Title	Functional and field performance of epoxy asphalt technology-state-of-the-art
Author(s)	Jamshidi, Ali; White, Greg; Kurumisawa, Kiyofumi
Citation	Road Materials and Pavement Design, 24(4), 881-918 https://doi.org/10.1080/14680629.2022.2060128
Issue Date	2022-04-11
Doc URL	http://hdl.handle.net/2115/88817
Rights	This is an Accepted Manuscript of an article published by Taylor & Francis in Road Materials and Pavement Design on 2023-04-03, available online: http://www.tandfonline.com/10.1080/14680629.2022.2060128.
Type	article (author version)
File Information	RMPD-21-08-20.R1_Proof_hi.pdf

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).

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.

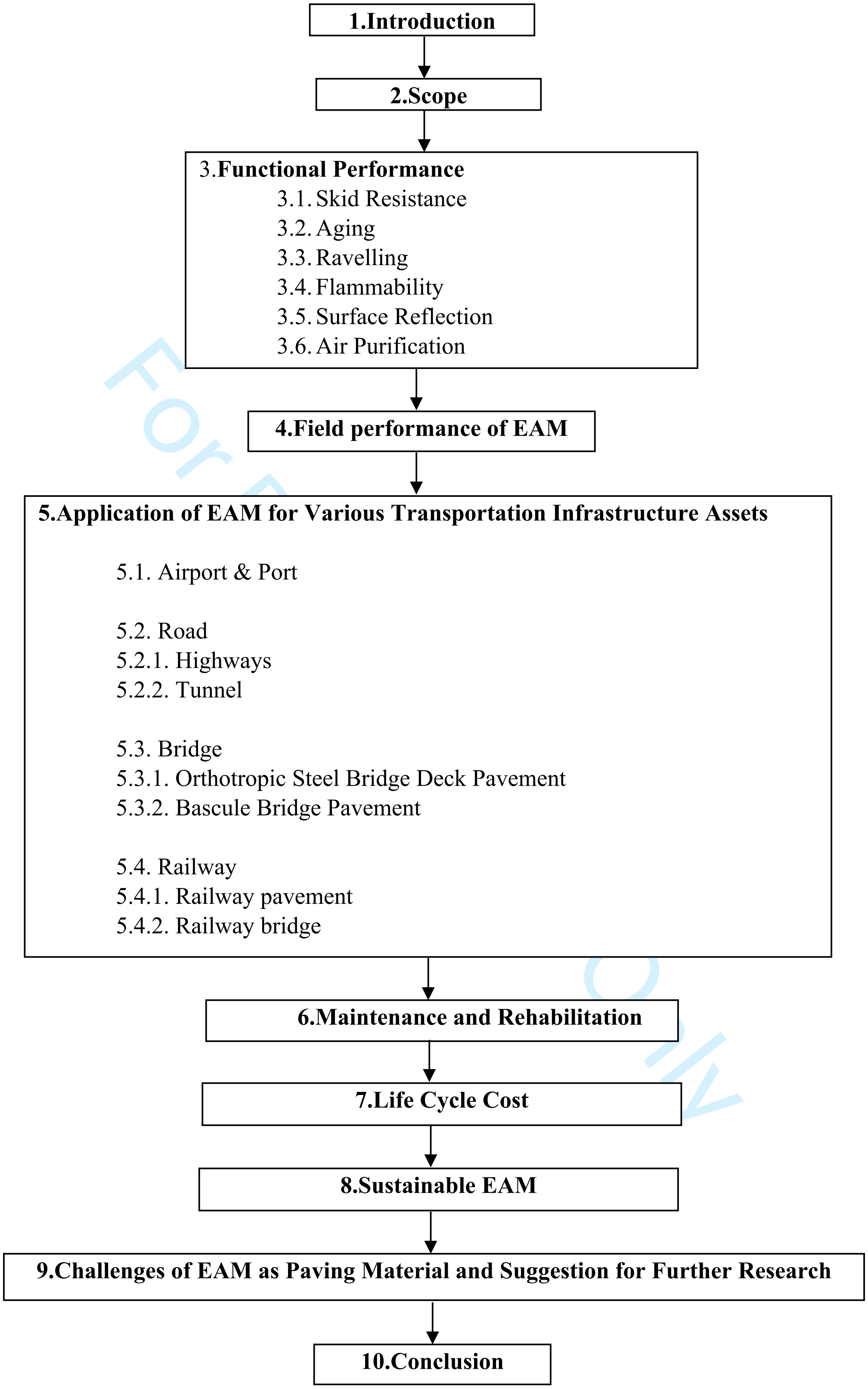


Figure 1 : Schematic illustration of the study structure.

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

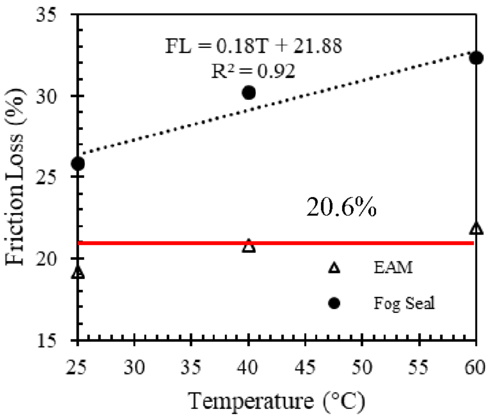


Figure 2 : Trend of friction loss as a function of temperature; plotted based on data outlined by Hu et al. (2016).

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

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

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

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

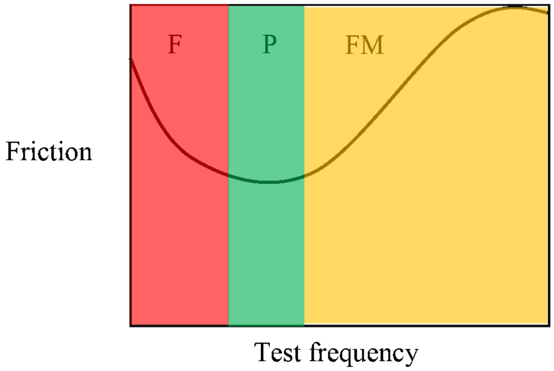


Figure 3: Trend of friction test over the test; F: fully covered (phase 1); P: Partial covered (phase 2); and FM: fully melted ice (phase 3), adopted based on the data reported by Xiaoning *et al.* (2012).

3.2. Aging

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

There are various procedures for laboratory aging of asphalt binders and mixtures. For example, ASTM D 2872 and D 6521 procedures are used to simulate short term aging of binder, by means of rolling thin film oven (RTFO), and long-term aging, using pressure aging vessel (PAV), respectively. To simulate short-term aging of the mix, the samples are conditioned for 2 h at the compaction temperature (SP-2 2000). According to AASHTO PP2, the samples can be conditioned at 80 °C for 120 h for long-term laboratory aging. In addition, there are recently developed methodologies to simulate field aging, which resulted in more realistic outputs. Mirwald et al. (2020) proposed a new methodology, called Viennese Binder Aging (VBA), for conditioning long-term aging in laboratory. This methodology considers reactive oxygen species (ROS), such as O3 and NOX, in aging process, which is neglected in PAV. It should be noted that the surface of the pavement exposes to air containing ROS, especially in cities. The results of laboratory tests and field investigations showed that VBA can reach and even surpass level pf aging by means of RTFO plus PAV within three days at 80°C. Therefore, VBA can provide more realistic understanding of the phenomenon of aging compared with commonly used methodologies such as PAV and RTFO. Furthermore, Steiner et al. (2016) developed a laboratory aging procedure, called Viennese Aging Procedure (VAPro), which can be used for conditioning compacted samples. VAPro enable researches and engineers to simulate short term and in-service aging through triaxial cell with forced flow of a gaseous oxidant agent through the compacted asphalt mixture. The results of conditioned recovered binder showed VAPro can simulate long term aging state at moderate temperatures (+60°C) and within 4 days and a flow rate of 1 l/min.

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

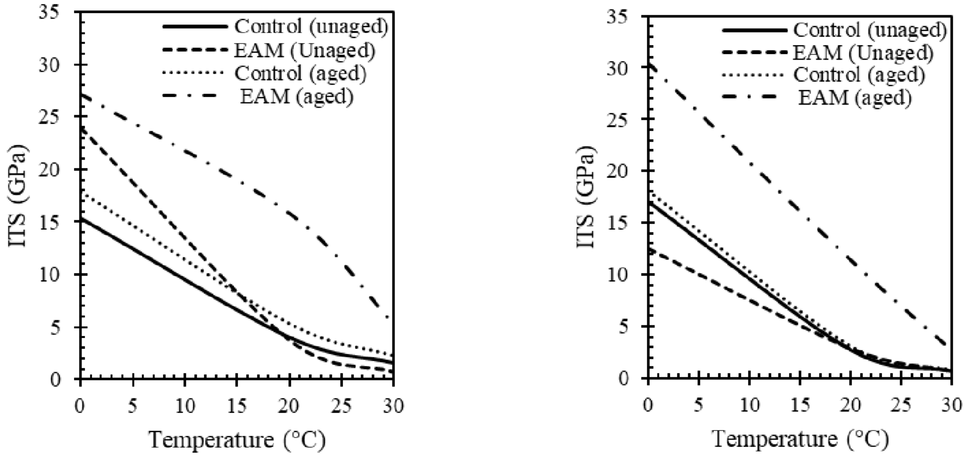
The result of initial studies showed that TEAGE has potential to simulate accurate field aging condition. It worth mentioning that Aging Index significantly depends on the types of parameters adopted for analysis of the ageing phenomenon (Jamshidi et al., 2012 and Hamzah et al., 2012). Therefore, it may not be as accurate as the other consecutive reaction model developed based on chemical reactions. For example, The Zero-order model was suitable to describe the long-term aging reaction kinetics of bitumen based on the oxygen-containing functional groups with the reaction rate constants in 0.7–3.3x10−4 (mol L−1·h−1), while the most optimum kinetics model for aromatic fraction was the Third-order reaction model and the corresponding reaction kinetics constant (k1) was 0.02 (mol·L−1)−2(h)−1 by means of Saturate, Aromatic, Resin and Asphaltene (SARA) test (Ren et al., 2020). Elwardany et al. (2017) reported that loose mix aging in an oven resulted in a promising laboratory long-term aging procedure to produce mixture for performance testing in terms of various factors such as efficiency, specimen integrity, and versatility. It is also a cost-effective methodology, which can be readily used for various mixture types. However, it should be noted that the methodologies mentioned above have not been standardized. It is essential to standardize and develop laboratory protocols to use in the pavement industry.

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

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

In a laboratory study, Widyatmoko *et al.* (2006a) evaluated the effects of aging on hot-rolled (HR) and SMA epoxy asphalt. Figure 4 shows the effects of aging based ITS results. It can be seen that aged ITS of HR-EAB was much higher than the control counterpart, in which such high stiffness is due to synergistic effects of curing and aging (Figure 4(a)). However, unaged ITS of HR-EAM beyond 20 °C is slightly less than that of unaged HR. This lack of strength can be compensated by the stiffening effects of aging or further curing.

Figure 4(b) reveals the results of aging in SMA. The difference between the aged and unaged ITS of SMA is not significant because of the dense matrix of the mixture. Furthermore, ITS of unaged SMA-EAM is less than that of the control sample up to 20 °C. Beyond 20 °C, the ITSs are almost identical for the unaged sample. In SMA, the lack of ITS strength is compensated by aging. Hence, irrespective of mix type, the lack of initial strength in both mixes can be balanced by the stiffening effects of aging.



(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

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

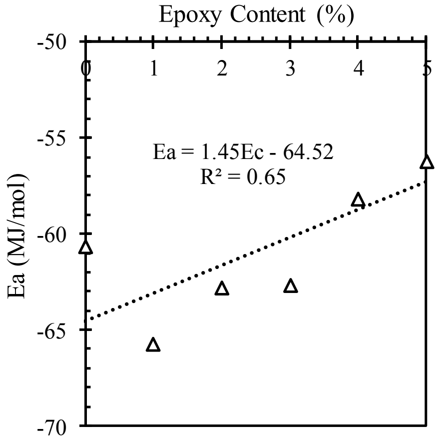


Figure 5: Effect of epoxy content on the activation energy of EAB, plotted based on data reported by Cubuk *et al.*, (2009).

