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Rheological Characteristics of Epoxy Asphalt Binders and Engineering Properties of Epoxy Asphalt Mixtures- State-of-the-Art

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Abstract

The asphalt industry is aiming to produce high quality materials and efficient technologies for pavement construction. One such technology that attracts attention is epoxy asphalt. This paper discussed the concepts, theories, and engineering properties of epoxy asphalt technology and products. As the initial step, the chemical structure of epoxy materials was explained. Then principles of epoxy asphalt technology were discussed. Subsequently, the rheological characteristics of epoxy asphalt binder (EAB) were characterized. Engineering properties of an epoxy asphalt mixture (EAM) were then evaluated. The results indicated that EAB has better rheological properties than the traditional modified and net asphalts. Moreover, the results showed that superior structural performance of EAM compared with the traditional hot and warm mixtures. However, recyclability, initial strength, and total cost of the pavement construction remain matters of concern.

1.Introduction

The asphalt manufacturing industry is currently faced with two challenges. The first one being the preference of oil refineries to produce high value-added products as opposed to low quality materials used as asphalt binders. A reasonable explanation may be related to the lack of oil pressure in the oil fields. Therefore, the production of binders is not the main priority for many refineries. As the main source of industrial fuel in the plants and raw material of asphalt binder, a lack of crude oil results in an increase in asphalt mix production costs.

The second challenge is that asphalt binder consumption is dramatically increasing due to the rapid development of transportation infrastructure worldwide. Therefore, various types of binders are required to meet all the requirements of utility conditions. At first glance, the higher demand for asphalt binders is an opportunity for the asphalt industry, but the production of many high quality binders using the limited sources of bitumen and carbon-based energy carriers are bottlenecks of the asphalt manufacturing industry. It is necessary to develop various technologies, additives, and recycling methods to cater the asphalt mix to paving projects to address the challenge. For example, various types of polymers are used to modify binders. These polymers can be divided into two main groups: elastomers and plastomers (Polacco *et al.* 2005, Sengoz *et al.* 2009). The elastomers, such as styrene-butadiene-styrene (SBS) and styrene-isoprenestyrene, modified binder produces asphalt mixtures with good elastic performance, enhanced cracking resistance, and improved complex modulus (Yildirim 2007).

The plastomers (e.g., polyethylene, polypropylene, and ethylene-vinyl acetate copolymer (EVA)) used for binder modification produce asphalt mixtures with higher stiffness and good rutting performance (Sureshkumar *et al.* 2010, Fuentes-Auden *et al.* 2008). Although the plastomer- or elastomer-modified asphalt mixes meet many structural requirements of pavements, there are still some drawbacks, such as limited improvement in elasticity, storage stability, and high thermal sensitivity (Lu and Isacsson 2001, Zhu *et al.* 2013).

The asphalt pavement technologists have also tried to find sources of asphalt rejuvenators for the extension of asphalt surface life, such as microalgae, bio-oil, swine manure, wood lignin, and waste cooking oil (Airey *et al.* 2008, Fini *et al.* 2011, Cao *et al.* 2019). Such developments have provided great progress in asphalt pavement technology; however, the quality of asphalt binders is still a significant concern for flexible pavement technology.

To meet the increasing demand for high-quality asphalt and reduce crude oil-based asphalt binder consumption, production of synthetic binders represents a potential new strategy. Molecular structures of such binders can be modified by synthetic methods to produce binders with appropriate properties in various temperature ranges and pavement ages. For instance, Airey *et. al* (2008) showed that the rheological characteristics of synthetic binders are comparable to those of traditional asphalt. However, the high cost of synthetic binders, and the lack of infrastructure to produce these products on a large scale have limited their application to date. Therefore, it is necessary to develop a new generation of asphalt binders that not only have better rheological characteristics than traditional and modified binders, but can also be produced and tested using current technologies. Epoxy asphalt technology can fulfill these requirements. There are different types of epoxy glues with a wide variety of applications from repairing shoes to machine manufacturing, construction materials, shipbuilding, electronic, electrical, and the aircraft industry. The binding property of epoxy together with asphalt can make a durable material to adhere to aggregate particles in the asphalt mixture because both are glues. Epoxy asphalt binder (EAB) as a multi-phase material is one of the reactive polymer-modified binders, in which thermosetting epoxy resin is mixed with a thermoplastic asphalt binder. Since there are many types of epoxy, different binders with the required properties can be produced. It is necessary to understand the rheological characteristics of EAB as well as the laboratory and field performance of the epoxy asphalt mix (EAM). This state-of-the-art study attempts to promote understanding of the epoxy asphalt binder rheology and analysis of mixture laboratory performance, which will support the development and wider application of the technology in academic research and industry practice. Field and functional performance of EAM were out of scope of this study.

2. Chemical Structure of Epoxy Resin

The most common used epoxy resins are products of epichlorohydrin polycondensation with phenols (diglycidylether of bisphenol A) (Vyrozhemskiy *et al.* 2017). Adding sodium hydroxide (NaOH) catalyses the formation of hydrochloride intermediates which performs as dehydrohalogens to neutralize the hydrochloric acid (HCl) (Xiang and Xiao 2020). This chemical reaction happens when the temperature is 110°C over 16 h. The final organic matters are separated, dried with sodium sulfate (NaSO_4), and then slightly distilled in a vacuum environment (Hsieh *et al.* 2020, Raquez *et al.* 2010). The common chemical structure of the epoxy resin can be expressed as linear polyether with epoxy groups and the hydroxyl groups in Figure 1. Table 1 shows 6 main typical types of epoxy resin categorized by ASTM D1763.

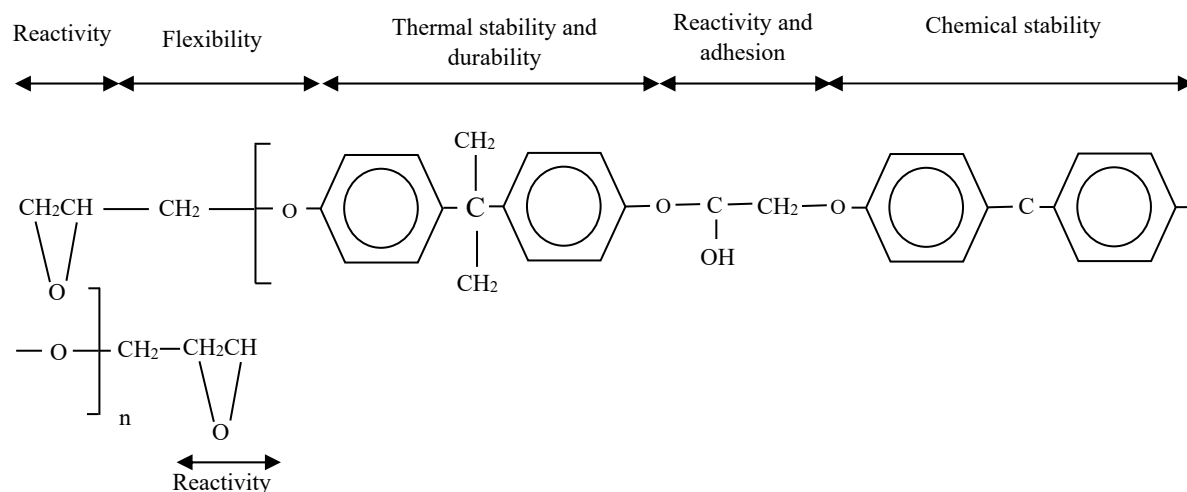


Figure 1: The typically chemical structure of epoxy resin (Osumi 1987).

Every engineering property can be attributed to the chemical structure that exists in the epoxy resin of the as follows (Osumi 1987, Petrie 2005):

1. Reactivity: this property can be characterized by hydroxyl and epoxy groups at the middle and ends of main chain respectively.
2. Flexibility and chemical resistance: they are related to inclusion of bonds in the main chain.
3. Thermal stability: this parameter depends on benzene rings.
4. Adhesion: this depends upon secondary hydroxyl groups which are located along the main chain.

