pavement can decrease over time. However, the early-life rutting of porous EAM
512   is not likely to be greater than that of the traditional porous asphalt pavement (Alabastar *et al.* 2008).
513   However, Holleran *et al.* (2017) found the dynamic modulus and fatigue life of the porous EAM
514   containing 25% epoxy are lower than the figures for the polymer-modified porous mixes.
515   Furthermore, the use of a small aggregate size can improve the performance of porous EAM in terms
516   of friction, moisture resistance, and high and low-temperature stability (Qian and Lu, 2014, 2015).

5.2.2. Tunnel Pavement

518   Structural performance and high visibility are key factors for pavement in tunnels. The pavement in
519   tunnels is less prone to rutting and aging, due to the tunnels' lower temperatures. For better visibility
520   of the pavement surface, the tunnels are usually equipped with a lighting system, which is costly and
521   not an environmental-friendly approach. Signs are also used to reflect the vehicles' light more
522   effectively. However, it is necessary that the signs are periodically washed, which enhances
523   maintenance costs. Another solution is the use of waste glass in the asphalt mixes to increase
524   pavement albedo (Jamshidi *et al.* 2016). In Japan, brightly colored EAM is used to improve the
525   visibility in the pavement tunnels. For example, a layer of the brightly colored EAM was overlaid on
526   the old concrete pavement in the tunnel. After 10 years, the EAM was evaluated based on the normal
527   serviceability prescribed by the Japan Road Association. The results indicated neither cracks nor a
528   change in the density of mix (Takahashi *et al.* 2004). The level of visibility of EAM was also higher
529   than the concrete pavement, which increases the safety of road traffic.
530   Additionally, survey results show that the first maintenance was 30 years after the evaluation.
531   Therefore, the life cycle of the overlay is 40 years because the first survey was 10 years after the first
532   construction. The life cost analysis using the Taniguchi methodology (Taniguchi 2003), standardized
533   by Japan Society Civil Engineering, showed that the total costs of brightly colored EAM are 80% and
534   73% of the concrete pavement and polymer-modified asphalt pavement, respectively. Therefore, the
535   use of EAM overlay not only improved the safety and structural performance of the pavement but also
536   decreases the costs of the pavement management system.

5.3. Bridge

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

Tianjin Jinbu	China	2007	Steel box girder	50 (double layer)
XiamenWushi	China	2007	Steel box girder	60 (double layer)
Wuhan Yangluo Chang-jiang	China	2007	Steel box girder	60 (double layer)
Shenzhen Houhai	China	2007	Steel box girder	60 (double layer)
The Second Shenzhen Houhai	China	2007	Steel box girder	60 (double layer)
Tianjin Fumin	China	2008	Steel box girder	65 (single layer)
Nanjing Xuanwu Huayuan	China	2008	Concrete	30 EAM+40 SMA
Zhoushan Xihoumen	China	2008	Steel box girder	55 (double layer)
Nanjing Cupinggang	China	2008	Concrete	30 EAM+40 SMA
Shanghai Yunzaobin	China	2008	Concrete	40 EAM+40 SMA
Guangzhou Dongsha	China	2008	Steel box girder	10 (single layer)
Zhujiang Huangpu	China	2008	Steel box girder	60 (double layer)
Sutong Yangtze River	China	2008	Steel box girder	55 (double layer)
The Third Ji'nan Yellow River	China	2008	Steel box girder	50 (double layer)
Wuhan Tianxingzhou	China	2009	Steel box girder	60 (double layer)
Nanjing Binjiang Road Xiaguan	China	2009	Steel box girder	70 (double layer)
Chongqing Fish Mouth Yangtze River	China	2009	Steel box girder	55 (double layer)
Shanghai Min Pu	China	2009	Steel box girder	55 (double layer)
Guizhou Baling	China	2009	Steel box girder	55 (double layer)
Humen	China	2009	Steel box girder	70 (double layer)
Jiangyin Sanjiang	China	2009	Steel box girder	50 (double layer)
Wuhan Baishazhou	China	2009	Steel box girder	50 (double layer)
Shanghai Yangtz	China	2009	Steel box girder	55 (double layer)
Shanghai Longhua	China	2010	Steel box girder	80 (double layer)
Huzhou Xindatong	China	2010	Steel box girder	55 (double layer)
Shanghai Ji Chang East Road	China	2010	Steel box girder	95 EAM+ 40 SMA
Tianjin Guotai	China	2011	Steel box girder	55 (double layer)
Chongqi	China	2011	Steel box girder	55 (double layer)
Guangdong Mafang	China	2011	Steel box girder	55 (double layer)
Tianjin Binhai	China	2012	Concrete	75 (double layer)
Taizhou Yangtze River	China	2012	Steel box girder	80 (double layer)
Wuxi Wuyue	China	2012	Steel box girder	50 EAM+ 40 HMA
Nanjing Shuanglong	China	2012	Steel box girder	60 (double layer)
Beijing Hangzhou Grand Canal	China	2012	Concrete	75 (double layer)
The Second Ningbo Daxie	China	2013	Steel box girder	55 (double layer)
Gaokan	China	2013	Steel box girder	55 (double layer)
Jiangshun	China	2013	Steel box girder	55 (double layer)
Li Shunchen	Korea	2013	Concrete	50 (double layer)
Xiamen Fenhe	China	2014	Pre-stressed concrete box girder	70 (double layer)
Panjin Neihu	China	2016	Steel box girder	60 (double layer)
Fanli	China	2016	Steel box girder	80 (double layer)