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

3.4. Flammability

Since EAM can be used for different infrastructure types, the safety of the pavement is a matter of concern because epoxy resins and asphalt binders are combustible and emit smoke and toxic substances (Pack 2015). Consequently, retardants added to the asphalt binder should meet the standard requirements. Inorganic flame retardants are commonly used in the asphalt pavements (Bonati *et al.* 2012, Xu *et al.* 2011, Wan *et al.* 2015, Zhang *et al.* 2015). Additionally, one of the widely used flame retardants is a brominated flame in the asphalt concrete (Cong *et al.* 2008, Yu *et al.* 2009b). Because of concerns about the persistence, bioaccumulation, and toxic materials, some brominated flaming agents, such as brominated diphenyl ethers and polybrominated biphenyl halogenated flame retardants have not been allowed (Mitchel 2014). Instead of brominated flaming retardants, halogen-free flame retardants are used (Zhang *et al.* 2016a). Among the halogen-free materials, mineral fillers, such as aluminum trihydrate and magnesium hydroxide are increasingly used in asphalt binders (Barral *et al.* 2012, Ren *et al.* 2013, Bonati *et al.* 2013, Šušteršicˇ *et al.* 2014). Therefore, it is necessary to find the most appropriate flame retardant materials for EAM, depending on the epoxy resin, curing agent, asphalt modifier, and additive type. In this regard, Chen *et al.* (2018c) carried out a laboratory study on the synergistic effects of aluminum trihydrate and zinc borate on the flammability of EAB. The results showed that the limited oxygen index of EAM containing 20% of aluminum trihydrate and zinc borate are the highest compared to control EAB (without flammability retardant) and samples containing aluminum trihydrate or zinc borate. The results indicated that incorporation of aluminum trihydrate and zinc borate had the best flame retardancy in this study because aluminum trihydrate decomposes in Al_2O_3 and creates strong endothermic reactions when heating the flame-retardant polymeric material, which leads to an incremental ignition time. Moreover, the porous, ceramic-like structure of char of boric oxide and alumina produced at high temperatures (>600 °C) performs as an insulating material or thermal shield for the underlying, unburned polymeric material. Decomposition of zinc borate also releases water that decreases the polymer's surface temperature (Bourbigot *et al.* 1999, Weil and Levchik, 2016). Chen *et al.* (2021a) also proposed to use reactive polymeric flame retardant in the binder which is composed of a reactive polymeric brominated epoxy oligomer and antimony oxide. The results showed that level of limited oxygen index (LOI) improved, which increased flame retardant loading of EAB.

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

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

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

3.5. Surface Reflectance

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

There are different procedures to evaluate thermal emission paving materials and pavement surfaces, such as ASTM C1371, C 1549 and E 1918. The brightness and thermal emissions of pavements depend on the angle of the sunrays, time of measurement and the pavement material type. Furthermore, when the pavement is new, the concrete pavement shows a higher albedo due to its bright surface in comparison with the asphalt pavement (Jamshidi *et al.* 2017), even though the albedo levels of concrete and asphalt pavement are almost identical after approximately 7 years (Cambridge Systematic 2005).

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

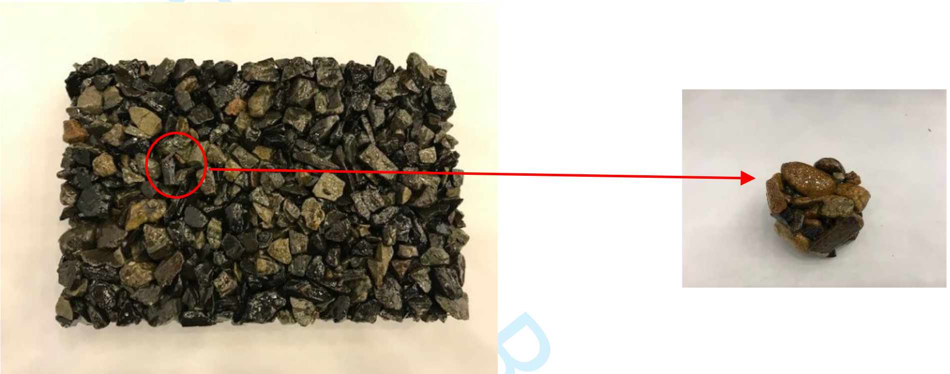


Figure 6: Use of resin as a transparent binder.

3.6. Air purification

Surface of EAM pavement can degrade hazardous gases via using titanium dioxide (TiO_2). The mechanism is that hydrogen carbon (HC), nitric oxide (NO) and carbon monoxide (CO) compounds due to fuel burning can be degraded into salt and water by nano-TiO2 under photocatalysis that is an irradiation by a light source with a wavelength less than 387.5 nm (Liu *et al.* 2015, Wang *et al.* 2016, Toro *et al.* 2016, Tang *et al.* 2016, Leng and Yu, 2016, Jin *et al.* 2018). In a laboratory study, Huang and Wen (2019) evaluated effect of size and content of nano-TiO_2 on the degradation performance of emulsified EAM. Results indicated that EAM containing 5nm TiO_2 increases degradation of CO, HC, CO_2, and NO by 46%, 48%, 21%, and 60% respectively, compared to those of 10 nm. Therefore, 5nm can be chosen as optimum size of nano TiO_2. In addition, general trend is that higher contents of TiO_2 in the EAM increases degradation of hazardous materials. TiO_2 can be sprayed on the surface of pavement, however long-term durability is cause of concern. As a result, air purification in EAM leads to the health of pavement users and residents. In other words, the pavements as multi-role infrastructure assets can create better environment in the cities.

4. Field Performance of EAM

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

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

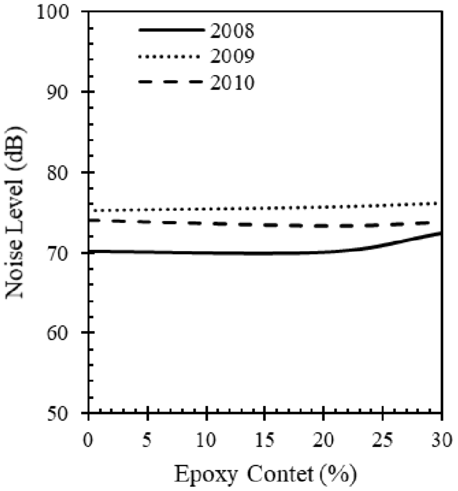


Figure 7: Noise level of EAM, plotted based on data reported by Herrington (2010).

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

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

There is a substantial long-term performance of EAM in different countries. For example, EAM was used on the San Mateo-Hayward Bridge and has been in service since 1967 and was only recently replaced (Chen *et al.* 2018a). The EAM used on Fremont Bridge in Portland, Oregon lasted for 40 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

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

Porous asphalt is another paving system that has been used for the construction of roads and parking lots. Porous asphalt is a multi-role infrastructure that improves the landscape and urban design. Porous asphalt pavements have high air voids contents (around 20%) compared with the dense asphalt pavement (around 4% to 6%). Due to the high porosity, the binder drain-down results in clogging. Various methods are used to evaluate the drain-down process, such as the Caltran (Test Method 368), the Pyrex plate method (GDT 2011), the metal wire basket method standardized by ASTM D 7064, and the Schellenberg binder drainage test (BSI 2004). However, clogging in the pavement is complex. A solution to reduce binder drain-down is to use a polymer-modified asphalt binder (Ongel *et al.* 2008). EAB can be an appropriate binder to avoid binder creep and drain down due to its high viscosity. Additionally, the porous asphalt pavement's service life is relatively short, around 8 to 12 years. EAB can also extend the pavement's life due to its high stiffness (Kandhal *et al.* 1998, Bennert and Cooley 2014). For example, porous EAM showed the higher fatigue resistance compared with porous mixtures produced using high viscosity binder (Li *et al.* 2022b). However, the use of porous EAM is not new. It was first used in San Francisco-Oakland in 1969 (Brewer 1970). High-quality epoxy resin and other advanced materials have resulted in a more efficient porous EAM. For example, Cantabro test results clearly showed that the Cantabro losses of porous EAM were 76% and 60% lower than traditional porous pavements for the unaged and aged states, respectively (Lu *et al.* 2015). The Cantabro test shows the potential of raveling in the porous pavement. Therefore, the less mass loss, the less prone to the raveling. Also, oxidation decreases the loss modulus of porous EAM, based on the Cantabro test (Herrington and Alabaster 2008). Figure 8 shows that the mass loss of porous EAM decreased as epoxy content increased. However, the binder type played a significant role in the mass loss of EAM (Holleran et al. 2017).

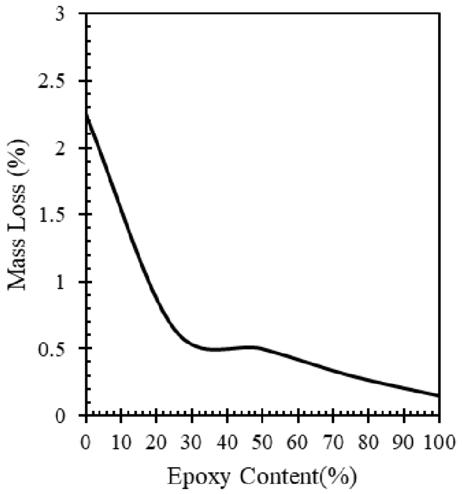


Figure 8: Trend of the mass loss as a function of epoxy content; plotted based on data reported by Wu *et al.* (2017).

The sound absorption coefficient of porous EAM fluctuates between 0.35 to 0.45, while the coefficient of traditional porous asphalt varies from 0.15 to 0.65, indicating a more efficient noise reduction of associated with EAM (Luo *et al.* 2015). The noise emissions can be reduced more via the use of crumb rubber in the porous pavement. For example, in Japan, a new type of porous mix containing crumb rubber was developed, referred to as PERS (Kubo 2011a). Analysis of road acoustics showed that the noise level could be decrease by around 20% according to the Japan Road Association (2006, 2009). Use of crumb rubber may decrease the surface friction (Kawakami and Kubo 2008, Kubo *et al.* 2011a, b), but the use of sand in PERS improves the friction.

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

5.2.2. Tunnel Pavement

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

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

5.3. Bridge

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

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

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

5.3.1. Orthotropic Steel Bridge Deck Pavement

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

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

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

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

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

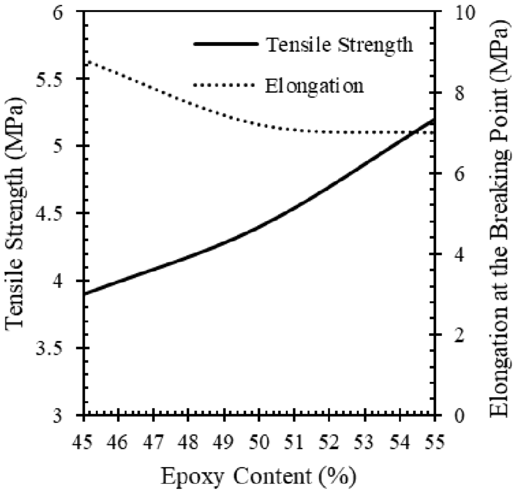


Figure 9: Effect of epoxy content on the tensile strength and elongation; plotted based on data reported by Yin *et al.* (2015).