Table 1: Typical types of epoxy resin based on ASTM D1763 (2013)

Types	Name
I	Bisphenol A and epichlorohydrin
II	Reaction product of phenol and formaldehyde (novolacresin) and epichlorohydrin
III	Cycloaliphatic and peracid epoxies
IV	Glycidyl esters
V	Reaction product of epichlorohydrin and paminophenol
VI	Reaction product of epichlorohydrin and glyoxal tetraphenol

In order to cure epoxy resin, a substance called curing agents reacts with the epoxy or hydroxyl groups. The process of curing usually takes place through two different mechanisms: opening- ring and/or polymerization. It should be noted that catalysts can begin the photopolymerization reaction within the epoxy resin. The selection of curing agent depends on many variables, including epoxy type, application, viscosity, pot life, curing temperature and method, shear strength and toughness (Collyer 2012, Sancaktar 1990). Table 2 lists typical curing agents and their benefits and drawback in more details.

Table 2: Various types of curing agent and properties (Meath 1990, Cranley 1994, Collyer 2012, Xiang and Xiao 2020).

Type	benefit	drawback
Aliphatic amines	Easy to use Low viscosity Normal cure at room temperature but rapid cure at the high temperatures Moderate chemical resistance	Critical mix ratios Relatively short life cycle High potential for skin irritant Rigid, poor peel and impact effects Relatively weak bond strength above 80°C High vapor pressure exothermic
Aromatic amines	Moderate thermal and chemical stability	Solid state at the room temperature Slow cure at the high temperature ranges
Anhydrides	High thermal and chemical stability	Critical mix ratios Rigid Slow cure at high temperature
Polyamids	Easy to use Low toxicity High bond strength and flexibility Normal curing at the room temperature	High formulation cost High viscosity Weak thermal and chemical resistance Slow curing at the elevated

	High peel and impact resistance	temperatures
Polysulfides and mercaptans	High moisture resistance Flexible	Odor Weak tensile strength Weak stability at the elevated temperatures
Catalytic and latent hardeners	Quick setting time High heat resistance Long pot life Catalytic action	Low speed curing at the elevated temperatures Weak moisture resistance Rigid

In the next section curing in the epoxy asphalt binder is explained in detail. It should be noted that the epoxy resin and curing agent can be produced through petrochemical processes and synthetic chemical reactions. In addition, resin and curing agents can be produced using renewable natural resources which increases the sustainability in the epoxy industry. For example, epoxy resin can be made from vegetables, soybean, cellulose, camellia sinensis, and lignin (Kumar *et al.* 2018). Also, the bio-based curing agent can be derived from citric acid, cashew nutshell, rosin, corncobs, and gallic acid (Kumar *et al.* 2018). This may indicate that the source biomaterials can influence the final epoxy resin and curing process (Cranley 1994, Mohan 2013).

3.Epoxy Asphalt Technology

3.1. Phase 1: EAB Production

Three different materials are required for the production of EAB: (1) epoxy material, (2) curing agent, and (3) an asphalt binder. EAB has a two-phase chemical-based system. The first phase is thermosetting epoxy resin or continuous phase (component A), and the second phase is the petroleum-based asphalt binder or disperses phase. For the production of EAB, the curing agent and asphalt binder are blended together (component B), refer to EAB production in Table 3. Subsequently, component A is mixed with component B. The blend of components is cured, which results in a set of irreversible chemical reactions. The reaction product is the three-dimensional, continuous spatial network of epoxy in the EAB structure. The asphalt binder spheres are dispersed among the resin (disperse phase) (Yu *et al.* 2009a, Huang *et al.* 2010, Cong *et al.* 2010).

Table 3: Different methods of EAB production (Xiang and Xiao 2020)

Source	Component	Condition of production
Chemcosystem	A: epoxy resin B: base asphalt, curing agents and other additives	Step 1: Preheat the component A to 87 ± 5 °C; Step 2: Preheat the component B to 128 ± 5 °C; Step 3: Blend the components A and B to achieve a homogeneous mix
Tough (TAF)	A: base asphalt B: epoxy resin C: curing agent	Step 1: Preheat the component A to 150 °C Step 2: Preheat the component B and Part C 60 °C Step 3: Blend the components B and C first, Step 4: Blend the components B and C with the component A until it is homogeneous

For EAB production based on TAF, the curing agent is a separate component called component C. In this production method, the components A and B are asphalt binder and epoxy resin respectively. In contrast to the previous method, the component B and C are blended together first. Then the blend is mixed with the asphalt (refer to Table 3 for more details).

Additionally, chemical reactions begin after mixing components. These reactions eventually lead to a cross-linked polymer structure throughout the binder structure. The final EAB is a rubber-like elastomeric asphalt binder with a built-up polymer structure. Additionally, EAB can be treated as a

heterogeneous blend of an asphalt binder and epoxy resin. More details about the curing reaction are explained in the following section.

3.2. Phase 2: Curing Process of EAB

Curing plays a pivotal role in the toughening or hardening of EAB. The mechanism of curing is complex and depends on several variables such as temperature, time, and the chemical components of the curing agent, asphalt binder properties, and aggregate gradation. Curing begins when the epoxy (component A) and blend of the asphalt binder and the curing agent (component B) are mixed together. The particle size of the asphalt binder increases as the chemicals cure. Consequently, a stable cross-linking network is formed between the asphalt binder and the epoxy resin (Yu *et al.* 2009a, Cong *et al.* 2010, 2019, Huang *et al.* 2010). The epoxy network structure can improve various properties of the binder (Dong and Li 2015). The epoxy resin forms a three-dimensional network that wraps around the asphalt particles (Ai *et al.* 2016). This network constrains the flow of the binder particles at elevated temperatures and makes the EAB flexible. The molecular structure obtained after curing is of a linear and straight-chain type. However, its rigidity and recovery can be compared to that of the resins (Takahashi *et al.* 2010). Both the epoxy material and asphalt are glues, and when the two are blended together, they can bind the particles and become stronger over time as well as absorb heat (thermosetting characteristics). Therefore, the thermosetting nature of epoxy improves the stability of EAB 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).

Epoxy resins and most curing agents, such as anhydrides and aliphatic and aromatic amines, are petroleum-based products. Some of these products are toxic, which limits their application due to environmental concerns (Fuhaid *et al.* 2018). To decrease effects of temperature variation on the curing, different types of the agents are produced. There are primarily four kinds of curing agents: low-temperature curing agent (Kim *et al.* 2000); room-temperature curing (Koji *et al.* 2015); Moderate temperature curing agent (Chen *et al.* 2007) and High-temperature curing agent (Guo 2014). The curing method also plays a pivotal role in the quality and performance of EAB. Without the proper curing process, epoxy resin materials may lose the ability to continue the chemical reaction, which results in a lack of stability (Miller and Bellinger 2003).

The size of asphalt granules in EAB depends on the asphalt content, and the time, rate, temperature, and method of curing. For example, Ai *et al.* (2016) reported that the asphalt particles cured by microwave were bigger than those in EAB cured by the conventional method. The extent of curing has been evaluated using various tests. As an example, the trend of curing can be characterized through the evaluation of changes in the peak of the area of the 917 cm⁻¹ epoxy band using Fourier-transform infrared spectroscopy (FTIR) (Herrington, 2010, Cong *et al.* 2019). Additionally, empirical tests, such as softening point, viscosity and Marshall Stability, can be useful to study the trend of curing (Cao *et al.* 2011, Ei Rahman *et al.* 2012, Qian *et al.* 2012).

Curing is a dynamic phenomenon and an endothermal reaction that requires time. Mixing the hot aggregate and EAB accounts for 50% of curing in EAM (Cao *et al.* 2011). The rest of the curing occurs after the construction of the pavement. For example, Chen *et al.* (2018a) recommended that the epoxy pavement be opened to traffic after 12 h of paving due to initial curing. Also, A field study of curing showed that the modulus of epoxy porous EAM increases by 78% after 13 days (Herrington and Alabaster 2008). Analysis of curing by FTIR showed that at 60 °C (as upper surface pavement temperature), the curing reaction, consisting of an epoxy ring, is completed after 7 days, while it cures after 58 days at 20 °C, which is consistent with results of the evaluation of full curing in the field by Widyatomoko *et al.* (2006). However, Takahashi *et al.* (2010) reported that the final strength of EAM was obtained at 1, 2, and 4 weeks at of curing at 55 °C, 40 °C, and 30 °C, respectively, which means the higher ambient temperature decreases curing time (Zhu 2013). In a similar study, the curing rate increased 10-fold if the pavement temperature increases from 30 °C to 60 °C (Cao *et al.* 2011). In

another study, Xu *et al.* (2021a) reported that the open traffic time from 21 h decreases to 6 h when the ambient temperature raised from 25 °C to 35 °C. It means that the waiting time to open the pavement to the traffic decreased by approximately 70% when the ambient temperature increased by 40%. It should be noted that aggregate packing plays key role in curing (Min *et al.* 2020). Additionally, other environmental factors influence curing in the field. For example, when the wind speed is higher than 10 m/s, the air is foggy, or there is dew, or relative humidity is more than 90%, laying EAM is not permitted (Zhu 2013). The reason is that the EAB is a thermosetting material, any type of moisture, due to humidity, fog and dew, can absorb thermal energy of EAB which results in reduction of temperature. Any temperature loss delays curing which results in lack of stiffness.