17

554 ### 5.3.1. Orthotropic Steel Bridge Deck Pavement

555 Construction of the orthotropic steel bridge decks (OSBD) is becoming popular owing to lower costs,
556 rapid assembly, and relatively easy maintenance and rehabilitation. OSBD were first introduced in
557 Germany and have since been built in different countries, such as the United States, China, Japan, and
558 Australia (Touran and Okereke 1991, Hulsey *et al.* 1999, Mangus 2000, Seim and Ingham 2004,
559 Austroad 2018). The term "orthotropic" is used for such bridges because of the use of stiffening ribs
560 at a right angle (orthogonal) to the floor beam, which results in an anisotropic characteristic of the
561 deck. Moreover, the bridges are not homogenous structures because of different construction
562 materials with various properties. For example, the elastic modulus of the steel deck is 210 GPa, but
563 the dynamic modulus of the EAM is 12 GPa (Wang and Zhang 2018). Furthermore, the utility
564 condition of asphalt surface course on OSBD is vastly different from the other pavements as follows:
565

566 - The wearing course is placed directly on top of OSBD steel. Therefore, the maximum
567   stress/strain and deflection usually happens on the top of the wearing course (Huang 2015),
568   while the maximum stress/strain occurs on the bottom of the traditional highway and airport
569   pavement. For example, Matsukawa *et al.* (1983) analyzed the top and bottom of EAM in
570   summer and spring and found that the maximum stress happened on the surface of EAM on
571   the main girder of the bridge.
572

573 - The wearing course is more prone to thermal stresses rather than the traditional pavement
574   because of the high thermal conductivity of steel. The high temperature in the steel structure
575   of the bridge increases the thermal stresses in the surface course. Therefore, expansion and
576   contraction of the bridge can result in failures in the asphalt due to different thermal
577   conductivity. For instance, Iwasaki (1997) analyzed the thermal stress generated in the
578   structure of the Nagoya Expressway Bridge in Japan. The results showed that the thermal
579   stresses produced in the steel plates proportionally increased by the temperatures of pavement
580   surface.
581

582 - As OSBDs are three-dimensional structures, the structure of the bridge can be deformed due
583   to dynamic loads stemming from the wind. The deformed structure (i.e., deflection, bending,
584   and torsion) impose internal strain/strains and deflection in the surface course throughout the
585   service life. Therefore, it is necessary the asphalt pavement deforms with the steel deck
586   synchronously.
587

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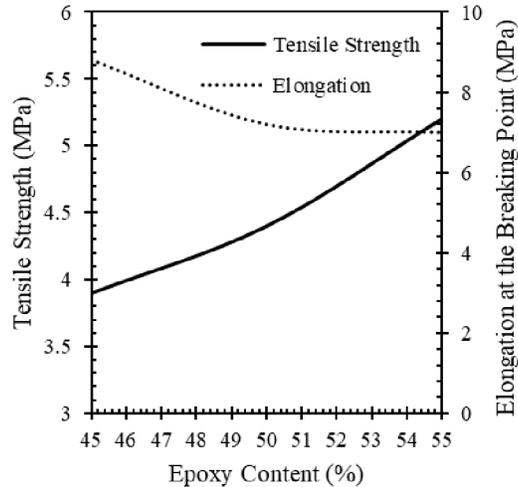594 design a synchronized EAM with the bridge decks.