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

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

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

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

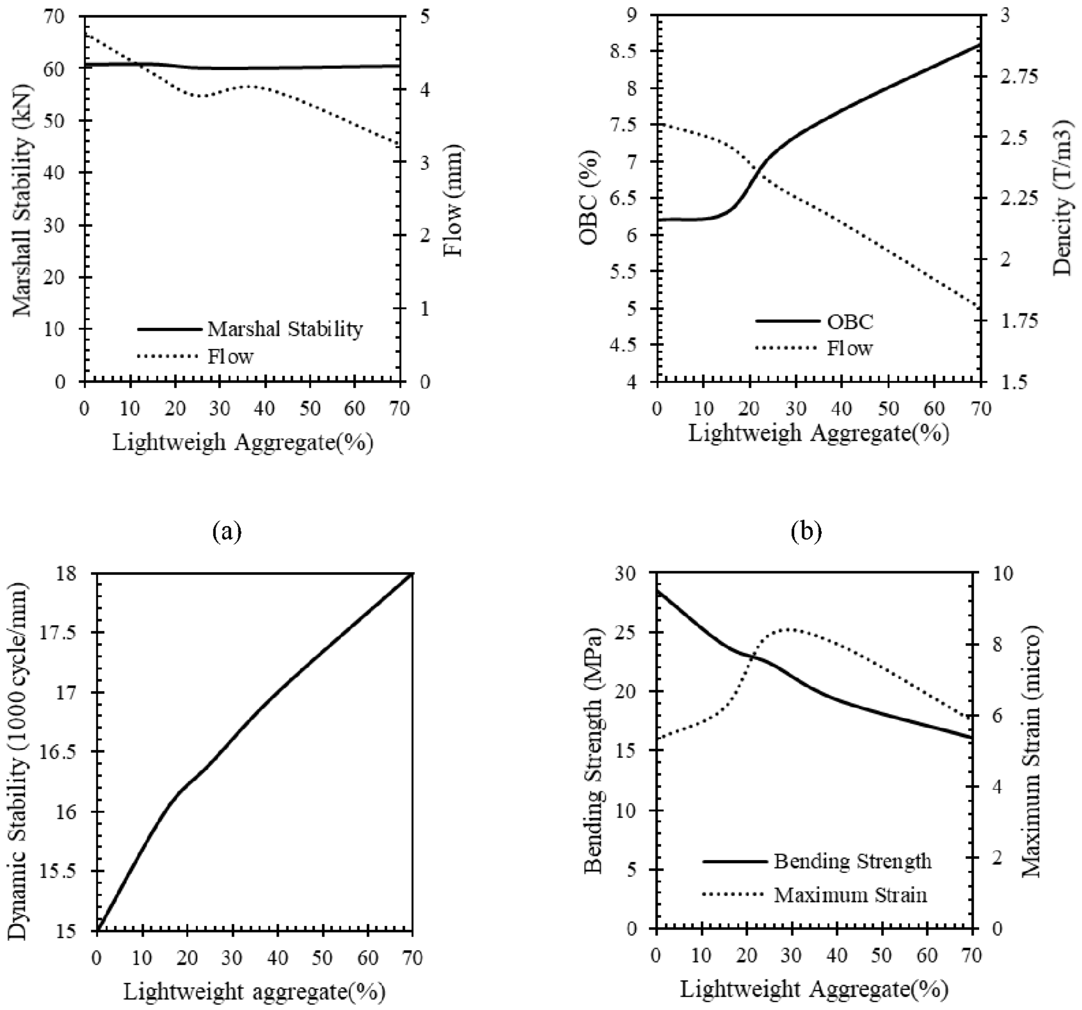
Moreover, the EAM may crack after 5 to 10 years (Li *et al.* 2010, Han *et al.* 2010). Since the cracks are so narrow, the crack sealing materials should be viscous enough to penetrate and fill throughout the openings. The sealing materials should gain strength at an appropriate time. Furthermore, the rapid cooling rate of the EAM can result in cracking due to residual thermal stress. Therefore, the selection of a suitable base binder, curing agent, ambient temperature, and the temperature gap of the upper and lower surface plates used in the bridge is vital. Otherwise, traditional crack sealing materials cannot be used efficiently. A comparative study carried out by Yin *et al.* (2016) showed that epoxy sealing materials could show higher penetration, bonding strength, and shorter curing time. The epoxy resin materials can therefore be used for the efficient maintenance and rehabilitation of the pavement. It is also necessary to understand EAM cracking via advanced methods (Qian *et al.* 2014). Additionally, based on viscosity and tensile strength, Gong *et al.* (2019) recommended warm-EAB containing 1.9% weight ethylene-vinyl acetate copolymer as an optimum binder blend for use on the bridge. Consequently, the structural requirements of EAM for bridge deck wearing course can be met via the appropriate selection of additive contents and binder types. Furthermore, development of predictive models based on rheological characteristics of EAB and engineering properties of EAM can be considered as a useful tool to structural performance of pavement on the bridge. For example, Huang *et al.* (2019) recommended to use the modified second-order extensive rheological Kelvin model for predicting stresses in EAM.

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

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

5.3.2. Bascule Bridge Pavement

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



(a) (b)

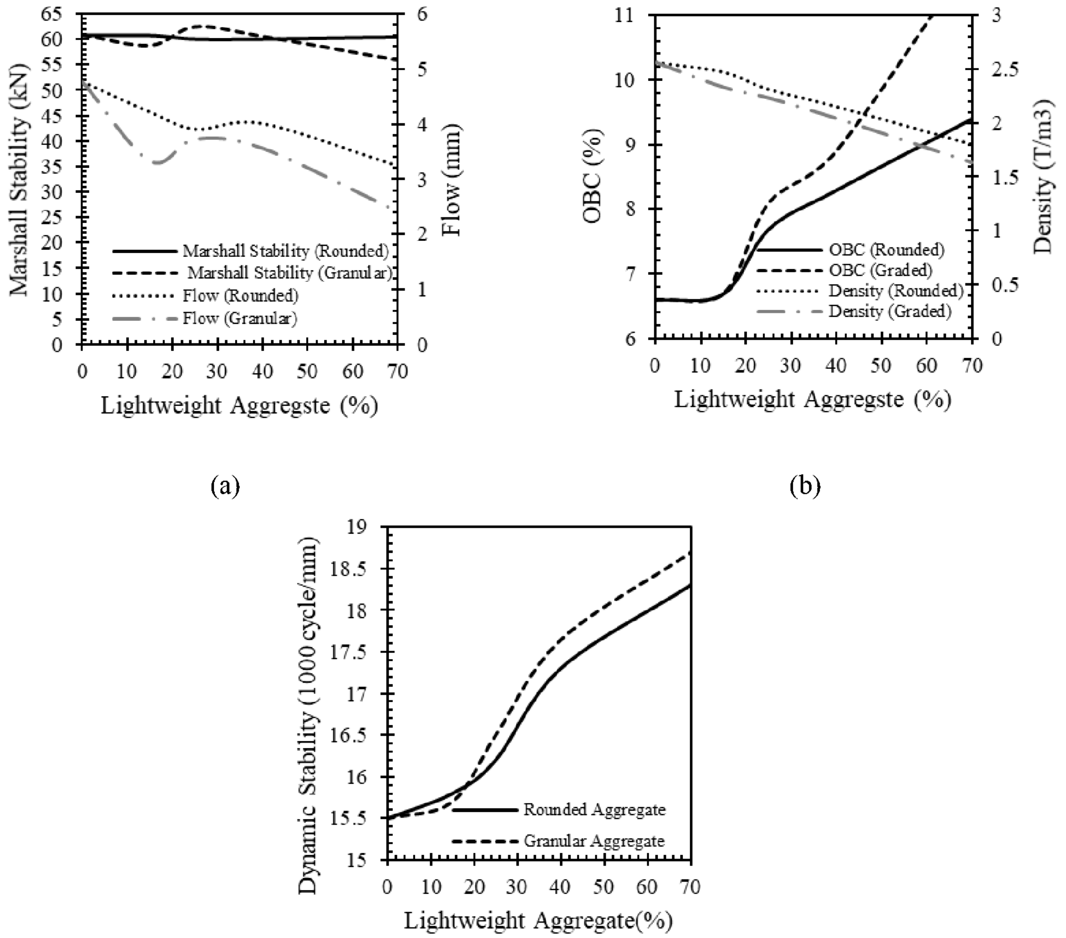
(c) (d)

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).

5.4. Railroad

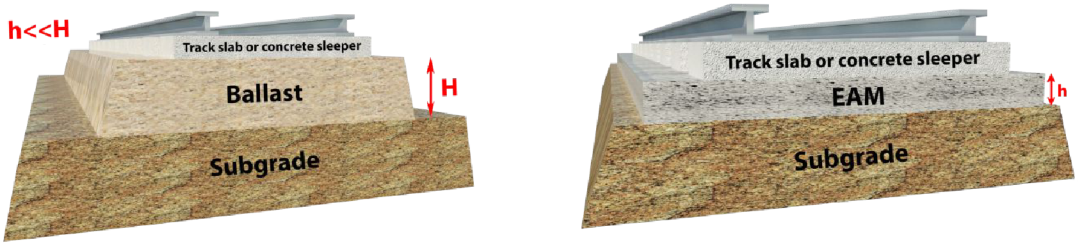
5.4.1. Railroad Pavement

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

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

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

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

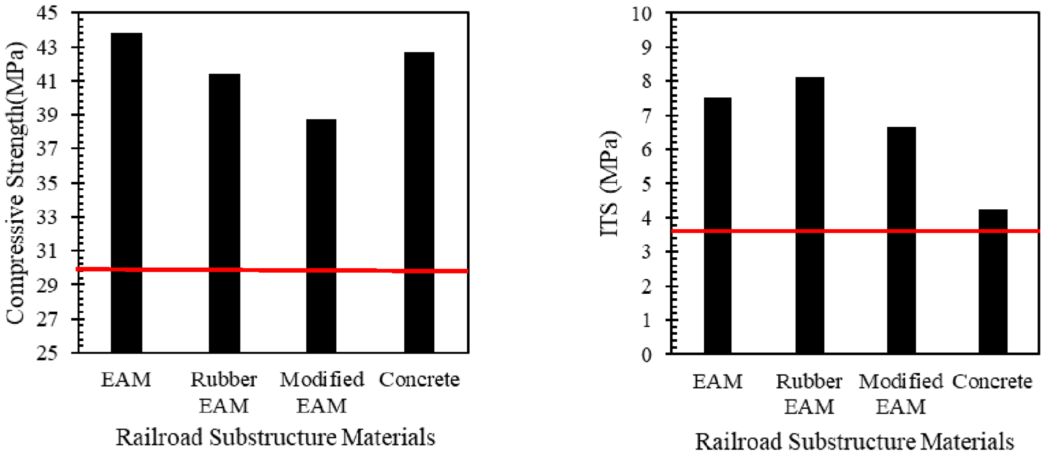


(a) Typical railway pavement (b) Ballastless pavement

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

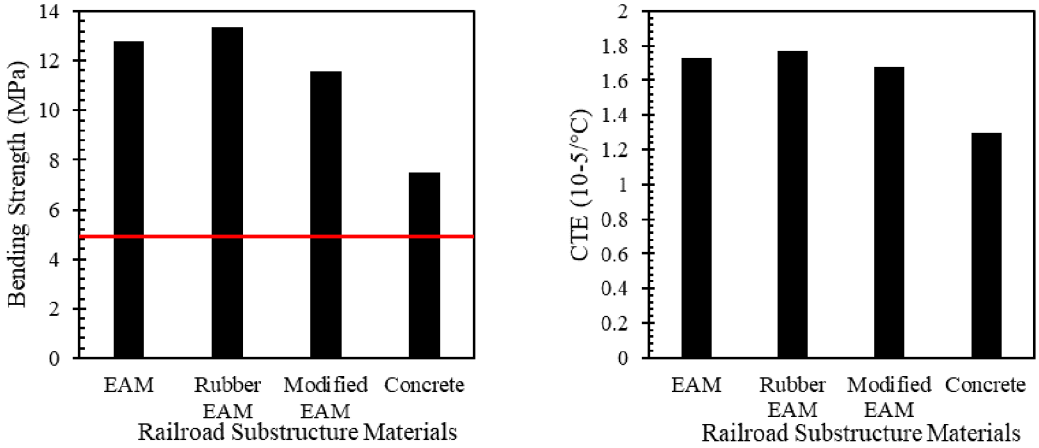
Figure 13 reveals the results of the compressive strength, ITS, bending strengths damping ratio (DR), and coefficient of thermal expansion (CTE) for various materials. The compressive strength of EAM is comparable to the concrete (Figure 13(a)). Although EAM is a viscoelastic material, the high stiffness of hardened EAM increased the compressive stiffness. Figure 13(b) shows that ITS of EAMs is almost two times that of concrete samples. The higher tensile strength of EAM provides improved resistance to cracking, which results in a longer service life of the substructure.

Additionally, Figure 13(c) shows the bending resistance of EAMs is higher than that of concrete samples. This means that the deformability of EAM is more than for the traditional concrete substructure due to high ductility of EAB. That is an important factor because the cumulative stress/strain due to structural loading results in cracking in the substructure. The bending strength of the rubber EAM is the highest. The use of rubber can therefore improve the fatigue properties of the substructure. However, the rheological characteristics of the base binder and curing methods play a pivotal role. Figure 13(d) reveals that the CTE of EAM is superior to the concrete materials. This means that EAM is less prone to cracking from the thermal stresses induced by ambient temperatures and the magnetic properties of the high-speed trains because of the thermosetting characteristics of EAB. The higher damper ratios of EAM show a high potential in the vibration attenuation, which significantly increases comfortability for the passengers. It also generates a sense of reliability among the passengers because the high speed of the trains (≥300 km/hr) may result in some psychological problems for users.