To simulate curing in the laboratory, the samples were cured for 50 min at 120 °C prior compaction, and then the samples were cured for an additional 5 h at 120 °C after compaction (Qian *et al.* 2013, Chen *et al.* 2018b). The EAM supplier recommended 121 °C as the mixing and compaction temperature (Luo *et al.* 2015). Additionally, Chen *et al.* (2012a) recommended 5 hours at 130 °C as the optimum laboratory curing conditioning of EAM.

When the surface is paved with EAM, the mix temperature drops to the ambient temperature. This can result in a delay in curing. Therefore, it is better to pave the surface during the hot season because EAM has the heat-storing capacity. For example, the heat-storing capacity of EAM used in the pavement of the 2nd and 3rd bridge of the Yangtze river was 45 days in the summer (Zhang 2007, Liu *et al.* 2010). Furthermore, curing of epoxy depends on the base or chemical compounds of the agent (Zhou *et al.* 2017). As an example, to quickly open the pavement to traffic using an acid-based EAM in cold temperatures in DaGuang Ming, China, 3000 sheets of electric blankets were applied for 13 days, called in-situ curing technique (Yan *et al.* 2013, Apostolidis *et al.* 2019a). To overcome such shortcomings, amine-based curing agents are often recommended (Liu *et al.* 2010, Yin *et al.* 2014, Kang *et al.* 2016). Amine-curing agents are more expensive than acid-curing agents, which increases the total price of EAM (Song *et al.* 2017). Therefore, the best approach to achieve a satisfying curing is selection of appropriate curing agent based on environmental factors and chemical characteristics of epoxy resin.

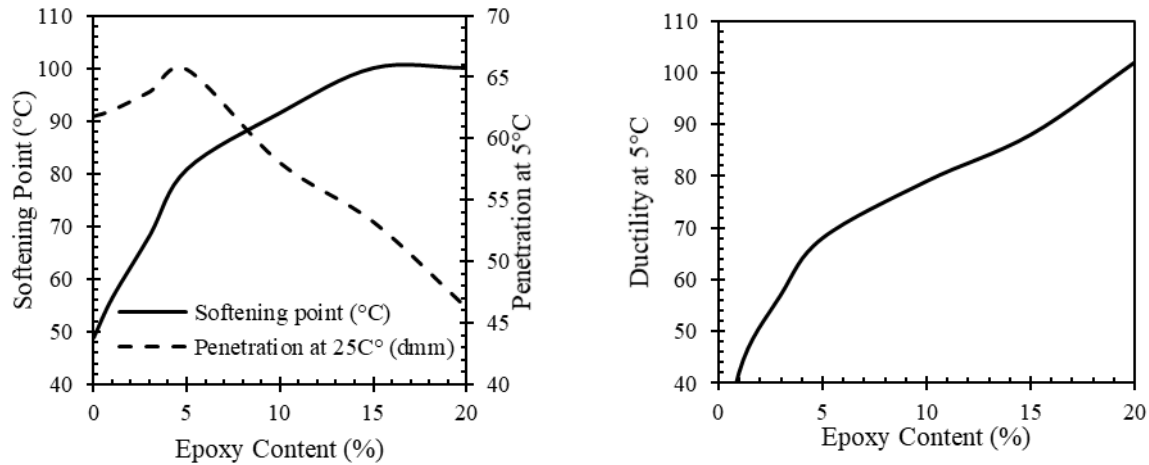
If EAB as a three-component system (unmodified binder, epoxy resin, and curing agent) is compared with traditional polymer-modified binder (PMB), as a two-component system (unmodified binder + reactive copolymers such as polyurethanes and unmodified binder + reactive elastomeric terpolymer (RET)), role of curing agent is the same as accelerators and activator exist in the polymers and reactive copolymers. In other words, catalyst in EAB production is a separate material added in the production, while the catalysts and reactive substance are incorporated in the chemical structure of polymer materials. Furthermore, the catalyst can be added in the binder during modification process. For example, polyphosphoric acid is added in the binder containing RET pills which leads to crosslinking in the binder. As polyphosphoric acid is used in the bitumen-polymer mixture, the amount of polymer needed for the modification is reduced (Jasso *et al.* 2015, Polacco *et al.* 2015). Interaction between the catalyst and polymer improves binder rheological and chemical properties. Selection of appropriate reactive polymer in PMB or curing agent in EAB is an effective approach to add functional groups for obtaining specific functions of the resultant binder (Functionalization). It should be noted that functionalization can improve rheological characteristics and chemical properties of the binder (Zhu *et al.* 2014). Obviously, the rheological properties and quality of the base binder play pivotal in the rheological properties of the PMB and EAB.

4. Rheological Characteristics of EAB

Rheological properties are one of the key indicators for the analysis of deformation and flow of a binder. Effects of any modification in the binder structures can affect rheological characteristics. Since asphalt binders are a multi-phase material, it is necessary to analyze binder performance at various temperatures through different indicators. The rheological tests for asphalt binders can be grouped into two main groups: empirical and advanced tests. The empirical tests, such as softening,

penetration or ignition, and ring and ball softening point, provide basic information which can be useful for contractors and consultants.

Advanced tests, using a dynamic shear rheometer, rotational viscometer, and bending beam rheometer, and testing direct tensile strength not only provide more information about the structural response of binder at various temperature ranges but is also useful for asphalt producers, material technologists, and researchers for the evaluation of mix performance. Both empirical and advanced tests of EAB are helpful. In this section, results of both the tests are evaluated. Figure 2(a) shows that the softening point of EAB decreases as the epoxy content increases, which is consistent with results yielded by Yu *et al.* (2009b), Huang and Huang (2011), and EI Rahman *et al.* (2012). Additionally, the penetration (Figure 2(a)) and ductility (Figure 2(b)) of EAB increase as the epoxy content increases.



(a) Softeningpoint versus epoxy content

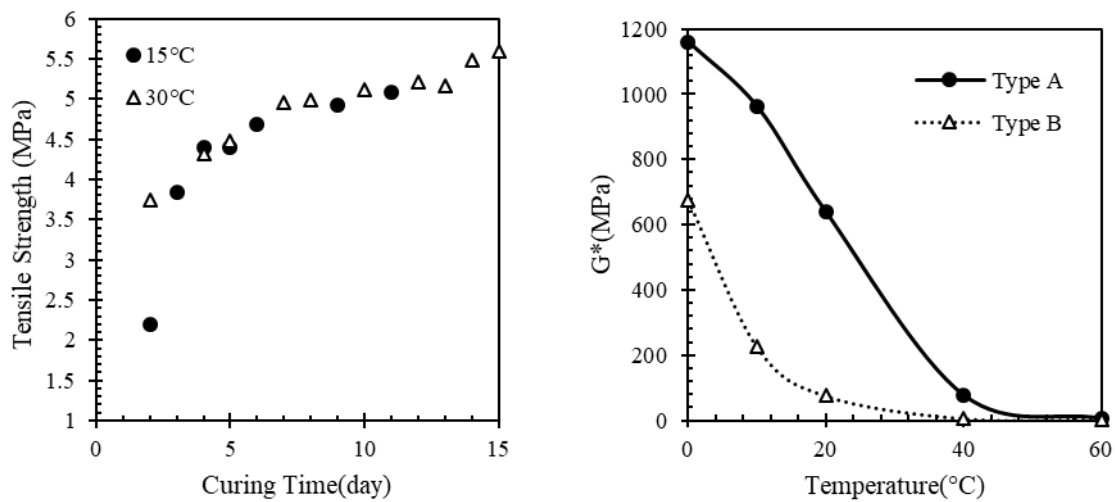
(b) Ductility versus epoxy content

Figure 2: Basic properties of EAB as a function of epoxy content; plotted based data reported by Dong and Li (2015).