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

19

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.

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
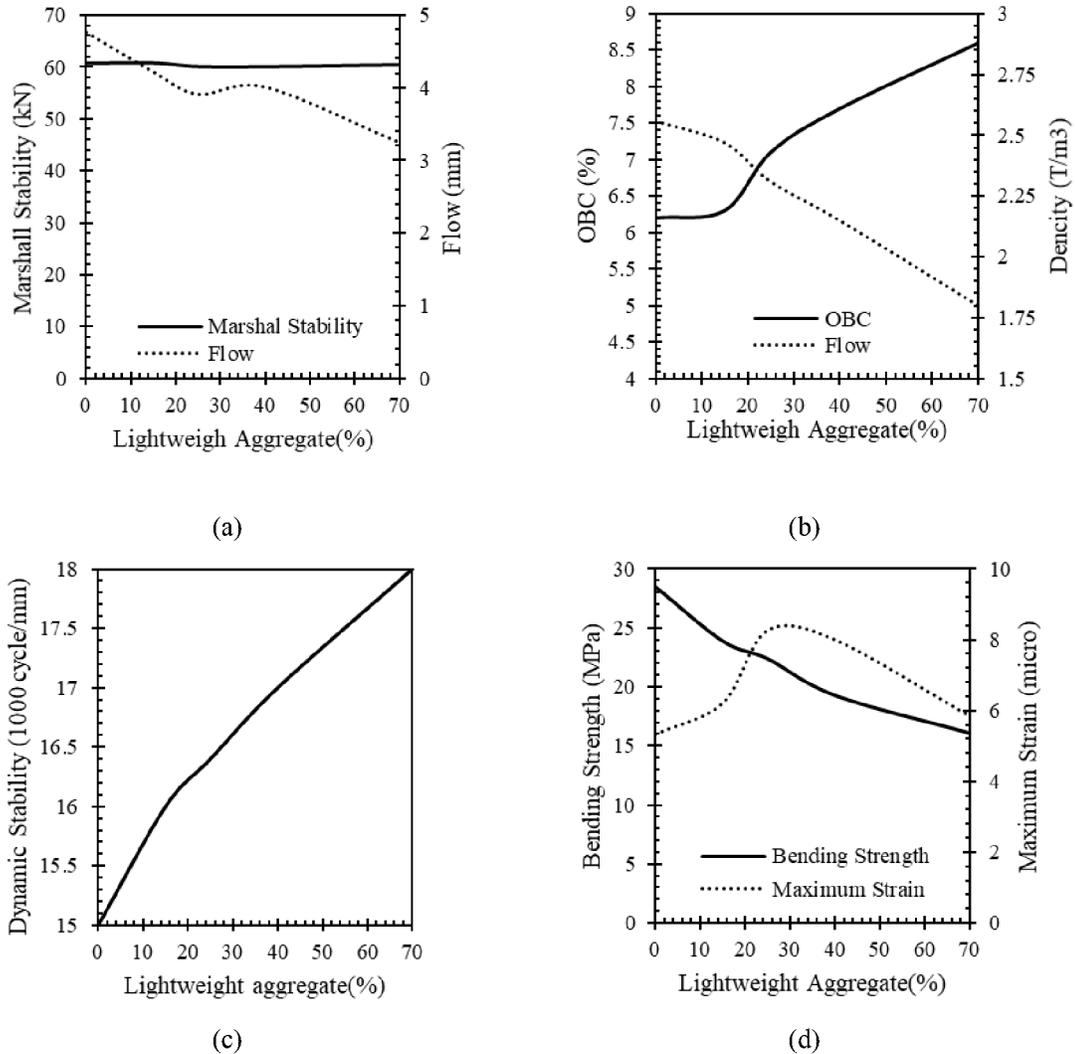666 aggregate improves the bending beam strength of the EAM (Figure 10(d)).