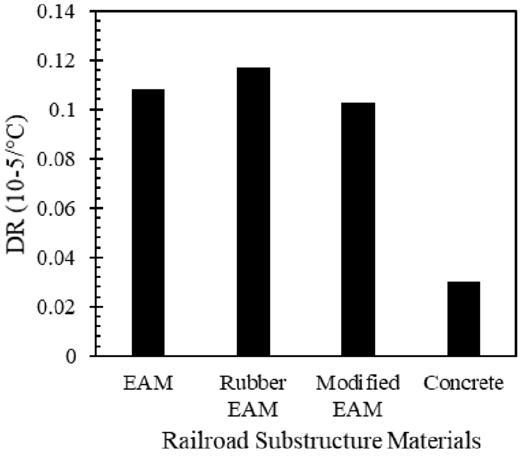
(a) compressive strength

(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.

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).

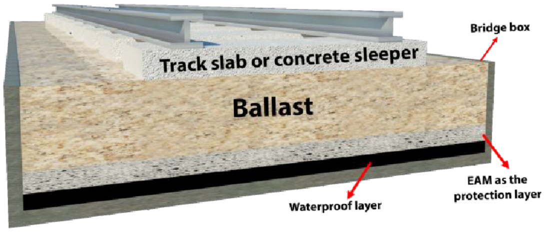
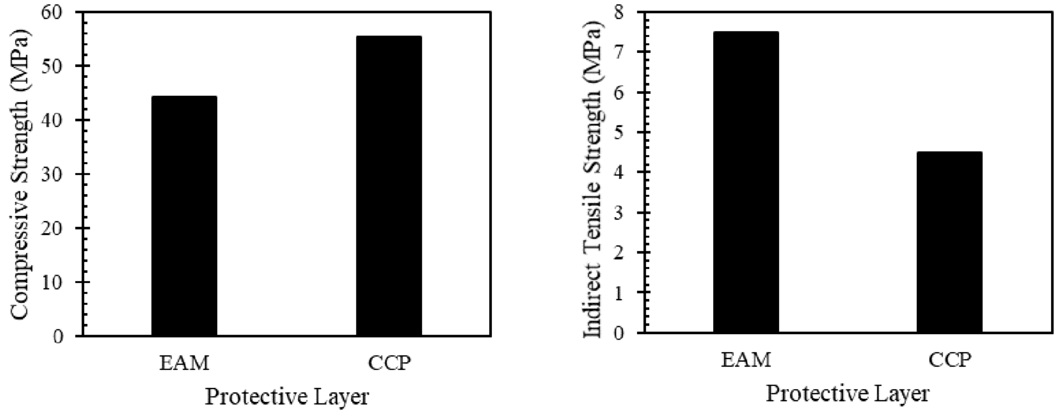


Figure 14: Schematic illustration of a typical cross-section of railway pavement structure on the bridge deck.

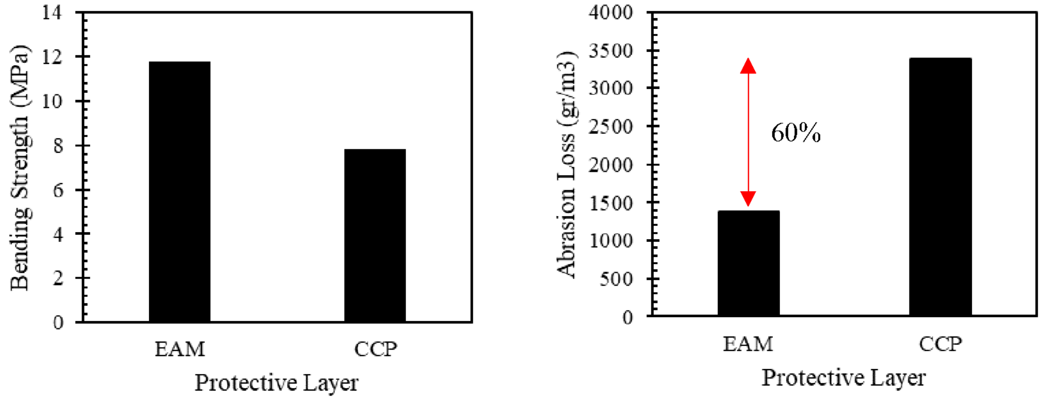
The performance of the EAM and cement concrete protective (CCP) layers were compared in terms of compressive strength, bending, and abrasion loss in Figure. Figure 15(a) shows that the compressive strength of CCP is higher than EAM samples. However, both samples meet compressive strength. Figure 15(b) 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 (≥ 30 MPa is acceptable)

(b) Indirect tensile strength (≥ 3.50 MPa is acceptable)



(c) Bending strength (≥ 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).

6. Maintenance and Rehabilitation

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

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

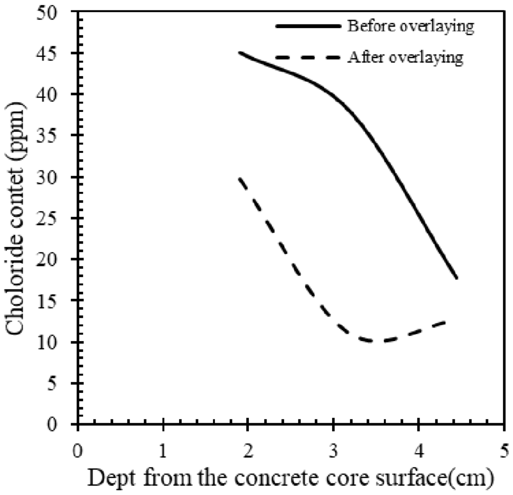


Figure 16: Trend of chloride content with depth of before and after overlaying using EAM; plotted by data reported by Young *et al.* (2012).

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

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

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

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

EAB does not melt at high temperatures (Chen 2009). Therefore, EAM is less prone to bleeding at the elevated temperatures. Although the high stiffness of EAM improves rutting resistance of the pavement, it can render the asphalt more brittle, which increases the risk of non-repaired brittle cracks at low temperatures. To address the problem, the toughness modulus of the mixture can be improved by rubber, thermoplastic resins, polymers, nanomaterials, basalt and polyester fibers (Bucknall and Dumpleton 1987, Bucknall and Gilbert 1989, Aspler *et al.* 1992, Jackson *et al.* 1993, Morrison and Hesp 1995, Kim *et al.* 1996, Ni-sheng *et al.* 2006, Jamshidi *et al.* 2015, Sun *et al.* 2018, Chen *et al.* 2019). Such materials can be used to modify the high toughness of EAM, which decreased the low temperature cracking. For example, Xu *et al.* (2016) proposed to use a hyperbranched polymer (HBP) in EAM. The results indicated that the optimum content of aromatic and aliphatic HBP into EAM reduces risk of low temperature cracking via improved binder elongation. However, hydroxyl end groups of HBP can accelerate the reaction rate of EAM (Xu *et al.* 2022), which may have a negative effect on the phase dispersion between the resin and asphalt binder. Therefore, hydroxyl end groups of HBP as inert alkyl end groups should be modified to avoid its rapid curing reaction with the epoxy resin (Xu *et al.* 2018). As such, further positive effects in HBP-EAM, including viscosity reduction and better compatibility, can be achieved. It should be noted that rapid curing can be an advantage in runway overlay and maintenance without interrupting traffic flow. To improve initial curing for such cases, a dense mix with chosen unit weight of 95%, coarse aggregate ratio of 40%, and fine aggregate coarse fraction of 35% is recommended for EAM (Min *et al.* 2020).

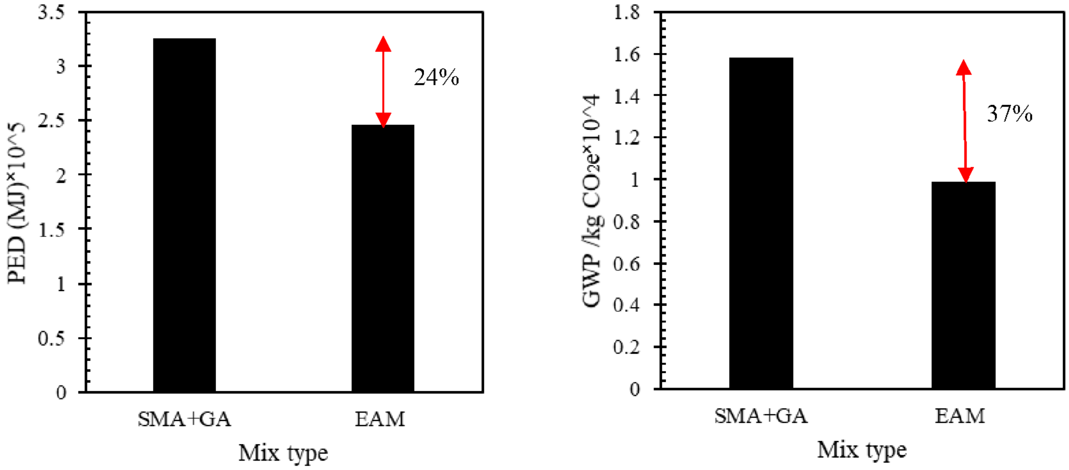
7. Life Cycle Cost

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

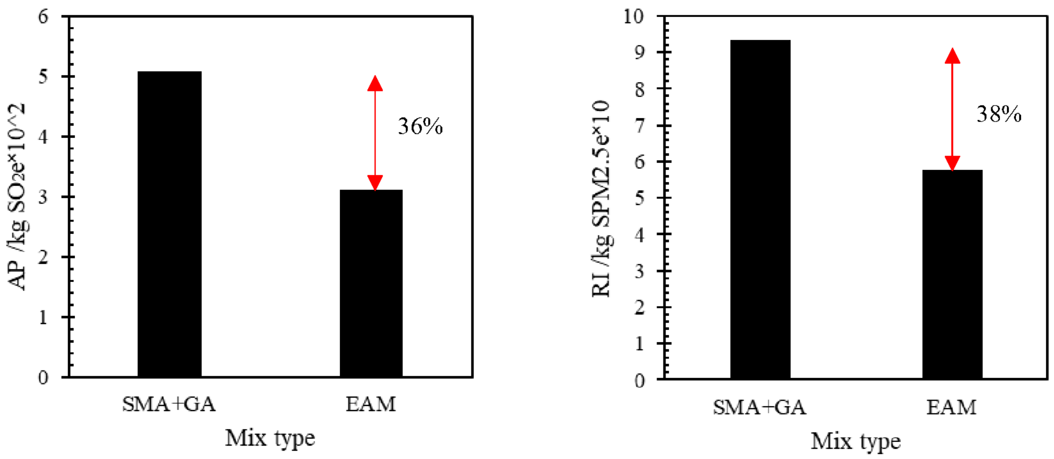
8. Sustainable EAM

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).

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

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

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

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

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

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

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

10. Conclusion

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

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

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

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

Given that the evaluation of the field performance of EAM in various projects showed acceptable results and EAM is a relatively energy-efficient material, structural and environmental requirements can be satisfied. Nevertheless, certain drawbacks continue to restrict the application of EAM. In conclusion, further research is required regarding the consideration of EAM as a potential option in pavement industry.

References

AASHTO PP2: Standard practice for mixture conditioning of hot mix asphalt. (2001). American Association of State Highway and Transportation Officials, Washington DC, USA.

Ai, T., Xiang, S., and Wang, Z. (2016). Effects of microwave curing on the chemical and physical properties of epoxy asphalt. *Materials in Civil Engineering (ASCE)*, 28(11), 06016013.

Alabaster D, Herrington P.R, Waters J.C. (2008). Long life open-graded porous asphalt. In: Third International Conference on Accelerated Pavement Testing, APT 2008, Madrid, Spain.

Alabaster, D., Herrington, P., and Waters J. (2016). Optimising long-life low noise porous asphalt. 12th International Society for Asphalt Pavements ISAP, Raleigh, North Carolina, USA.

Alamri, M., Lu, Q., and Xin, C. (2020). Preliminary evaluation of hot mix asphalt containing reclaimed epoxy asphalt materials. *Sustainability*, 12(9), 3531.

Al Nageim, H., Al-Busaltan, S. F., Atherton, W., and Sharples, G. (2012). A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials. *Construction and Building Materials*, 36, 743-748.

Al-Qadi, I., Xie, W., and Roberts, R. (2010). Optimization of antenna configuration in multiple-frequency ground penetrating radar system for railroad substructure assessment. *NDT & E International Journal*, 43(1), 20-28.