Two other parameters affecting the rheological characteristics of EMB are curing time and temperature. Higher curing time and temperature increase the tensile strength, complex modulus, and ductility of EAB. For example, Figure 3(a) illustrates the tensile trend of EAB as a function of curing time. From the figure, the tensile strength increases with the increase in curing time for both curing temperatures. Additionally, the epoxy type and method of preparation can influence the rheological properties of the resultant EAB. Figure 3(b) shows that the EAB prepared using epoxy Type A has a higher complex shear modulus (G^*) compared to that of Type B. The complex shear modulus of Type A is 962 MPa at 10 °C, which is twice that of Type B. Therefore, the stiffness of Type A is higher than of Type B. As a result, the design of EAB means the selection of the appropriate epoxy material, content, curing temperature, and curing time. Fuhaid *et al.* (2018) also reported that $G^*/\sin \delta$ of EAB containing a bio-based epoxy was more than 4 times higher than the value for the neat binder, indicating that the bio-based EAM is less prone to temperature susceptibility. Moreover, EAB has a higher storage modulus (G') compared with the moduli of other asphalt binders (Cong *et al.* 2015). The reason is that the elastic property of EAB is dominant at high temperatures (Xiao *et al.* 2013), because EAB retains its physical state at the high temperatures, while the conventional binders and polymer-modified binders become viscous (Kang *et al.* 2015). As an example, the storage modulus of EAM is much higher than the loss modulus in the high-temperature ranges (Cong *et al.* 2015), meaning higher elastic properties. In contrast, the loss modulus of conventional binders was higher than their storage modulus, indicating the viscous nature of the binders. Consequently, the high elastic characteristic of EAB decreases the creep compliance (Xiao *et al.* 2011, Kang *et al.* 2015, Holleran *et al.* 2017) thereby increasing the recovery rate of the binder. However, it is recommended to

characterize the effects of various epoxy types and curing agents on the viscoelastic characteristics of EAB through master curves, black and Cole-Cole diagrams. As an instance, Huang *et al.* (2019) developed some master curves for characterization of creep compliance of epoxy asphalt.

The optimum rheological design of EAB depends on the appropriate selection of curing time, asphalt type, and epoxy type and content, and also, the optimum epoxy content depends on temperature and the frequency test (Dong and Li 2015). Therefore, pavement service conditions, including the environmental ambient temperature and frequency of traffic loading, should be well understood for an optimum design of EAB. The curing method can affect the rheological characteristics of EAB. Figure 4 shows the difference in elongation and tensile strength due to curing methods. From the figure, it is observed that the elongation and tensile strength of microwave-cured EAB is 7.6% higher than the conventionally cured EAB. The tensile strength of microwave-cured EAB is also observed to be lower than its conventionally cured counterparts (Figure 4(b)). In addition, use of modifier may change curing rate and mechanism. To find optimized conditions for curing, more chemical and microstructural tests are essential (Li *et al.* 2021).



(a): Tensile strength versus curing time

(b) G^* versus temperature

Figure 3: Trends of tensile strength and G^* ; plotted based on data reported by Xiao *et al.* (2011).

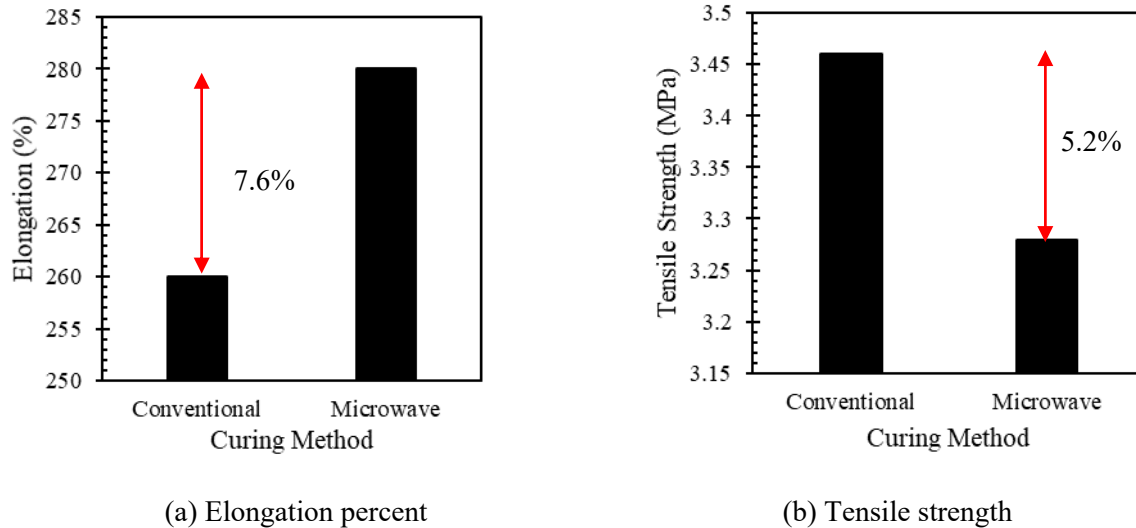
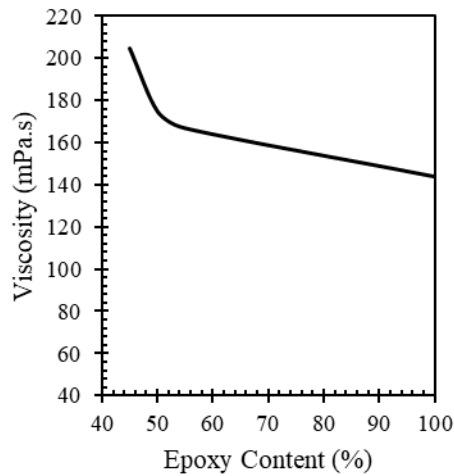


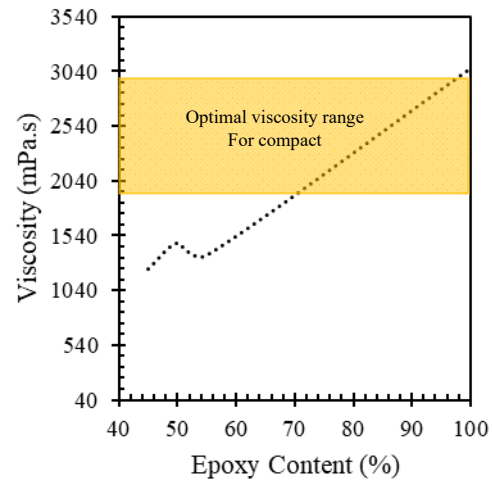
Figure 4: Effect of different curing methods on the engineering properties of EAB; plotted based on data reported by Ai *et al.* (2016).

Figure 5 shows the rotational viscosity of EAB containing various epoxies at various curing times at 160 °C. The viscosity of pure epoxy (100%) is less than the viscosity of EAB immediately after the materials are mixed (Figure 5a). However, the viscosity increases significantly after 2.5 h after mixing (Figure 5b), indicating that curing increases the viscosity, which is consistent with the results reported by Fuhaid *et al.* (2018) and Zhang *et al.* (2021). The incremental epoxy molecular weight results in higher viscosity due to curing (Liu *et al.* 2017a). For example, Wang *et al.* (2021) showed that the viscosity of the EAM increases at the higher temperatures due to the continuous cross-linking reaction occurs during curing.

EAM is typically mixed at approximately 110 °C to 120 °C that allows 57 to 94 min of hauling (Lu and Bors 2015). Furthermore, Cong *et al.* (2011) recommended 2,000 to 3,000 mPa.s as the optimal viscosity range of EAB for compaction (Figure 5 (b)), which is consistent with ranges recommended by Gallagher and Vermillion (1997) and Chen *et al.* (2012a). From Figure 5(b), the viscosities of the binders containing 45%, 50%, and 55% epoxy are 1,234; 1,473; and 1,360 mPa.s, respectively, which are much lower values than the recommended 2,000 mPa.s. Additionally, the time to reach 2,000 mPa.s at the curing temperature of 110 to 130 °C varies from 48 min to 70 min (Yu *et al.* 2009b). In another similar study, Li *et al.* (2014) recommended that the viscosity should be equal to or less than 1,000 mPa.s 50 min after mixing. Therefore, by knowing the target viscosity for compaction, a combination of curing time and epoxy content can be selected. The time until the epoxy reaches 1,000 mPa.s is an indicator of haul time and operational window or reserve time. Beyond that amount of time, the workability of mix decreases, which may result in poor EAM. For example, Takahashi *et al.* (2010) found that the degree of compaction of EAM proportionally decreases over time.