667

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

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

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

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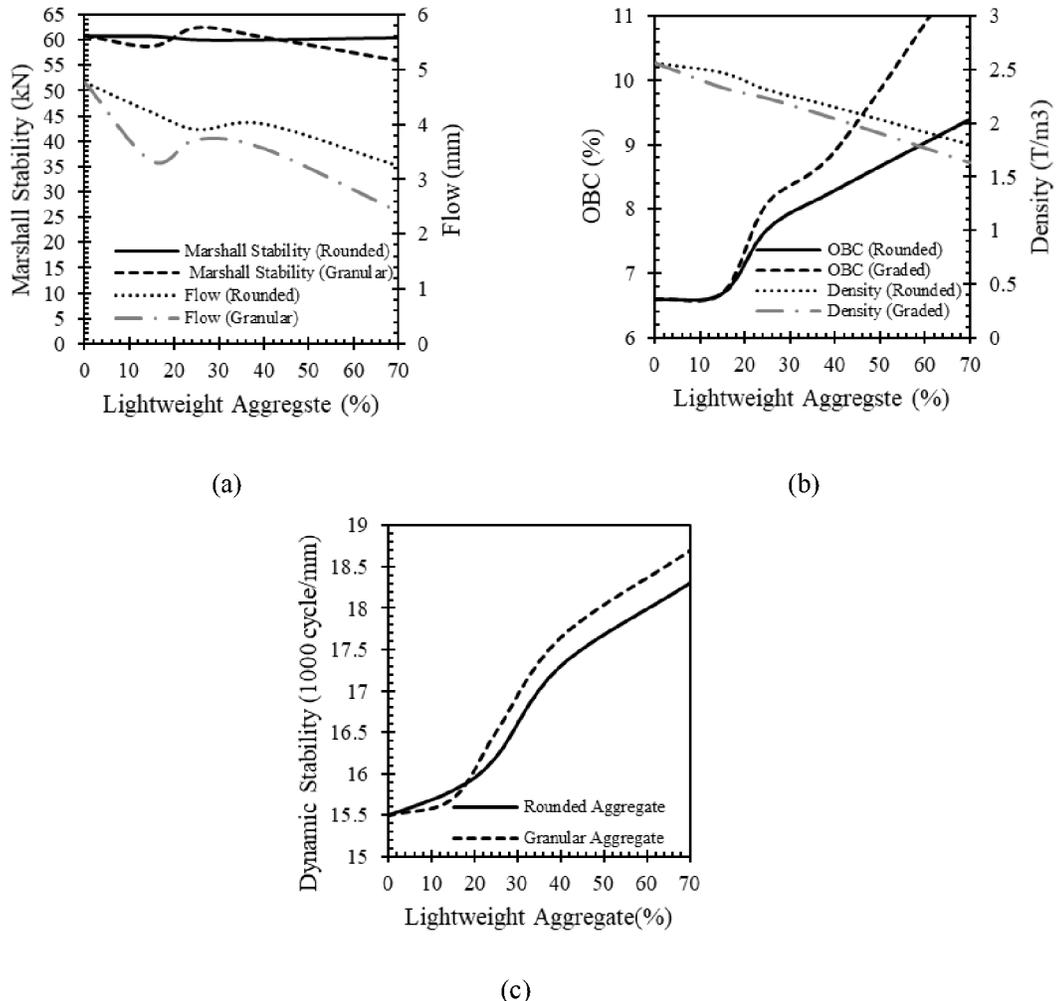
(a)

(b)

(c)

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 19th 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

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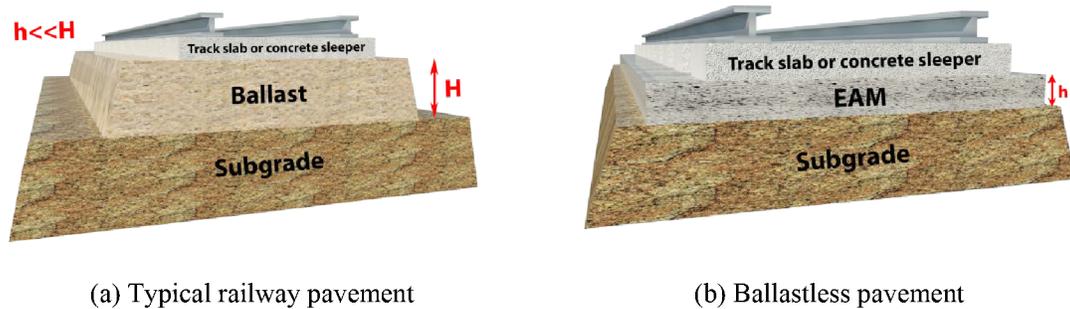706 railway substructures in comparison with traditional concrete materials.
707
708

(a) Typical railway pavement   (b) Ballastless pavement

Figure 12: Schematic illustration of a typical cross-section of railway pavement structure with and
without Ballast.