Anupam, B. R., Sahoo, U. C., Chandrappa, A. K., and Rath, P. (2021). Emerging technologies in cool pavements: A review. *Construction and Building Materials*, 299, 123892.

Apostolidis, P., Pipintakos, G., Liu, X., van de Ven, M., Erkens, S., Scarpas, A., ... and Kumar, A. (2018). Epoxy modified bitumen: chemical hardening and its interpretation. in advances in materials and pavement prediction, the International Conference on Advances in Materials and Pavement Performance Prediction (AM3P 2018), CRC Press, Doha, Qatar.

Apostolidis, P., Liu, X., van de Ven, M., Erkens, S., and Scarpas, T. (2019). Kinetic viscoelasticity of crosslinking epoxy asphalt. Transportation Research Record, 2673(3), 551-560.

Asi, I. M. (2007). Evaluating skid resistance of different asphalt concrete mixes. *Building and Environment*, 42(1), 325-329.

Aspler, J. S. (1992). NMR spectroscopy, polymer motion, and “Tack” of model printing inks. *Polymer Journal of Engineering & Science*, 32(18), 1379-1385.

ASTM C 1371. (2015). Standard test method for determination of emittance of materials near room temperature using portable emission meters. West Conshohocken, Pennsylvania, USA.

ASTM D 7064 / D7064M-08. (2013). Standard practice for open-graded friction course (OGFC) mix design. West Conshohocken, Pennsylvania, USA.

ASTM C 1549. (2016). Standard test method for determination of solar reflectance near ambient temperature using a portable solar reflectometer, West Conshohocken, Pennsylvania, USA.

ASTM D 2872. (2016). Standard test method for effect of heat and air on moving film of asphalt (Rolling Thin-Film Oven Test). West Conshohocken, PA, USA.

ASTM D 6521. (2004). Standard practice for accelerated aging of asphalt binder using a pressurized aging vessel (PAV). West Conshohocken, Pennsylvania, USA.

ASTM E 1918. (2016). Standard test method for measuring solar reflectance of horizontal and low-sloped surfaces in the field. West Conshohocken, Pennsylvania, USA.

Austroads. (2018). Guide to Bridge Technology Part 3: Typical Superstructures, Substructures and Components. Publication no: AGBT03-18, Sydney, NSW, Australia.

Bahmani, H., Sanij, H. K., & Peiravian, F. (2021). Estimating moisture resistance of asphalt mixture containing epoxy resin using surface free energy method and modified Lottman test. *International Journal of Pavement Engineering*, 1-13.

Balala B. (1969). Studies leading to choose of epoxy asphalt for pavement on steel orthotropic bridge deck of san Mateo-Hayward bridge, Highway Research Record 287, 12-18.

Barral, M., Garmendia, P., Muñoz, M.E., Palmillas, Z., Romera, R., Santamaria, A., Villanueva, S. (2012). Novel bituminous mastics for pavements with improved fire performance, *Construction and Building Materials*, 30 650–656.

Bendtsen, H., Qing, L., and Kohler, E. (2010). Acoustic aging of asphalt pavements A Californian/Danish comparison (No. 171). Federal Highway Administration (FHWA), No: CA101735A, Washington, USA.

Bennert, T., and Cooley, L. A. (2014). Evaluate the contribution of the mixture components on the longevity and performance of FC-5 (No. BDS15 977-01). Department of Transportation. Florida, USA.

Blazejowski, K. (2016). Stone matrix asphalt: Theory and practice. CRC Press. New York, USA.

Bocci, E., and Canestrari, F. (2012). Experimental analysis of structural compatibility at the interface between asphalt concrete pavements and orthotropic steel deck bridges. *Transportation Research Record*, No. 2293, 1–7.

Bonati, A., Merusi, F., Bochicchio, G., Tessadri, B., Polacco, G., Filippi, S., and Giuliani, F. (2013). Effect of nanoclay and conventional flame retardants on asphalt mixtures fire reaction. *Construction and Building Materials*, 47, 990–1000.

Bonati, A., Merusi, F., Polacco, G., Filippi, S., and Giuliani, F. (2012). Ignitability and thermal stability of asphalt binders and mastics for flexible pavements in highway tunnels. *Construction and Building Materials*, 37, 660–668.

Bourbigot, S., Bras, M.L., Leeuwendal, R., Shen, K.K., Schubert, D. (1999). Recent advances in the use of zinc borates in flame retardancy of EVA. *Polymer Degradation and Stability*, 64 (3), 419–425.

Brewer, R.A. (1970). Epoxy-asphalt open-graded pavement as a skid-resistance treatment on the San Francisco Bay Bridge. Highway Research Board Special Report No. 116; San Francisco, USA.

British Standard Institute (BSI). 12697–18. (2004). Bituminous mixtures – test methods for hot mix asphalt – Part 18: Binder drainage. British Standard, London, UK.

Bucknall, C. B., and Gilbert, A. H. (1989). Toughening tetrafunctional epoxy resins using polyetherimide. *Polymer*, 30(2), 213-217.

Bucknall, C. B., and Dumpleton, P. (1987). Effects of loading history on fatigue crack growth in high density polyethylene and toughened poly (methyl methacrylate). *Polymer Engineering & Science*, 27(2), 110-115.

Cambridge Systematics. (2005). Cool pavement report. Draft report, EPA Cool Pavements Study, Task 5. Chevy Chase, Md., Washington, USA.

California Department of Transportation (Caltrans). (2010). Method of test for optimum bitumen content (OBC) for open graded friction course. California Test 368, Sacramento (California), USA.

Chaohui, W., Yi, F., Qian, C., Bao, C., and Liwei, Z. (2018). Application and research advances in epoxy asphalt concrete serving as deck pavement material. Materials Reports, 32(17): 2992-3009.

Chen X. (2009). On the fracture properties of epoxy asphalt mixture with SCB test. Taylor & Francis Group, ISBN 978-0-415-55854-9, London, UK, 531–540.

Chen, X., Qian, Z., Liu, X., and Lei, Z. (2012b). State of the art of asphalt surfacing on long-spanned orthotropic steel decks in China. *Testing and Evaluation (ASTM)*, 40(7), 1252-1259.

Chen, L., Qian, Z., and Hu, H. (2013). Epoxy asphalt concrete protective course used on steel railway bridge. *Construction and Building Materials*, 41, 125-130.

Chen, C., Eisenhut, W. O., Lau, K., Buss, A., and Bors, J. (2018a). Performance characteristics of epoxy asphalt paving material for thin orthotropic steel plate decks. *International Journal of Pavement Engineering*, 1-11.

Chen, R., Gong, J., Jiang, Y., Wang, Q., Xi, Z., and Xie, H. (2018c). Halogen-free flame retarded cold-mix epoxy asphalt binders: Rheological, thermal and mechanical characterization, *Construction and Building Materials*, 186, 863-870.

Chen, Z., Wang, T., Pei, J., Amirkhanian, S., Xiao, F., Ye, Q., and Fan, Z. (2019). Low temperature and fatigue characteristics of treated crumb rubber modified asphalt after a long-term aging procedure. *Cleaner Production*, 234,1262-1274.

Chen, R., Zhao, R., Liu, Y., Xi, Z., Cai, J., Zhang, J., ... & Xie, H. (2021a). Development of eco-friendly fire-retarded warm-mix epoxy asphalt binders using reactive polymeric flame retardants for road tunnel pavements. *Construction and Building Materials*, 284, 122752.

Chen, Y., Hossiney, N., Yang, X., Wang, H., & You, Z. (2021b). Application of epoxy-asphalt composite in asphalt paving industry: a review with emphasis on physicochemical properties and pavement performances. Advances in Materials Science and Engineering, 2021:1-35, Article ID 3454029, https://doi.org/10.1155/2021/3454029

Cong, P., Yu, J., Wu, S., and Luo, X. (2008). Laboratory investigation of the properties of asphalt and its mixtures modified with flame retardant. *Construction and Building Materials*, 22 (6), 1037–1042.

Cong, P. (2009). Preparation and properties of asphalt and its mixtures, Wuhan University of Technology, China.

Cong, P., Jianying, Y., and Shuanfa, C. (2010). Effects of epoxy resin contents on the rheological properties of epoxy-asphalt blends. *Applied Polymer Science*, 118(6), 3678-3684.

Cong, P., Chen, S., and Yu, J. (2011). Investigation of the properties of epoxy resin-modified asphalt mixtures for application to orthotropic bridge decks. *Applied Polymer Science*, 121(4), 2310-2316.

Cong, P., Liu, N., Shang, H., and Zhao, H. (2015). Rheological and fatigue properties of epoxy asphalt binder. *International Journal of Pavement Research and Technology*, 8(5), 370-376.

Cong, P., Luo, W., Xu, P., and Zhang, Y. (2019). Chemical and physical properties of hot mixing epoxy asphalt binders. *Construction and Building Materials*, 198, 1-9.

CROW. (2011). D11-01: Specification for runway surface dressings on airfields. The Netherlands.

Crucho, J. M. L., de Picado-Santos, L. G., das Neves, J. M. C., & Capitão, S. D. (2020). The TEAGE ageing method for asphalt mixtures. *Transportation Engineering*, 2, 100030.

Cubuk, M., Gürü, M., and Çubuk, M. K. (2009). Improvement of bitumen performance with epoxy resin. *Journal of Fuel*, 88(7), 1324-1328.

Danish Road Institute (DRI). (2005). Noise reducing pavements in Japan (Study Tour Report), Technical Note 31, Dansih Ministry of Transport and Energy, Copenhagen, Denmark.

Devulapalli, L., Kothandaraman, S., & Sarang, G. (2021). Fracture characterization of stone matrix asphalt mixtures incorporating reclaimed asphalt pavement and rejuvenator. *Journal of Materials in Civil Engineering*, 33(11), 04021320.

Dong, Z., and Li, L. P. (2015). *Study on dynamic mechanical properties and microstructure of epoxy asphalt. In 2015 International Conference on Applied Science and Engineering Innovation*. Atlantis Press.

Dubowik DA, Ross GC. (2001). A novel waterborne epoxy resin for zero-void, two component coating. In: 2000, International Waterborne High-Solids and Powder Coatings Symposium, New Orleans, USA.

EI Rahman, A. A., El-Shafie, M., and El Kholy, S. A. (2012). Modification of local asphalt with epoxy resin to be used in pavement. *Egyptian Journal of Petroleum*, 21(2), 139-147.

Elwardany, Michael D., Farhad Yousefi Rad, Cassie Castorena, and Y. Richard Kim. (2017). Evaluation of asphalt mixture laboratory long-term ageing methods for performance testing and prediction. *Road Materials and Pavement Design*, 18 (1), 28-61.

Flintsch, G. W., de Leon, E., McGhee, K. K., and AI-Qadi, I. L. (2003). Pavement surface macrotexture measurement and applications. *Transportation Research Record*, 1860(1), 168-177.

Forrest, E. (2002). A 21st birthday treat for Humber Bridge. Construction News. <http://www.cnplus.co.uk/news/a-21st-birthday-treat-for-humber-bridge/875234.article#.U_9HzfldXmd>. Accessed May 12, 2019.

Freudenstein, S. (2005). Modifications to getrac ballastless track approved. I*nternational Railway Journal*, 45 (3), 26-27.

Fuhaid, A. A., Lu, Q., and Luo, S. (2018). Laboratory Evaluation of biobased epoxy asphalt binder for asphalt pavement. *Materials in Civil Engineering (ASCE)*, 30(7),1-8.

Gaul R.W. (1996). Epoxy Asphalt Concrete–A polymer concrete with 25 years experience, properties and uses of polymers in concrete. Edited by Fontana J.J., Kaeding Al O.,Krauss P.D. American Concrete Institute Publication SP: 166, No. 13, p. 233-251.

Gendy, A. E., and Shalaby, A. (2007). Mean profile depth of pavement surface macrotexture using photometric stereo techniques. *Transportation Engineering*, 133(7), 433-440.

Georgia Department of Transportation (GDT). (2011). Determining optimum asphalt content for open-graded bituminous paving mixtures. GDT 114, Atlanta (Georgia), USA.

Gingras, J. P., Tanguy, P. A., Mariotti, S., and Chaverot, P. (2005). Effect of process parameters on bitumen emulsions. *Chemical Engineering and Processing: Process Intensification*, 44(9), 979-986.

Gong, J., Liu, Y., Wang, Q., Xi, Z., Cai, J., Ding, G., and Xie, H. (2019). Performance evaluation of warm mix asphalt additive modified epoxy asphalt rubbers. *Construction and Building Materials*, 204, 288-295.