(a) Immediately after mixing (0 h)



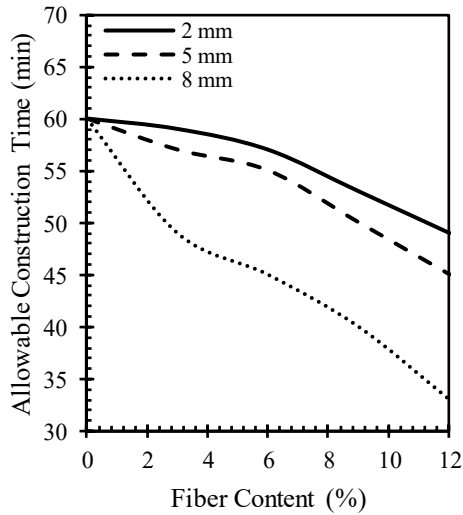
(b) 2.5 h after mixing

Figure 5: Viscosity of EAB containing various epoxy; plotted based on data reported by Yin *et al.* (2015).

The use of any additives or modifiers can influence the allowable construction time. For example, Figure 6 shows the effects of mineral fiber size on the construction time. The fiber size is an effective variable that affects viscosity. From the figure, two different trends can be observed. The first trend is that the allowable construction time decreases as the mineral fiber size increases because the bigger size increases EAB viscosity, thereby decreasing the workability of the mix. Therefore, determining the optimum size of the mineral fiber is a key factor. The second trend is that the increase in fiber content decreases the allowable construction time. To compare the effect of fiber content on the reduction of allowable time, refer to the set Equation (1).

The slope of the equation shows the reduction of allowable time per 1% fiber content. For instance, the slope of the equation for 8 mm fiber is 2.1 min, which indicates the allowable time decreases 2.1 min as 1% of 8 mm-fiber is added, which is 41% and 54% larger than those related to 2-mm and 5-mm fiber, respectively. Consequently, the lower fiber content responds to a lower extension of allowable time of EAM construction.

In another study, Liu *et al.* (2017b) reported that the incorporation of ethylene vinyl acetate (EVA) copolymer in EAM decreases the construction time from 56 min (for the control EAM or 0% EVA) to 38 min (for 4% by weight of EVA). To extend the operational window, different methodologies can be used. For example, the use of a natural fibrous nanoclay, namely attapulgite (chemical formula $\text{Si}_8\text{O}_{20}\text{Mg}_5(\text{Al})(\text{OH})_2(\text{H}_2\text{O})_4 \cdot 4\text{H}_2\text{O}$ with a 2:1 phyllosilicate structure) (Bradley 1940), in EAB decreases the viscosity because of the hindrance impact of fibrous nanoclays on the molecular movement of epoxy monomers, curing agents, and asphalt binder particles (Esmizadeh *et al.* 2016). The analysis by a rotational viscometer of different percentages of attapulgite, from 0% (control) to 5%, shows that the viscosity decreases with the increased percentage (Sun *et al.* 2015, 2018). Therefore, the higher percentages of attapulgite extend the paving window, and the attapulgite performance as a viscosity-reducing agent can be compared with the warm-mix additives. Consequently, the characteristics of modifiers play a key role in the trend of EAB viscosity. For instance, the incorporation of mineral fibers increases the EAB viscosity, depending on fiber content and length of the fibers (Xue and Qian, 2016).



$$T = \begin{cases} -0.93F + 61.12 & \text{for 2 mm fiber} \\ -1.23F + 61.80 & \text{for 5 mm fiber} \\ -2.10F + 58.00 & \text{for 8 mm fiber} \end{cases} \quad (1)$$

Figure 6: Effect of the mineral fiber size and content on the allowable construction time; plotted based on data reported by Xue and Qian (2016). where T is allowable time; F is fiber content ($R^2=94\%$)

A useful technology to extend the paving window is the foaming process. The binder foaming phenomenon increases the surface area of the system, resulting in lower viscosity. Afterward, the lower viscosity of EAM enhances the workability of the mixture, prolonging the allowable time of EAM construction. In this regard, Yu *et al.* (2016) found that the construction time, based on the target viscosity of 1,000 mPa.s, of 64 min for the non-foamed EAB extended to 108, 101, and 97 min as 1%, 2%, and 3% water was added, respectively concluding that 1% is the optimum foaming-water percentage in the study. Beyond 1%, the viscosity of foamed EAM increased because of the deeper degree of the chemical reaction between the epoxy resins and the curing agent, resulting in a higher viscosity and less workability. The optimum percentage may vary depending on the curing agent and binder type. In another study, Huang *et al.* (2017) recommended 2% as the optimum content of foaming water. Also, the higher percentage of water may deaccelerate the curing process between the epoxy and curing agent. The higher percentage of water results in an inferior rutting resistance of the mixture due to a lack of structural consistency. Therefore, the foaming water content should not exceed the optimum value. However, morphological analysis shows that the higher percentages of foaming water results in smaller size epoxy granules with a more uniform distribution in the EAM microstructure. Additionally, there is a new EAM technology that can be mixed at 160 °C to 180 °C, which increases the hauling time from 60 to 150 min (Liu and Zhang, 2010). The use of warm mixture asphalt (WMA) additives also decreases the viscosity of EAB, increasing the hauling time of EAM. For example, Gong *et al.* (2021) showed that the elongation, tensile strength, and toughness of EAB modified with 1% Sasobit® (as a common WMA additive) were 12%, 8%, and 15% higher than neat EAM (without Sasobit®), respectively. Therefore, the crystalline network due to the incorporation of Sasobit®, together with the higher stiffness of the epoxy materials, increased the elongation and toughness of EAB. The optimum additive content depends on the additive type. Thus, different additives have different effects on the rheological properties of EAM. The optimum additive content or modifier depends on the target rheological characteristics because of various mechanisms. For example, the optimum content of SBS-modified binder for EAB was 40% (by weight), based on toughness and tensile strength of the binder, while the results of the elongation test showed the 60% (by weight) is the optimum content (Liu *et al.* 2018). Therefore, it is necessary to choose the critical rheological property or properties to be targeted for modification.

Additionally, the complex interaction between the epoxy resin, binder, modifiers, and additives increases the uncertainty of the conventional thermo-rheological constitute models, such as the fractional linear solid (FLS) model and the Huet-Sayegh (HS) model (Wu *et al.* 2018). The uncertainty is due to the complicated synergistic effects of the resin, binder, additive, temperature, and intermolecular forces. Consequently, there are no highly accepted models to predict the rheological properties of EAB. Thus, it is recommended that the rheological behaviors of EAB are modeled by a set of micromodels valid for a specific temperature and frequency range.

Additionally, it is necessary for the compatibility between the asphalt binder and the epoxy resin to be evaluated. Compatibility is an essential indicator for selection of binder type and epoxy material (Min 2011). Although the higher toughness of EAB reduces temperature susceptibility, it can lead to low temperature cracking. To improve the compatibility and toughness of EAM at a low temperature, three different methods are proposed:

- To add natural rubber, SBS, styrene isoprene styrene block copolymers (SIS), or other elastic materials, which effectively improve the toughness of EAB (Jiang *et al.* 2018, Cong *et al.* 2016, Yin *et al.* 2014, Kang *et al.* 2010). However, the shortcoming is that the viscosity of the modified EAB increases substantially. The lack of compatibility between the modifier and the epoxy can be problematic.
- To use cis-butenedioic anhydride and maleic acid as an asphalt modifier (Herrington *et al.* 1999). Although cis-butenedioic anhydride improves the viscoelastic properties of asphalt binder, the higher viscosity and cost limit its application in epoxy asphalt technology (Zher'akova and Kochkan'an 1990).
- To use curing agents with a long-chain fatty acid or anhydride that have a high compatibility with both the asphalt binder and epoxy material (Li *et al.* 2014, Zhang *et al.* 2010, Araki *et al.* 2008). This method can be consistent with epoxy asphalt technology.
- To use polyethylene glycol (PEG) in EAM. The PEG with number-average molecular weight (Mn) of 400-800 g/mol could improve the toughness of epoxy asphalt (Min *et al.* 2021a). As the Mn of PEG increases, the low-temperature resistance, toughness, and hydrophilicity of asphalt binder improve. However, PEG chains may slightly decrease high temperature characteristics of the asphalt.