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

(a) compressive strength

(b) ITS
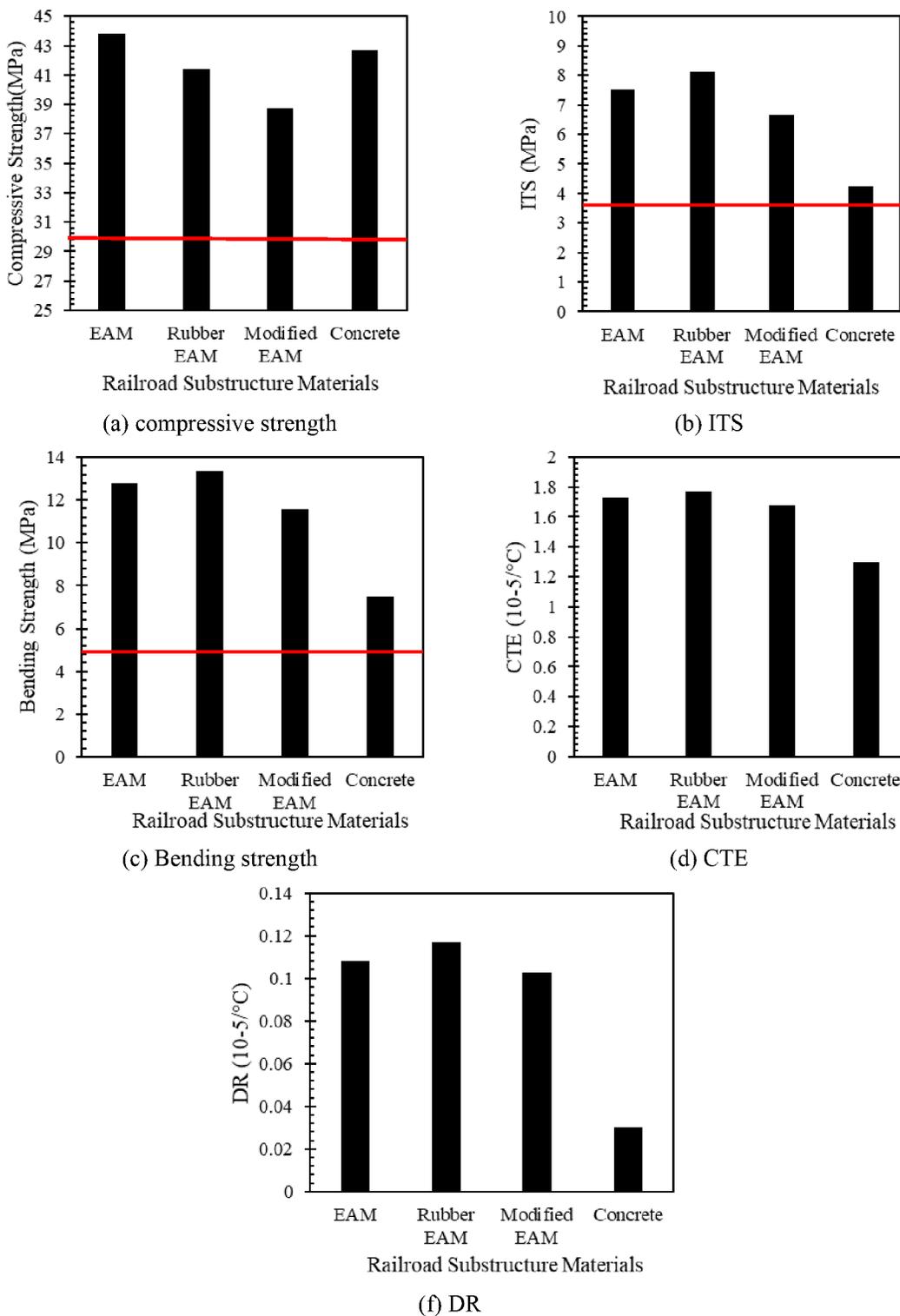

(c) Bending strength

(d) CTE

(f) DR

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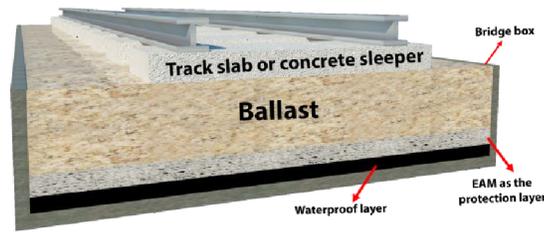
Figure 14: Schematic illustration of a typical cross-section