Haider, S. W., Mirza, M. W., Thottempudi, A. K., Bari, J., and Baladi, G. Y. (2011). Characterizing temperature susceptibility of asphalt binders using activation energy for flow. I*n Transportation and Development Institute Congress 2011: Integrated Transportation and Development for a Better Tomorrow*. 493-503.

Hamzah, Meor O., Seyed R. Omranian, Ali Jamshidi, and Mohd R. M. Hasan. (2012). Simulating laboratory short term aging to suit Malaysian field conditions. World Academy of Science, Engineering and Technology, *International Journal of Civil, Architectural, Structural and Construction Engineering,* 6, 117-121.

Han, C., H. Li, and Y. Jia. (2010). Research of epoxy asphalt steel deck pavement disease based on normal inspection. *Highway Engineering*, Vol. 1, No. 36, 50–54. (In Chinese)

Herrington, P.R, and Alabaster, D. (2008). Epoxy modified open-graded porous asphalt. *Road Materials and Pavement Design*, 9(3), 481-498.

Herrington, P.R. (2010). Epoxy-modified porous asphalt, New Zealand Agency Transportation Report No.410, Wellington, New Zealand.

Hicks, R. G., Dussek, I. J., and Seim, C. (2000). Asphalt surfaces on steel bridge decks. *Transportation Research Record*, 1740(1), 135-142.

Hicks, C.G., Jacoben, K.F., and Hicks, R.G. (2012). Epoxy asphalt concrete (EAC) used to repave the Fremont bridge in Portland Oregon. Available from https://ine.uaf.edu/autc/files/2012/03/Hicks-Fremont-Bridge- Project-Write-Up-3-18-12-final-A-4.pdf

Holleran, G., Holleran, I., Bearsley, S., Dubois, C. J., and Wilson, D. (2017). Epoxy asphalt for durability of open graded mixes: part 1 performance approaches. *In 17th AAPA International Flexible Pavements Conference,* Australian Asphalt Paving Association, Melbourne, Australia, 13-16.

Huang, K., Xia, J. L., and Ding, H. Y. (2010). Properties of thermosetting epoxy asphalt materials prepared from modified epoxy resin. *Thermosetting Resin*, 25(1), 35-39.

Huang, M., and Huang, W. (2011). *Analyses of viscosity variation in solidifying procedure of epoxy asphalt. In Third International Conference on Transportation Engineering (ICTE) American Society of Civil Engineers China Communications and Transportation Association*.

Huang, W. (2015). Integrated design procedure for epoxy asphalt concrete–based wearing surface on long-span orthotropic steel deck bridges. *Materials in Civil Engineering (ASCE)*, 28(5), 04015189.

Huang, m., Wen, X., and Wang, L. (2017). Influence of foaming effect, operation time and health preserving properties of foam epoxy asphalt mixtures. *Construction and Building Materials*, 151, 931-938.

Huang, W., Guo, W., and Wei, Y. (2019). Thermal effect on rheological properties of epoxy asphalt mixture and stress prediction for bridge deck paving. *Materials in Civil Engineering (ASCE)*, 31(10), 04019222.

Huang, Q., Qian, Z., Chen, L., Zhang, M., Zhang, X., Sun, J., and Hu, J. (2020). Evaluation of epoxy asphalt rubber with silane coupling agent used as tack coat for seasonally frozen orthotropic steel bridge decks. *Construction and Building Materials*, 241, 117957.

Hulsey, J. L., Yang, L., and Raad, L. (1999). Wearing surfaces for orthotropic steel bridge decks. *Transportation Research Record*, 1654(1), 141-150.

Hu, J., Qian, Z., Xue, Y., and Yang, Y. (2016). Investigation on fracture performance of lightweight epoxy asphalt concrete based on microstructure characteristics. *Materials in Civil Engineering (ASCE)*, 28(9), 04016084.

Hu, C., Zhao, J., Leng, Z., Partl, M. N., and Li, R. (2019a). Laboratory evaluation of waterborne epoxy bitumen emulsion for pavement preventative maintenance application. *Construction and Building Materials*, 197, 220-227.

Ismael, M., Fattah, M. Y., & Jasim, A. F. (2022). Permanent Deformation characterization of stone matrix asphalt reinforced by different types of fibers. *Journal of Engineering*, 28(2), 99-116.

Iwasaki., O. (1997). Field measurement and fatigue assessment of orthotropic steel deck with asphalt pavement. *Structural Mechanics and Earthquake Engineering*, No.563-39, 161-171.

Jackson, M. B., Edmond, L. N., Varley, R. J., and Warden, P. G. (1993). Toughening epoxy resins with polyepichlorohydrin. *Applied Polymer Science*, 48(7), 1259-1269.

Jamshidi, A., Hamzah, M. O., & Aman, M. Y. (2012). Effects of Sasobit® content on the rheological characteristics of unaged and aged asphalt binders at high and intermediate temperatures. *Materials Research*, 15(4), 628-638.

Jamshidi, A., Hasan, M. R. M., Yao, H., You, Z., and Hamzah, M. O. (2015). Characterization of the rate of change of rheological properties of nano-modified asphalt. Construction and Building Materials, 98, 437-446.

Jamshidi, A., Kurumisawa, K., Nawa, T., and Igarashi, T. (2016). Performance of pavements incorporating waste glass: The current state of the art. *Renewable and Sustainable Energy Reviews*, 64, 211–236.

Jamshidi, A., Kurumisawa, K., Nawa, T., Jize, M., and White, G. (2017). Performance of pavements incorporating industrial byproducts: A state-of-the-art study. *Cleaner Production*, 164, 367-388.

Jamshidi, A., White, G., Hosseinpour, M., Kurumisawa, K., and Hamzah, M. O. (2019). Characterization of effects of reclaimed asphalt pavement (RAP) source and content on dynamic modulus of hot mix asphalt concrete. *Construction and Building Materials*, 217, 487-497.

Jamshidi, A., White, G., and Kurumisawa, K. (2021). Rheological characteristics of epoxy asphalt binders and engineering properties of epoxy asphalt mixtures–state-of-the-art. *Road Materials and Pavement Design*, 1-24.

Japan Road Association. (2006). Evaluation methods for pavement performance, Tokyo, Japan. (In Japanese).

Japan Road Association. (2009). Guidebook for eco-friendly pavement technologies, Tokyo, Japan. (In Japanese)

Jia, X., Huang, B., Chen, S., and Shi, D. (2016). Comparative investigation into field performance of steel bridge deck asphalt overlay systems. *KSCE Journal of Civil Engineering*, 20(7), 2755-2764.

Jin, J., Xiao, T., Tan, Y., Zheng, J., Liu, R., Qian, G., ... and Zhang, J. (2018). Effects of TiO2 pillared montmorillonite nanocomposites on the properties of asphalt with exhaust catalytic capacity. *Cleaner Production*, 205, 339-349.

Joseph, A.H. (1965). Behavior of epoxy-asphalt airfield pavements 1963 inspections. Miscellaneous Paper No. 4–704, USA Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, USA.

Kandhal, P. S., and Mallick, R. B. (1998). Open graded friction course: state of the practice. Transportation Research Board, National Research Council, Washington D.C. USA.

Katagiri, H., Maeno, H., Tokumitsu, K., and Iida, R. (2010). Application of epoxy asphalt mixture to the binder course in orthotropic steel deck pavement. *11th International Symposium of Asphalt Pavements (ISAP)*, Nagoya, Japan.

Kawakami., A. and Kubo, K. (2008). Accelerated loading test on durability of cool pavement in PWRI, *the 3rd International Conference on Accelerated Pavement Testing*, Madrid, Spain, 1-25.

Ke, X. (2008). Preparation and properties of epoxy modified asphalt. Master Thesis, Wuhan University of Technology, Wuhan, China.

Khattak, M. J., and Alrashidi, M. (2013). Performance of preventive maintenance treatments of flexible pavements. *International Journal of Pavement Research and Technology*, 6(3), 184-196.

Kim, D. S., Cho, K., Kim, J. K., and Park, C. E. (1996). Effects of particle size and rubber content on fracture toughness in rubber-modified epoxies. *Polymer Engineering & Science*, 36(6), 755-768.

Kim, J.S., Chin, I.J., Lee, B.S. (2000). Curing of DGEBA epoxy with modified low- temperature curing agents, Environmental Sciences and Pollution Management, Seoul, Korea.

Kim, T. W., Baek, J., Lee, H. J., and Lee, S. Y. (2014). Effect of pavement design parameters on the behaviour of orthotropic steel bridge deck pavements under traffic loading. *International Journal of Pavement Engineering*, 15(5), 471-482.

Kubo., K. (2011a). Present status of porous elastic rubber (PERS) in Japan. INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Vol: (4), Institute of Noise Control Engineering, Osaka, Japan, 3147-3153.

Kubo., K, Terada., M and Watanabe., K. (2011b). Evaluation methods of road surface performance in Japan, *the 3rd International Road Surface Friction Conference*, Gold Coast, Australia, 1-12.

Laxal, J. (2013). Orthotropic deck wear surface system selection lions gate bridge north approach viaduct, Vancouver BC. *The Conference and Exhibition of the Transportation Association of Canada-Transportation: Better-Faster-Safer*, Winnipeg, Manitoba, Canada.

Lay, M., Metcalf, J., & Sharp, K. (2020). Paving Our Ways: A History of the World's Roads and Pavements. CRC Press, New York, USA.

Lee, S. H., Hsiao, T. Y., and Lee, G. S. (2015). Audio–vocal responses of vocal fundamental frequency and formant during sustained vowel vocalizations in different noises. *Hearing Research*, 324, 1-6.

Leng, Z., and Yu, H. (2016). Novel method of coating titanium dioxide on to asphalt mixture based on the breath figure process for air-purifying purpose. *Materials in Civil Engineering (ASCE)*, 28(5), 04015188.

Liao, M., and Luo, R. (2022). Influencing factors and mechanisms of blistering in epoxy asphalt mixtures for steel deck pavements. *Construction and Building Materials,* 316, 126036.

Liu, W., Wang, S., Zhang, J., and Fan, J. (2015). Photocatalytic degradation of vehicle exhausts on asphalt pavement by TiO2/rubber composite structure. *Construction and Building Materials*, 81, 224-232.

Liu, Y., Zhang, J., Jiang, Y., Li, C., Xi, Z., Jun Cai, J., and Xie, H. (2018a). Investigation of secondary phase separation and mechanical properties of epoxy SBS-modified asphalts. *Construction and Building Materials*, 165, 163-172.

Liu, Y., Qian, Z. D., Zheng, D., and Huang, Q. B. (2018b). Evaluation of epoxy asphalt-based concrete substructure for high-speed railway ballastless track. *Construction and Building Materials*, 162, 229-238.

Li, H., Y. Guan, and Jia., Y. (2010). Research on long-term behavior of epoxy asphalt deck surfacing. *Chinese and Foreign Highway*, Vol. 6, No. 30, 2010, 230–233.

Li, Q., Ding, H., Rahman, A., and He, D. (2016). Evaluation of Basic Oxygen Furnace (BOF) material into slag-based asphalt concrete to be used in railway substructure. *Construction and Building Materials*, 115, 593-601.

Li, R., Leng, Z., Zhang, Y., and Ma, X. (2019). Preparation and characterization of waterborne epoxy modified bitumen emulsion as a potential high-performance cold binder. *Cleaner Production*, 235, 1265-1275.

Li, H. (2012). Evaluation of cool pavement strategies for heat island mitigation. University of California, Davis, USA.

Li, Mingyue, Zhaohui Min, Qichang Wang, Wei Huang, and Zhiyong Shi. (2022a). Effect of epoxy resin content and conversion rate on the compatibility and component distribution of epoxy asphalt: A MD simulation study. *Construction and Building Materials* 319: 126050.

Li, X., Shen, J., Ling, T., and Yuan, F. (2022b). Fatigue Properties of Aged Porous Asphalt Mixtures with an Epoxy Asphalt Binder. *Materials in Civil Engineering (ASCE),* 34(3), 04021488.

Luo, S., Qian, Z. D., and Harvey, J. (2013). Experiment on fatigue damage characteristics of epoxy asphalt mixture. *China Journal of Highway and Transport*, 26(2), 20-25.

Luo, S., Lu, Q., and Qian, Z. (2015). Performance evaluation of epoxy modified open-graded porous asphalt concrete. *Construction and Building Materials*, 76, 97-102.