5. Engineering Properties of EAM

5.1. Marshall Stability and Flow

Marshall Stability and Flow are common conventional asphalt mix tests to determine the optimum binder content (OBC). This test set is relatively inexpensive and very user-friendly. Therefore, the required test equipment can be found in many laboratories. Figure 7 shows the Marshall Stability of EAM. It can be seen that the increase in epoxy has no significant effect on the Marshall Stability but increases the flow. Therefore, the epoxy resin has no effect on the binder content in terms of the Marshall Stability. This trend was similar to the other trends reported by Fuhaid *et al.* (2018). Additionally, they reported that the air-void percentage of EAM and the control mixture was almost identical. However, Ei-Rahman *et al.* (2012) reported that more epoxy materials increased the Marshall Stability. Consequently, different resin types may result in various effects on the volumetric properties of the mix and the Marshall properties. Also, the interlocking of aggregate particles plays a pivotal role in the initial Marshall Stability of EAM (Huang *et al.* 2011). Further investigations are required to characterize the effect of the epoxy resin content, type, and their interaction with aggregate particles. In addition, the method of EAM production can affect the Marshall stability, flow and the other mix properties. For example, Cong (2009) evaluated the effect of different blending methods of

components for EAM production (Table 4). The effect of aggregate and filler properties should be considered in analysis of Marshall Stability of EAM. In this regard, Xu *et al.*, (2021b) evaluated effect of two types of filler on the Marshall Stability of EAM. The results showed that the Marshall Stability of EAM containing filler dust was 73% higher than the mixtures with mineral filler.

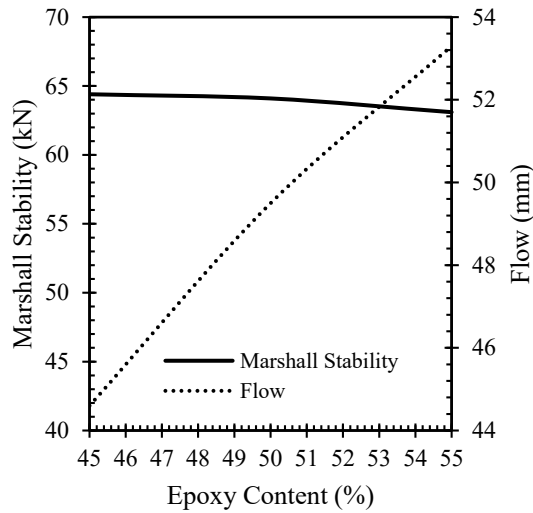


Figure 7: Marshall Stability and flow as a function of epoxy content; plotted based on data reported by Yin *et al.* (2015).

Table 4: Different blending methods in EAM production

Blending Method	Description	Blending Time (sec)
I	Blending aggregate particles with components A and B	120
II	Step 1: Blending aggregate particles with part B	30
	Step 2: Adding component B to the blend prepared in the step 1	90
III	Step 1: Mixing aggregate particles with Component B	30
	Step 2: Adding component A to the blend prepared in the step 1	90

Figure 8 illustrates the effect of different blending methods on the Marshall stabilities and volumetric properties of EAM. From the Figure, the maximum Marshall Stability can be achieved from the method I, while the air void and voids in the mineral aggregate (VMA) of EAM in all the methods are almost identical. As a result, selection of the blending method may play a key role to quality control and mix design of EAM. It should be noted that every epoxy material supplier will provide instructions and guidelines to blends of the components and aggregate that should be followed carefully.

EAM can also be produced with other waste materials and binder modifiers (Figure 9). For example, Figure 9(a) shows that the Marshall stability of the EAM samples is much higher than the PMB, indicating the higher structural performance. Furthermore, the Marshall stability of the PMB samples decrease as the glass content increases, but the Marshall Stability of the EAM samples do not change. The trend of the flow for both mixes are also similar; however, the flow of EAM are higher than those of PMB. The Marshall Stability of EAM is consequently less sensitive to the glass content.

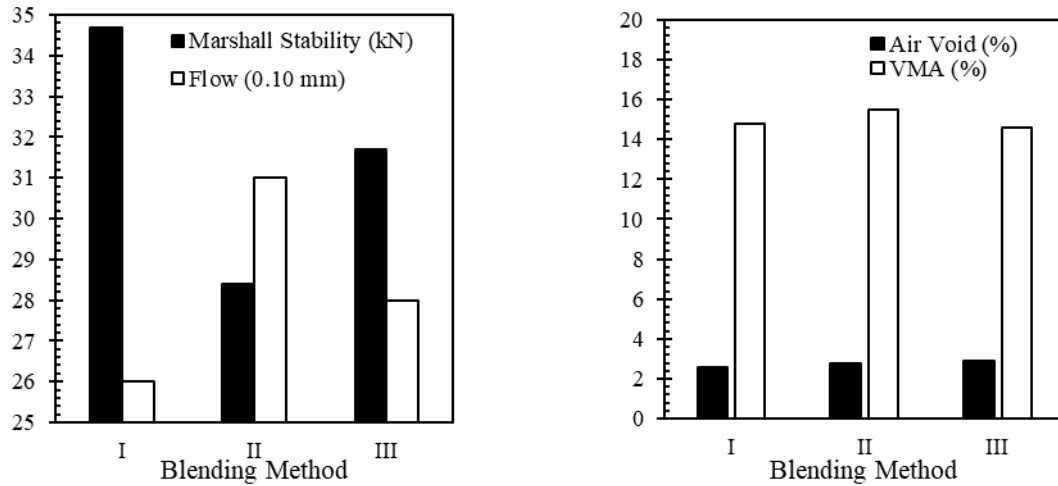
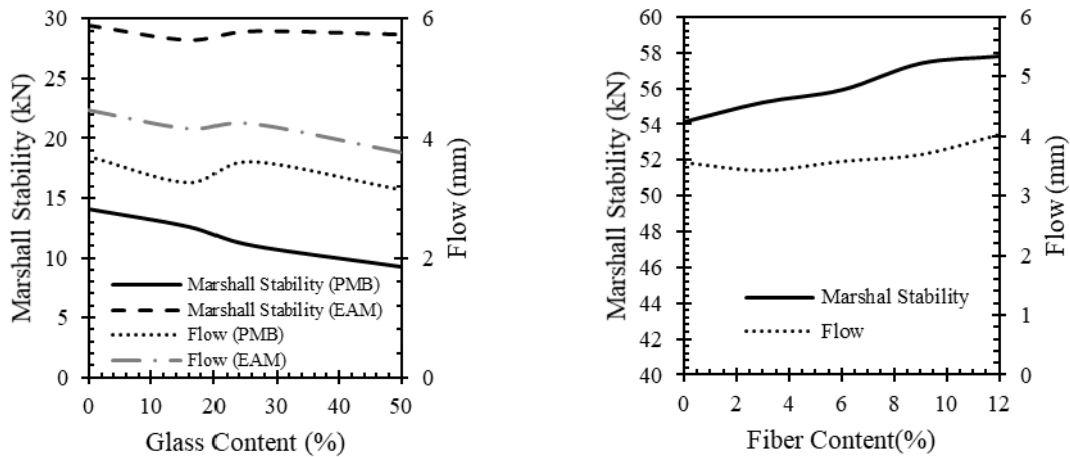


Figure 8: Effect of different blending methods on the Marshall Stability and volumetric properties of EAM, plotted based on data reported by Cong (2009).



(a): Plotted based on data reported by Min *et al.* (2019).

(b): Plotted based on data reported by Xue and Qian (2016).

Figure 9: Marshall Stability and flow of EAM.

Figure 9(b) also shows that the Marshall Stability of EAM modified by mineral fibers increases. The reason is that the fiber increases the binder viscosity and bridge the microcracks formed in the mix during the loading. Consequently, the structural performance of EAM can be improved by adding waste glass and mineral fiber. However, the OBC may be different because of the absorption of the modifiers or additives. For example, the waste glass particles do not absorb the binder because of their hydrophobic nature, while the mineral fibers are hydrophilic materials. Therefore, it is expected that the OBC in EAM increases by adding higher percentages of fiber. Moreover, the compatibility of EAM and fiber or any modifiers/alternative materials needs further investigation. It should be noted that adding fiber requires facilities in the production line of EAM which incurs initial costs. In addition, workability of EAM containing fiber is matter of concern. Also, the long-term performance of the fiber-modified EAM in terms of field aging and durability should be addressed in the life cycle of mixture. As a result, all the uncertainty and risks in the performance EAB should be analyzed.