of railway pavement structure on the bridge deck.

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.
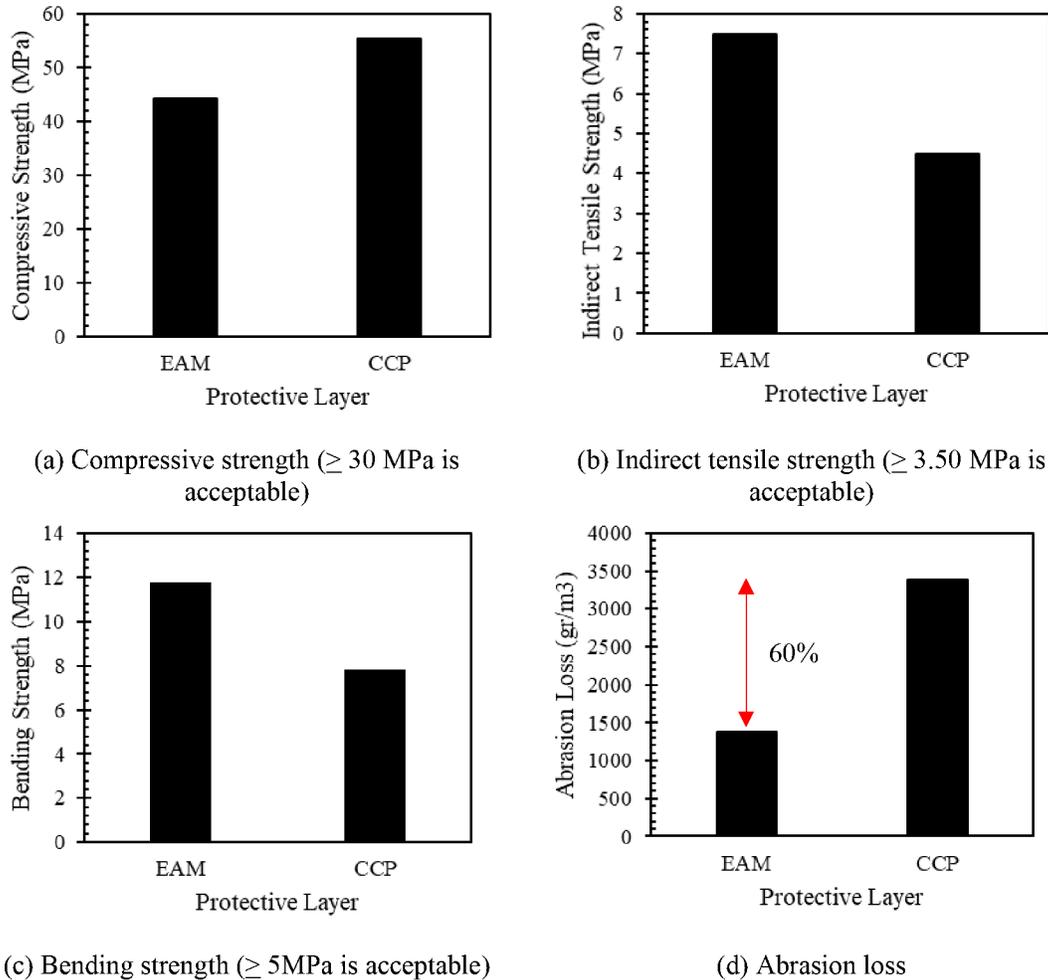
(a) Compressive strength ($\geq$ 30 MPa is acceptable)

(b) Indirect tensile strength ($\geq$ 3.50 MPa is acceptable)

(c) Bending strength ($\geq$ 5MPa is acceptable)