Lu, W.M. (1994). Research and application of epoxy asphalt concrete material at home and abroad, *Chinese Petroleum Asphalt*, 3, 11-15. (In Chinese)

Lu, W.M., Guo Z.Y., Wang X.L., Li J.H. (1996). Characteristic performance and application of cold mix epoxy asphalt. *East China Highway*. No. 2 (Total No. 99); p. 64–68.

Lu, Q., Kohler, E., Harvey, J., Ongel, A. (2009). Investigation of noise and durability performance trends for asphaltic pavement surface types: three-year results. California: University of California Pavement Research Center; 2009 [UCPRC-RR-2009-01].

Lu, Q., and Bors, J. (2015). Alternate uses of epoxy asphalt on bridge decks and roadways. *Construction and Building Materials*, 78, 18-25.

Lu, Q., Xin, C., Alamri, M., & Alharthai, M. (2021). Development of porous asphalt mixture with bio-based epoxy asphalt. *Cleaner Production*, 128404.

Maggenti, R., and Shatnawi, S. (2017). Initial and replacement riding surface for the orthotropic San Mateo/Hayward Bridge. *Bridge Structures*, 13, 81–92.

Mamlouk, M. S., and Dosa, M. (2014). Verification of effectiveness of chip seal as a pavement preventive maintenance treatment using LTPP data. *International Journal of Pavement Engineering*, 15(10), 879-888.

Mangus, A.R. and Sun, S. (2000). Orthotropic deck bridges. bridge engineering handbook. Ed. Wai-Fah Chen and Lian Duan Boca Raton: CRC Press, New York, USA.

Matsukawa et al. (1983). Study on the strain behaviour of the steel plate deck pavement using epoxy Asphalt concrete, *Proceeding of 15th Japan Road Congress*, Tokyo, Japan, 385- 386.

Miao, Y., Wang, S., Sun, F., & Yang, J. (2022). A laboratory investigation into the polishing behavior of stone matrix asphalt with different lithology types of coarse aggregates. *Journal of Testing and Evaluation*, 50(5).

Miller, J. S., and Bellinger, W. Y. (2003). Distress identification manual for the long-term pavement performance program. Rep. No. FHWARD- 03-031, Federal Highway Administration, Washington, DC, USA.

Min, Z., Xia, Y., Li, X., and Tao, Z. (2017). Performances evaluation of epoxy asphalt mixture containing snow-melting agent. *Construction and Building Materials*, 155, 762-769.

Min, Z., Zhou, L., Wang, Q., and Zhang, Y. (2019). Performance Evaluation of epoxy-asphalt mixture blended with glass aggregate. *Materials in Civil Engineering (ASCE)*, 31(6), 04019083.

Min, Z., Sun, L., Wang, Q., and Yu, Z. (2020). Influence of aggregate packing on the performance of uncured and cured epoxy asphalt mixtures. *Materials in Civil Engineering (ASCE)*, 32(5), 04020103.

Mitchell, J.W. (2014). The history and future trends of non-halogenated flame retarded polymers, in: A.B. Morgan, C.A. Wilkie (Eds.), Non-Halogenated Flame-Retardant Handbook, John Wiley & Sons, Inc., 1–16.

Mirwald, J., Maschauer, D., Hofko, B., & Grothe, H. (2020). Impact of reactive oxygen species on bitumen aging–The Viennese binder aging method. *Construction and Building Materials*, 257, 119495.

Mo, L. T., Fang, X., Yan, D. P., Huurman, M., & Wu, S. P. (2012). Investigation of mechanical properties of thin epoxy polymer overlay materials upon orthotropic steel bridge decks. *Construction and Building Materials*, 33, 41-47.

Momoya, Y., and Sekine, E. (2004). Reinforced roadbed deformation characteristics under moving wheel loads. Quarterly Report of RTRI, 45(3), 162-168.

Moriyoshi, A., Jin, T., Nakai, T., Ishikawa, H., Tokumitsu, K., and Kasahara, A. (2014). Construction and pavement properties after seven years in porous asphalt with long life. *Construction and Building Materials*, 50, 401-413

Morrison, G. R., and Hesp, S. A. M. (1995). A new look at rubber-modified asphalt binders. *Materials Science*, 30(10), 2584-2590.

Nai-sheng, G., Ying-hua, Z., and Lue-lun, S. (2006). Effect of fiber contents on toughness of polyester fiber asphalt concrete. *Traffic and Transportation Engineering*, 4.

Nguyen, Q. T., & Tran, T. C. H. (2021). *Experimental investigation of fatigue behavior for polymer modified asphalt and epoxy asphalt mixtures. In Proceedings of the 3rd International Conference on Sustainability in Civil Engineering*, Springer, Singapore, 161-166.

Nicholas, R.F. (2009). Comparison of macrotexture measurement methods, civil and environmental engineering and geodetic science. Master Thesis, The Ohio State University, USA.

Nie, Wen, Duanyi Wang, Yangguang Sun, Wei Xu, and Xiaoquan Xiao. (2022). Integrated design of structure and material of epoxy asphalt mixture used in steel bridge deck pavement. *Buildings* 12, no. 1: 9.

Nunn, M. E., Brown, A., Weston, D., and Nicholls, J. C. (1997). Design of long-life flexible pavements for heavy traffic. Transportation Research Laboratory, ISSN 0968-4107, London, UK.

Oden, J. T., and Martins, J. A. C. (1985). Models and computational methods for dynamic friction phenomena. *Computer Methods in Applied Mechanics and Engineering*, 52(1-3), 527-634.

Ongel, A., Harvey J, Kohler, E., Lu, Q., Steven, B. (2008). Investigation of noise, durability, permeability, and friction performance trends for asphaltic pavement surface mix types: first- and second-year results. California: University of California Pavement Research Centre [UCPRC-RR-2007-03].

Pack, S. (2015). A review of non-halogen flame retardants in epoxy-based composites and nanocomposites: flame retardancy and rheological properties, in: P.M. Visakh, Y. Arao (Eds.), Flame Retardants: Polymer Blends, Composites and Nanocomposites, *Springer International Publishing, Cham*, 115–130.

Possehl Spezialbau. (2022). POSSEHL ANTISKID®: The special High-Friction Surface for takeoff and landing runways, available through https://www.possehl-spezialbau.de/fileadmin/Download/Prospekte/POSSEHL_Folder_Antiskid_E_0417_w.pdf

Put., R. (2006). Managing the risks of an international brand name. Master Thesis. University of Twente, Netherland.

Qian, Z., Chen, L., Jiang, C., and Luo, S. (2011). Performance evaluation of a lightweight epoxy asphalt mixture for bascule bridge pavements. *Construction and Building Materials*, 25(7), 3117-3122.

Qian, Z., Chen, C., Jiang, C., and de Fortier Smit, A. (2013). Development of a lightweight epoxy asphalt mixture for bridge decks. *Construction and Building Materials*, 48, 516-520.

Qian, Z., and Lu, Q. (2014). Design and laboratory evaluation of small particle porous epoxy asphalt concrete (No. 14-2354). *Transportation Research Record*, Washington D.C., USA.

Qian, Z. D., Wang, J. Y., Chen, L. L., and Wang, L. B. (2014). Three-dimensional discrete element modelling of crack development in epoxy asphalt concrete. *Testing and Evaluation (ASTM)*, 43(2), 1-13.

Qian, Z., and Lu, Q. (2015). Design and laboratory evaluation of small particle porous epoxy asphalt surface mixture for roadway pavements. *Construction and Building Materials*, 77, 110-116.

Rebbechi J.J. (1980). Epoxy asphalt surfacing of West Gate Bridge, *Proceedings of the 10th Australian Road Research Board Conference*, Sydney, Australia, Vol. 10, Part 3, 136-146.

Read, J., Whiteoak, D., and Hunter, R. N. (2016). The shell bitumen handbook. Thomas Telford Publication, London, UK.

Rebbechi, J., and Lancaster, J. (1994). Resurfacing of steel bridge decks. Conference Proceedings: 9th Australian Asphalt Pavement Association (AAPA). *International Asphalt Conference*, Surfers Paradise, Queensland, Australia.

Ren, R., X. Zhang, X., Z. Wei, Z., J. Chen, J., D. Dong, D., X. Li, X., L. and Zhang, L. (2013). Effect of particle size and content of magnesium hydroxide on flame retardant properties of asphalt. *Applied Polymer Science*, 129 (4), 2261–2272.

Ren, S., Liu, X., Lin, P., Jing, R., & Erkens, S. (2022). Toward the long-term aging influence and novel reaction kinetics models of bitumen. *International Journal of Pavement Engineering*, 1-16.

Rooijen., V and De Bondt, C. (2004). Performance evaluation of jet fuel resistant polymer-modified asphalt for airport pavements. Federal Aviation Administration Worldwide Airport Transfer Conference, Washington DC, USA.

Rossi, F., Castellani, B., Presciutti, A., Morini, E., Anderini, E., Filipponi, M., & Nicolini, A. (2016). Experimental evaluation of urban heat island mitigation potential of retro-reflective pavement in urban canyons. *Energy and Buildings*, 126, 340-352.

Saed, S. A., Kamboozia, N., & Mousavi Rad, S. (2022). Performance evaluation of stone matrix asphalt mixtures and low-temperature properties of asphalt binders containing reclaimed asphalt pavement materials modified with nanosilica. *Journal of Materials in Civil Engineering*, 34(1), 04021380.

Sang, L. U. O., & Zhen-dong, Q. I. A. N. (2012). Experimental research on surface characteristics of epoxy asphalt concrete pavement. Beijing University of Technology, Beijing, China.

Seim, C. (1979). An Innovative Pavement System for Long Span Bridge Decks. In Preprint 3771, *American Society of Civil Engineering (ASCE)*, Convention, Atlanta, GA, USA.

Seim., C, and Tim Ingham. (2004). Influence of wearing surfacing on performance of orthotropic steel plate decks. *Transportation Research Record*,1892, no. 1, 98-106.

Shao, W. X., & Zhou, B. J. (2021, June). Study on performance of new type cold mix epoxy asphalt and mixture for steel deck pavement. *In IOP Conference Series: Earth and Environmental Science* (Vol. 787, No. 1, p. 012004). IOP Publishing.

Simpson, W.C., Sommer H.J., Griffin R.L., and Miles T. K. (1960). Epoxy asphalt concrete for airfield pavements. Journal of the Air Transport Division, *Proceedings of the American Society of Civil Engineer*, vol. 86, No. AT 1; p. 57–71.

Si,J., Jia,Z., Wanga, J., Yu, X., Li,Y., Dong, F., and Jiang, R. (2018). Comparative analysis of cold-mixed epoxy and epoxy SBS-modified asphalts: Curing rheology, thermal, and mechanical properties, *Construction and Building Materials*, 176, 165-171.

Si, J., Wang, J., Yu, X., Ding, G., Ruan, W., Xing, M., and Xie, R. (2022). Influence of thermal-oxidative aging on the mechanical performance and structure of cold-mixed epoxy asphalt. *Cleaner Production,* 130482.

SP-2. (2000). Superpave mix design, Superpave Series. Lexington, KY, USA.

SP-1. (2001). Superpave performance graded asphalt binder specifications and testing, Superpave Series. Lexington, KY, USA.

Steiner, D., Hofko, B., Hospodka, M., Handle, F., Grothe, H., Füssl, J., ... & Blab, R. (2016). Towards an optimised lab procedure for long-term oxidative ageing of asphalt mix specimen. I*nternational Journal of Pavement Engineering*, 17(6), 471-477.

Sun, X., Qin, X., Chen, Q., and Ma, Q. (2018b). Investigation of enhancing effect and mechanism of basalt fiber on toughness of asphalt material. *Petroleum Science and Technology*, 36(20), 1710-1717.

Sun, Y., Liu, Y., Gong, J., Han, X., Xi, Z., Zhang, J., ... & Xie, H. (2021). Thermal and bonding properties of epoxy asphalt bond coats. *Journal of Thermal Analysis and Calorimetry*, 1-13.

Šušteršicˇ, E., Tušar, M., and Zupanc, A. (2014). Valant, Asphalt concrete modification with waste PMMA/ATH. *Materials and Structure*, 47 (11),1817–1824.

Takahashi, M., and Shimazaki, M., and Aoki, M. (2010). Applicability of bright-colored epoxy asphalt mixture for repair of concrete pavements in tunnels, 1*1th International Symposium of Asphalt Pavements (ISAP)*, Nagoya, Japan.