Other industrial by-products that can be used as an asphalt modifier are sulfur or sulfur-derived polymers, resulting from the bulk polymerization reaction between sulfur and dicyclopentadiene above the melting point of sulfur (Salman *et al.* 2016, Adam *et al.* 2003). Additionally, the melting

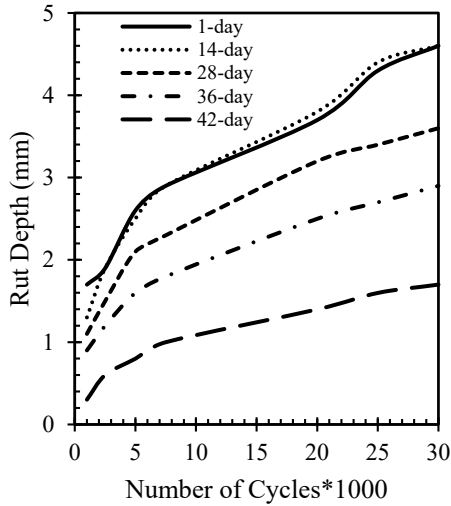
point of the polymerized sulfur decreases with the increase in the amount of the dicyclopentadiene. Kwon *et al.* (2017) showed that the melting point of the polymerized sulfur decreases to as low as room temperature when 60% dicyclopentadiene is blended. Therefore, a cold mix of EAM can be produced using a liquid sulfur polymer. The results show that the Marshall Stability test of the liquid sulfur polymer EAM is 1.5 to 2.3 times higher than those of neat binders. The reason is a more stable polymer network formed in the presence of sulfur and the curing of epoxy materials. It should be noted that the samples should be tested after curing because the Marshall stability of samples without enough curing does not represent structural consistency of EAM. The lack of curing results in less stiffness which results in low Marshall stability. In addition, plastic deformation increases because of the low stiffness in EAB.

Use of alternative aggregate is another approach to improve engineering properties of EAM. In a laboratory study, Min *et al.* (2021b) studied the effect of ceramsite as an aggregate alternative on the Marshall Stability. The results indicated that EAM samples could meet the Marshall Stability requirement for all the ceramsite contents under heavy and light compaction, while SBS-EAM could only meet the requirement at lower percents. The higher strength was achieved under light compaction of EAM because of less aggregate degradation. As a result, Min *et al.* (2021b) recommended the light compaction for EAM containing ceramsite.

5.2. Rutting

EAM is characterized by a high modulus and high resistance to the rutting (Burns 1964, Dinnen 1981). In this regard, Nakanishi *et al.* (2000) reported that the dynamic modulus of EAM was higher than the stone matrix asphalt (SMA) and gussasphalt. EAM is also less prone to premature rutting owing to a low initial dynamic stability (Ishibashi *et al.* 1990). The possible reason is that the higher stiffness in EAM increases the dynamic modulus owing to a relatively higher complex Poisson's ratio of EAM (Wang *et al.* 2021, Bocci *et al.* 2015, Mayama 1978a, b).

Figure 10 illustrates the trend of rutting with EAM compared with that with the control sample (traditional asphalt mix) at different instances in a laboratory study for different curing days. From the figure, the rutting depth of EAM after 14 days of construction is equal to that of the traditional asphalt mix (1-day mix or control mix). Subsequently, rutting decreases significantly over time with EAM, and the rate of rutting depth varies. To characterize the effect of time, Equation 2 is proposed, which corresponds to Figure 10. The slopes of the aforementioned equation show the rate of rutting depth development over 1,000 cycles of loading. For example, the rutting rate of control mix (1-day control mix) is 0.1, which means 0.1 mm per 1,000 cycles of loading while the corresponding value is 0.04 for 42-day EAM. The effect of curing on the structural response of EAM can be characterized by the reduction in rutting using the slopes of Equation 2.



$$RD = \begin{cases} 0.10L + 1.87 & R^2 = 95\% \text{ control mixture} \\ 0.10L + 1.71 & R^2 = 94\% \text{ 14 - day EAM} \\ 0.08L + 1.42 & R^2 = 93\% \text{ 28 - day EAM} \\ 0.64L + 1.11 & R^2 = 94\% \text{ 36 - day EAM} \\ 0.04L + 0.49 & R^2 = 94\% \text{ 42 - day EAM} \end{cases} \quad (2)$$

where RD is rut depth; L is the number of load cycles.

Figure 10: Trend of rutting as a function of time at 45 °C; plotted based on data reported by Vyrozhemskyi *et al.* (2017). Note: 1-day rutting results for the control asphalt mix, but the other samples are EAM.

Although the stiffness of EAM is relatively much higher, the behavior of EAB is still assumed to be viscoelastic. Therefore, the dynamic modulus test of EAM should be in the range of linear viscoelasticity, which is lower or equal to 150 microstrains (Yao *et al.* 2013a). This linear viscoelastic limit of EAB is much higher than that of the conventional and modified asphalt binders, that are 20 and 100 micro-strain, respectively (Airey *et al.* 2004).

Furthermore, the incorporation of modifiers and additives improves rutting resistance and the dynamic stability of EAM. For example, mineral fibers decrease the rut depth of EAM because the fiber increases the stiffness of the EAB (Figure 11). From the figure, the rut depth decreases, and the dynamic stability increases when the mineral fiber content increases. Additionally, the maximum dynamic stability and minimum rut depth (maximum structural capacity regarding rutting) are for 6% fiber.

Rutting, together with other failures, can accelerate failures in the asphalt pavement. Therefore, it is better to evaluate the interaction between rutting and other failures. To characterize the effect, Zhong *et al.* (2017) analyzed the performance of EAM using the Hamburg wheel tracking test. The result showed that no yield point after 20,000 loading cycles at 60 °C indicating superior performance. The yield point indicates that rutting depth development transfers from rutting to moisture damage (i.e., moisture damage is a dominant factor in the development of rutting beyond the yield point). The excellent rutting performance of EAM prevents rapid failures due to moisture because of the high bonding between the aggregate and EAM. Furthermore, moisture sensitivity of EAM increases due to the binder and aggregates adhesion as well as increasing the wettability of the aggregate particles surface with binder (Bahmani *et al.* 2021).

As discussed earlier, the cured samples should be tested because EAMs without sufficient curing show misleading results. The samples with poor curing show the higher rut depth owing to lack of stiffness.

Although laboratory tests, such as Hamburg wheel tracking or traditional wheel tracking test and asphalt pavement analyzer, may provide satisfying results of rutting and the other properties, it is necessary to develop new test protocols, procedures, and setups to better simulate the realistic conditions in the field.

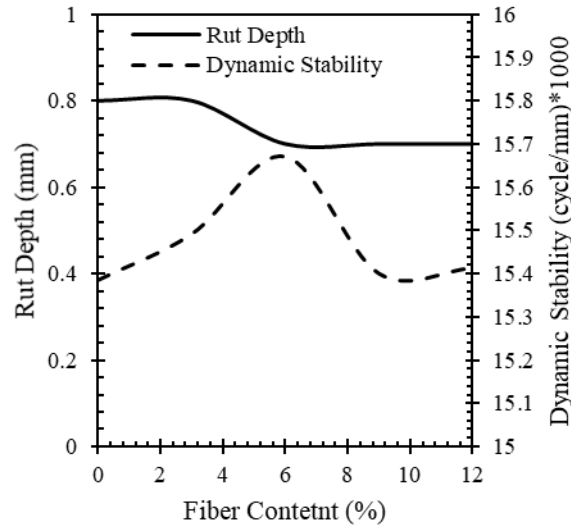


Figure 11: Effect of fiber content on the rut depth and dynamic stability of EAM; plotted based on results reported by Xue and Qian (2016).

5.3. Crack Resistance

Indirect tensile strength (ITS) is a parameter used to evaluate the potential of cracking in asphalt concrete mixtures. Laboratory results showed that EAM has a higher stiffness in terms of ITS compared with the other modified mixtures (Zhu *et al.* 2004, Apostolidis *et al.* 2019b) because of the high stiffness of EAB (Chen *et al.* 2018a, Wang *et al.* 2013). Additionally, oxidative aging of samples increased the ITS of EAM. For example, Herrington and Alabaster (2008) showed that the ITS of porous EAM are higher than for the traditional asphalt regardless of oxidation time. Furthermore, they found that the ITS increases linearly up to 120 h for both pavements. At 186 h, there is an inflection point, and then the ITS increases in EAM. The same inflection point is observed for the porous control mix. The change in the trend can be related to the stiffening effects of the binders. Although both pavements display the same trend, the values are different. 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).