(d) Abrasion loss

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^2 was overlayed using
767 EAM on the Evergreen Point Bridge in 1972 (Luo *et al.* 2013). Additionally, 11,000 m^2 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
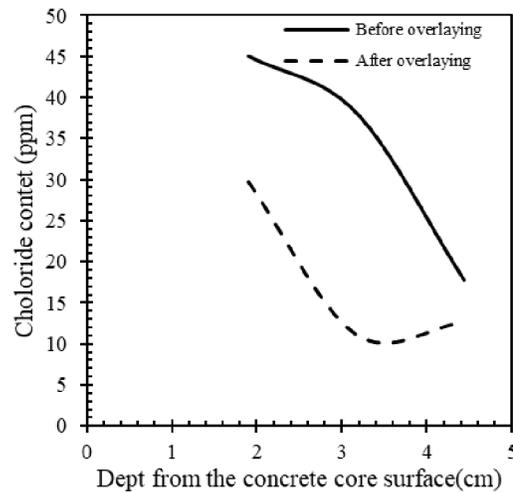
783
784   Figure 16: Trend of chloride content with depth of before and after overlaying using EAM; plotted by
785   data reported by Young et al. (2012).
786

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

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

7. Life Cycle Cost

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

(a) PED   (b) GWP

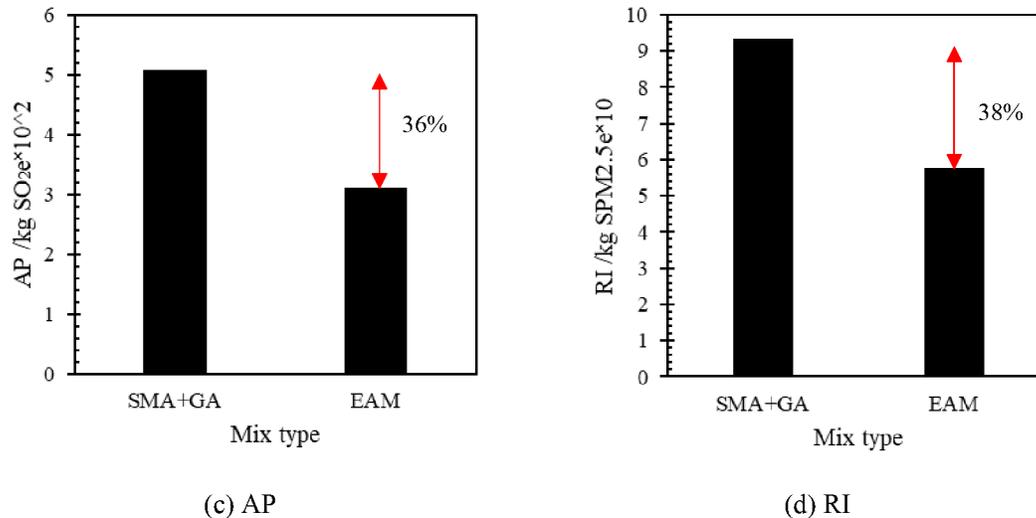(c) AP   (d) RI
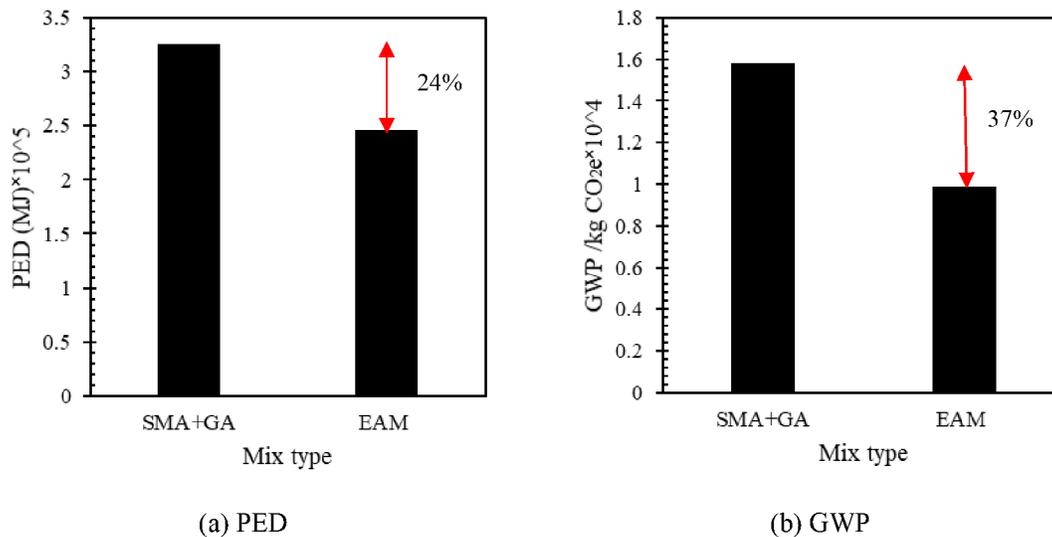
Figure 17: Results of the LCA model based on the selected environmental burdens, plotted based on data provided by Zhang *et al.* (2018b).