Taniguchi., Ito., Nomura., and Abe., 2003. Developments a study on creating method of performance curve using pavement data base in MLIT-PMS. Pavement Engineering, Japan Society of Civil Engineering (JSCE), Tokyo, Japan.

Toan, DV. (2005). Runway friction performance in NZ, In: International conference on surface friction for road and runways. Christchurch, New Zealand.

Toro, C., Jobson, B. T., Haselbach, L., Shen, S., and Chung, S. H. (2016). Photoactive roadways: Determination of CO, NO and VOC uptake coefficients and photolabile side product yields on TiO2 treated asphalt and concrete. Atmospheric Environment, 139, 37-45.

Touran, A., and Okereke, A. (1991). Performance of orthotropic bridge decks. *Performance of Constructed Facilities*, 5(2), 134-148.

Tran, N., Powell, B., Marks, H., West, R., and Kvasnak, A. (2009). Strategies for design and construction of high-reflectance asphalt pavements. *Transportation Research Record*, 2098(1), 124-130.

Ullidtz, P. (1998). Modelling flexible pavement response and performance, Tech Univ. of Denmark Polytekn, Copenhagen, Denmark.

Van Leest AJ, and Gaarkeuken G. (2005). The F.O.D. resistance of surface layers on airfields in the Netherlands; in situ and laboratory testing. FAA Airport Technology Transfer Conference, Atlantic City, New Jersey, USA.

Vyrozhemskyi, V., Kopynets, I., Kischynski, S., and Bidnenko, N. (2017). *Epoxy asphalt concrete is a perspective material for the construction of roads, IOP Conference Series: Materials Science and Engineering. Building up Efficient and Sustainable Transport Infrastructure (BESTInfra2017),* Prague, Czech Republic.

Wang, H, Al-Qadi, I.L., and Stanciulescu, I. (2010). Effect of friction on rolling tire – pavement interaction, in: USDOT Region V Regional University Transportation Center Final Report, Washington DC, USA.

Wan, J., Gan, B., Li, C., Molina-Aldareguia, J., Li, Z., Wang, X., and Wang, D. Y. (2015). A novel biobased epoxy resin with high mechanical stiffness and low flammability: synthesis, characterization and properties. *Materials Chemistry A*, 3(43), 21907-21921.

Wang, D., Leng, Z., Hüben, M., Oeser, M., and Steinauer, B. (2016). Photocatalytic pavements with epoxy-bonded TiO2-containing spreading material. Construction and Building Materials, 107, 44-51.

Wang, Z., and Zhang, S. (2018). Fatigue endurance limit of epoxy asphalt concrete pavement on the deck of long-span steel bridge. *International Journal of Pavement Research and Technology*, 11(4), 408-415.

Wang, X., Wu, R., and Zhang, L. (2019). Development and performance evaluation of epoxy asphalt concrete modified with glass fibre. *Materials and Pavement Design*, 20(3), 715-726.

Wang, X., Ma, B., Chen, S., Wei, K., & Kang, X. (2021). Properties of epoxy-resin binders and feasibility of their application in pavement mixtures. *Construction and Building Materials*. 295, 123531.

Weil, E.D., and Levchik, S.V. (2016). Flame retardants for plastics and textiles: Practical applications, second ed., Hanser Publishers, Munich, Germany.

White, G. (2017). Airfield pavement essentials. Airport Practice Note 12, Australian Airport Association, Canberra, Australia.

Wilding, R., Wagner, B., Seuring B., and Gold, S. (2012). Conducting content-analysis based literature reviews in supply chain management, *Supply Chain Management*, 17 (5), 544–555.

Widyatmoko, I., Zhao, B., Elliot, R. C., and Lloyd, W. G. (2006a). Curing characteristics and the performance and durability of epoxy asphalts. In Proceedings of the 10th Conference on Asphalt Pavements, Quebec, Canada, 12-17.

Widyatmoko, I., Elliott, R.C., and Lloyd, W.G. (2006b). Development of long-life deformation resistant hot rolled asphalt surfacing, *Asphalt Professional* No:18, ISSN 1479-6341.

Wu, J., Wang, X., Wang, L., Zhang, L., Xiao, Q., & Yang, H. (2020). Temperature correction and analysis of pavement skid resistance performance based on riohtrack full-scale track. *Coatings,* 10(9), 832.

Wu, J.P., Herrington, P.R., and Alabaster, D. (2017). Long-term durability of epoxy-modified open-graded porous asphalt wearing course. *International Journal of Pavement Engineering*, 20:8, 920-927,

Xiaoning, Z., Shunxian, Z., and Wei, X. (2012). Application performance-based design of epoxy asphalt concrete applied to steel bridge deck pavement. *Southern China University Technology*, (Nat. Sci. Ed.), 40 (7), 1-7.

Xiao, Y., Van de Ven, M. F. C., Molenaar, A. A. A., Su, Z., and Chang, K. (2013). Design approach for epoxy modified bitumen to be used in antiskid surfaces on asphalt pavement. *Construction and Building Materials*, 41, 516-525.

Xiang, Q., and Xiao, F. (2020). Applications of epoxy materials in pavement engineering. *Construction and Building Materials*, 235, 117529.

Xue, Y., and Qian, Z. (2016). Development and performance evaluation of epoxy asphalt concrete modified with mineral fiber. *Construction and Building Materials*, 102, 378-383.

Xu, T., Huang, X., and Zhao, Y. (2011). Investigation into the properties of asphalt mixtures containing magnesium hydroxide flame retardant. *Fire Safety*, 46 (6), 330–334.

Xu, P., Cong, P., Li, D., and Zhu, X. (2016). Toughness modification of hyperbranched polyester on epoxy asphalt. *Construction and Building Materials*, 122, 473-477.

Xu, P., Zhu, X., Cong, P., Du, X., and Zhang, R. (2018). Modification of alkyl group terminated hyperbranched polyester on paving epoxy asphalt. *Construction and Building Materials*, 165, 295-302.

Xu, X., Yang, X., Huang, W., Xiang, H., and Yang, W. (2019). New damage evolution law for steel–asphalt concrete composite pavement considering wheel load and temperature variation. *Materials*, 12(22), 3723.

Xu, J., Ma, B., Mao, W., & Wang, X. (2021). Strength characteristics and prediction of epoxy resin pavement mixture. *Construction and Building Materials*, 283, 122682.

Xu, P., Du, X., Cong, P., and Zhou, Z. (2022). Properties of paving epoxy asphalt with epoxy-terminated hyperbranched polyester. *Road Materials and Pavement Design,* 23(1), 234-246.

Yang, Y., Qian, Z., and Song, X. (2015). A pothole patching material for epoxy asphalt pavement on steel bridges: Fatigue test and numerical analysis. *Construction and Building Materials*, 94, 299-305.

Yao, B., Cheng, G., Wang, X., Cheng, C., and Liu, S. (2013a). Linear viscoelastic behaviour of thermosetting epoxy asphalt concrete – experiments and modelling. *Construction and Building Materials*, 48, 540-547.

Yao, B., et al., (2013b). Research on the dynamic bending behavior of a composite beam model for the asphalt overlay on steel bridge deck. *Transportation Research Board 92th Annual Meeting*, Washington, USA.

Yao, B., Li, F., and Chen, J. (2016). Experimental study on the low temperature performance of an epoxy asphalt binder and mixture. *Fourth Geo-China International Conference Shandong University Shandong Department of Transportation University of Oklahoma, Chinese National Science Foundation*, American Society of Civil Engineers (ASCE), Shandong, China.

Yao, B., Chen, C., and Loh, K. J. (2019). Performance characteristics of diluted epoxy asphalt binders and their potential application in chip seal. *Materials in Civil Engineering (ASCE)*, 31(12), 04019290.

Yi, Xingyu, Huimin Chen, Houzhi Wang, Chenguang Shi, and Jun Yang. (2022), The feasibility of using epoxy asphalt to recycle a mixture containing 100% reclaimed asphalt pavement (RAP). *Construction and Building Materials,* 319 (2022): 126122.

Yin, H., Zhang, Y., Sun, Y., Xu, W., Yu, D., Xie, H., and Cheng, R. (2015). Performance of hot mix epoxy asphalt binder and its concrete. *Materials and Structures*, 48(11), 3825-3835.

Yin, C., Zhang, H., and Pan, Y. (2016). Cracking mechanism and repair techniques of epoxy asphalt on steel bridge deck pavement. *Transportation Research Record*, 2550(1), 123-130.

Young, Logan M., and Stephan A. Durham. (2012). Performance of an anti-icing epoxy overlay on asphalt surfaces. *Performance of Constructed Facilities*, 27, no. 6: 836-840.

Yu, J., Cong, P., and Wu, S. (2009a). Laboratory investigation of the properties of asphalt modified with epoxy resin. Applied Polymer Science, 113(6), 3557-3563.

Yu, J., Cong, P., and Wu, S. (2009b). Investigation of the properties of asphalt and its mixtures containing flame retardant modifier. *Construction and Building Materials*, 23 (6), 2277– 2282.

Zegard, A., Smal, L., Naus, R., Apostolidis, P., Liu, X., van de Ven, M., ... & Scarpas, A. (2019). Field trials with epoxy asphalt for surfacing layers: province of North Holland case study. *In Transportation Research Board 98th Annual Meeting. Transportation Research Board (TRB)*.Washington DC, USA.

Zhao, Y., Jiang, J., Ni, F., and Zhou, L. (2019). Fatigue cracking resistance of engineered cementitious composites (ecc) under working condition of orthotropic steel bridge decks pavement. *Applied Sciences*, 9(17), 3577.

Zhang Y, Pan X, Sun Y, Xu W, Pan Y, and Xie H, et al. (2014b). Flame retardancy, thermal, and mechanical properties of mixed flame-retardant modified epoxy asphalt binders. *Construction and Building Materials*, 68:62–7.

Zhang, H., Yu, J., and Zhu, C. (2015). Flame retardants in bitumens and nanocomposites, in: P.M.

Zhang, X., Sühring, R., Serodio, D., Bonnell, M., Sundin, N., and Diamond, M.L. (2016a). Novel flame retardants: estimating the physical–chemical properties and environmental fate of 94 halogenated and organophosphate PBDE replacements, *Chemosphere*, 144, 2401–2407.

Zhang, H., Hao, P. W., and Zhang, H. W. (2016b). Initiation and propagation mechanism of blisters on the epoxy asphalt concrete paving course of steel deck bridge pavement. *Beijing University of Technology*, 42(5), 737-741.

Zhang, Q., Xu, Y-H., and WenbIn, Z-G. (2017). Influence of water-borne epoxy resin content on performance of waterborne epoxy resin compound SBR modified emulsified asphalt for tack coat. *Construction and Building Materials*, 153: 774-782.

Zhang, Z., Wang, S., and Lu, G. (2018a). Properties of new cold patch asphalt liquid and mixture modified with waterborne epoxy resin. *International Journal of Pavement Engineering*, 1-11.

Zhang, X. F., Qian, Z. D., & Gao, H. (2018b). *Life-Cycle environmental impact assessment of steel bridge deck pavement. In Developments in International Bridge Engineering: Istanbul Bridge Conference*, Istanbul, Turkey, 223-233.

Zhang, Y. H., Qian, Z. D., Chen, L. L., Liu, Y., Zhang, H., and Zhang, X. (2022). Impact of train vibration on physical and mechanical properties of epoxy asphalt concrete in the road-railway bridge. *Construction and Building Materials,* 317, 125637.

Zheng, D., Qian, Z. D., Liu, Y., and Liu, C. B. (2018). Prediction and sensitivity analysis of long-term skid resistance of epoxy asphalt mixture based on GA-BP neural network. *Construction and Building Materials*, 158, 614-623.

Zheng., W. (2015). Research on deployment technology and performance of epoxy asphalt and thermoplastic bitumen, Master Thesis, Southeast University, Nanjing, China.

Zhong, K., Yang, X., and Wei, X. (2017). Investigation on surface characteristics of epoxy asphalt concrete pavement. International Journal of Pavement Research and Technology, 10(6), 545-552.

Zhu, C. (2013). Japan TAF epoxy asphalt concrete design and steel bridge deck pavement construction technology. In Applied Mechanics and Materials. Transportation Technical Publications, Genev, Switzerland, 330, 905-910.

Zhu, J., Chen, Z, Min, Z., Huang, W., and Wang, J. (2004). Study on epoxy resin modified asphalt materials for highway. *South East University (Natural Science Edition)*, 515-517 (In Chinese).