Fatigue cracking is another mode of structural failures in the pavement. Cong *et al.* (2015) and Nguyen and Tran (2021) carried out research on the fatigue behavior of EAM. A role of thumb, the outputs indicated that the effect of temperature on the fatigue life of EAM significantly depends on the stress level and epoxy content. The fatigue life of a mixture increases at the lower stress level and temperature due to the high elastic property (storage modulus) of EAB. The elastic strain recovers after unloading, which results in the dominant action of the elastic behavior in fatigue. At elevated temperatures, the EAB may have insufficient elasticity to recover. Therefore, the plastic behavior becomes the dominant action, which results in micro-cracks. The rates of crack initiation and propagation are different, which depend on aggregate gradation and particle distribution. The analysis of crack initiation and propagation based on the results of three-point bending beam samples clearly showed that crack propagation is stopped when the coarse aggregate particles are in the process of cracking (Chen *et al.* 2014), but the crack propagation continues due to cumulative stress and strain until the pavement fails. However, the performance of EAM is superior to traditional mix in terms of fatigue life (Yin *et al.* 2015, Huang 2015).

Additionally, the high ductility of EAB (Figure 2(b)) results in the higher flexural strength in the EAM (Figure 12). The flexural strength of EAM is almost three times higher than those of PMB-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 mixtures (Wang *et al.* 2021). Also, Xu *et al.* (2019a) found that fatigue life of EAM is two to three times higher than SMA and

gussasphalt. Furthermore, type of filler has significant effect on the fatigue life of EAM. As an instance, Xu *et al.* (2021a) reported that the EAM samples containing filler composed of dust from aggregate had a significantly longer fatigue life than that of the samples containing filler composed of mineral powder.

The flexural strength of PMB is much higher than for mixes produced using the neat or unmodified binders. The higher flexural stiffness and strain result in a high structural capacity under traffic loading. Therefore, the thickness of the pavement layer decreases due to use of EAM. Consequently, the use of EAM can result in lesser consumption of raw material due to lower pavement thickness. Similarly, the superior performance of EAM in fatigue leads to less maintenance and rehabilitation, especially for pavements subjected to heavy traffic loads.

Some field investigations showed significant fatigue failures of EAM (Changjiang *et al.* 2007, Xiaohua *et al.* 2010), which is inconsistent with laboratory results. The reason for these failures includes the concept of fatigue endurance in the field compared to the laboratory samples.

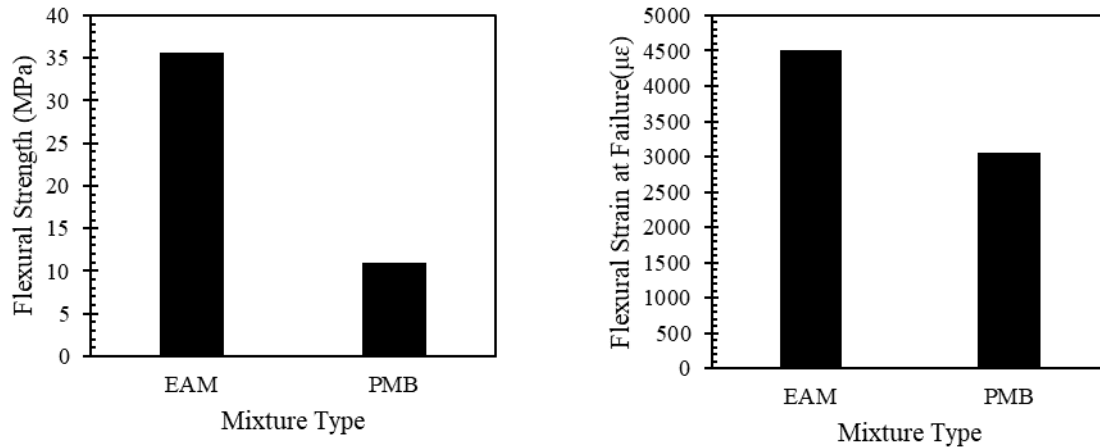
If the EAM is subjected to stress or strain lower than the fatigue endurance, the fatigue failures do not appear. Once the cumulative stress/strain reaches the fatigue endurance, the fatigue failures appear quickly. Consequently, the analysis of fatigue endurance is recommended as a criterion for the EAM mix design and evaluation (Wang and Zhang 2019). A lack of knowledge of the fatigue response of EAM can lead to the early failures reported in different studies (Seim 1973, Cheng *et al.* 2011, Chen *et al.* 2011). Furthermore, the structural performance of substrate layers plays important roles in the fatigue life of the pavement system. Thus, it is necessary to evaluate the surface and the substrate layers together to understand the combined EAM fatigue properties better.

Moreover, there are different methodologies for the selection of fatigue endurance, which may result in different fatigue life prediction. For example, Bhattacharjee *et al.* (2009) used the visco-elastic theory to find fatigue endurance, while Brown *et al.* (2006) proposed the Weibull function to find the fatigue failure criteria. Carpenter *et al.* (2003) and Schapery (1984) used the concepts of dissipated energy and work potential theory for the determination of fatigue endurance, respectively.

The potential performance of EAM in terms of fatigue stiffness can be improved using fiber. The fiber improves the structural performance of asphalt concrete via two different mechanisms:

- The fiber dispersed throughout the mixture forms a network that resists crack propagation and prevents aggregate material from sliding to the pavement surface. Furthermore, the fiber can evenly distribute stress and strain throughout the matrix of the mix, reducing local micro-failures. Furthermore, the fiber bridges the cracks, which results in fewer openings. Also, load transferring does not develop into micro-cracks due to the fibers. Therefore, fiber decelerates the propagation of cracking, which results in higher fracture strength.
- The fiber performs as a stabilizer in the asphalt binder which decreases asphalt drain down or binder creep due to the higher viscosity of the asphalt binder. This property is particularly important for the porous asphalt mix or open-graded friction courses or mixes constructed for high-temperature service condition.

There are various types of fiber materials used in asphalt mixtures. Depending on the fiber type, the optimum content based on fatigue life is chosen. For example, Wang *et al.* (2019) showed that the flexural strength of EAM increased as the fiber glass content increased. It was also shown that the maximum fatigue life was for the EAM containing 6% and 9% fiber glass. Beyond 9%, the fatigue life decreased because of the poor dispersion of fibers in the EAM. In another study, 9% mineral fiber increased the fatigue life by 55% (Xue and Qian 2016). Therefore, it is expected that 9% fiber is the optimum fiber content for EAM.



(a) Flexural strength

(b) Flexural Strength at the failure point

Figure 12: Comparison between EAM and mixture using PMB; plotted based data reported by Min *et al.* (2019).

6. Conclusion

A new generation of asphalt binders could be produced using a thermosetting epoxy technology instead of a thermoplastic process relied on by traditional asphalt materials. A network formed by the curing of epoxy materials in the structure of EAB, improving rheological characteristics. EAB can be produced using various binder types and additives, but the compatibility should be evaluated for quality assurance.

Due to the thermosetting nature of epoxy, it cannot be remelted by heat. Therefore, any extra curing decreases the workability of the mix significantly. As a result, there is a limited time for transportation of EAM because curing drastically decreases workability. WMA additives, foam technology, and some nanomaterials can be used to extend the time of paving. However, the optimum content of WMA additives, water for foam production, and nanomaterials depends on curing type, epoxy content, chemical properties of the base binder. Additionally, optimum epoxy content, type, and any modifier can be determined based on results of rheological characteristics of EAM and utility service of pavement. A well-designed EAB is not prone phase separation, which significantly reduces the durability of the modified asphalts.

Laboratory structural performance of EAM has been evaluated in terms of Marshall properties, ITS, rutting, and fatigue. The results clearly indicated that the structural performance of EAM is much higher than the conventional HMA and WMA due to strong binding of aggregate particles and binders, as well as high stiffness of EAB. Additionally, the structural performance of EAM can be improved using waste materials and additives. Epoxy asphalt technology is therefore compatible with many waste materials available on the market. However, the mixing time must be carefully controlled so that it is long enough to give a uniform coating of EAB to the aggregate particles and short enough to delay EAB during construction.

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