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

915   ERAP with the other waste materials are a matter of concern which should be addressed in laboratory
916   tests and field investigations.
917   In the railroad pavement system and on the deck of bridges and airport pavements, the resonance of
918   EAM may affect the models of the failures of pavement. It seems that there is a gap in research that
919   addresses the effect of epoxy type, content and curing agent on the resonance characteristics of EAM
920   utilized in the railroad and heavy-duty pavements.
921   There is another gap that the current fatigue and rutting criteria may not be applicable for structural
922   design and functional assessment of asphalt pavements incorporating EAM. Therefore, it is essential
923   the current methodologies for the structural design and functional assessment of EAM are evaluated
924   and the norms and new criteria are proposed, as necessary. New design charts and construction
925   standards may be developed, which can be used as a platform to develop application of EAM in
926   various infrastructure assets. In addition, further research is required to study the effect of gas
927   emission and fumes of burnt EAB and EAM on human health. The results of this research will be
928   helpful for the risk assessment of paving sites, which improves the level of safety.
929

10. Conclusion

931   The functional performance of EAM was characterized based on skid resistance, aging, moisture
932   sensitivity, flammability, and surface reflectance. The better macro texture of EAM results in higher
933   skid resistance and safety level at different time and temperature. However, it seems that the trend of
934   the dynamic friction coefficient changes at higher speeds. Therefore, the maximum allowable speed of
935   traffic based on skid resistance property of EAM should be determined. EAM can also improve the
936   reflectance of a pavement surface which results in lower heat-island effects in urban areas, and
937   relatively low flammability of EAM improves the safety of EAM in the service conditions.
938   Also, various mix types, including SMA, porous, hot-rolled, traditional mix, can be produced using
939   EAM, which results in the use of EAM in various transportation infrastructures. The findings of
940   performance-related assessments showed that the complicated construction technology of EAM
941   restricts its applications. In addition, results of field performance showed promising results in
942   different countries. However, the construction technology and technical norms should be reset for
943   EAM because of incorporation of waste materials and new modifiers.
944   The pavement material should be synchronized with steel bridges, and the materials should be durable
945   against shear stresses of traffic loads and thermal stresses of a temperature gradient. To meet these
946   requirements, EAM can be suggested as a premium surfacing material used for the construction of
947   heavily trafficked pavements on the decks of different types of bridges for highways and railroads.
948   Although the cost of production EAM is higher than traditional asphalt mixtures, due to the high price
949   of epoxy materials, the extra cost can be compensated by the considerable material and energy
950   savings in the construction phase and less maintenance in the utility phase. However, the life cycle
951   cost and environmental burdens of EAM in a paving project should be evaluated separately. High
952   strength, excellent adhesion, high-temperature durability and flexibility are the main contributive
953   factors result in the superior engineering characteristics of EAM. Such advantages make EAM as best
954   mixture in the construction of heavy-duty pavements. However, the thermosetting characteristics of
955   EAB, since it does not have reversible viscosity (i.e. EAB cannot be remelted) after curing, will
956   render the EAM more sensitive to the skills of paving crews and workmanship. Therefore, any error
957   cannot be rectified once the epoxy has cured. Another disadvantage of EAM is recyclability and
958   carbon footprint emission which require further laboratory studies and field investigations. As a result,
959   both advantages and disadvantages of EAM should be considered in the paving projects through a
960   strong engineering judgement in terms of the material characterization, practical experiences, life
961   cycle analysis, cost analysis, and environmental impact assessment.
962   Given that the evaluation of the field performance of EAM in various projects showed acceptable
963   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.
967

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