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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).

47 The asphalt pavement technologists have also tried to find sources of asphalt rejuvenators for the  
 48 extension of asphalt surface life, such as microalgae, bio-oil, swine manure, wood lignin, and waste  
 49 cooking oil (Airey *et al.* 2008, Fini *et al.* 2011, Cao *et al.* 2019). Such developments have provided  
 50 great progress in asphalt pavement technology; however, the quality of asphalt binders is still a  
 51 significant concern for flexible pavement technology.  
 52 To meet the increasing demand for high-quality asphalt and reduce crude oil-based asphalt binder  
 53 consumption, production of synthetic binders represents a potential new strategy. Molecular structures  
 54 of such binders can be modified by synthetic methods to produce binders with appropriate properties  
 55 in various temperature ranges and pavement ages. For instance, Airey *et. al* (2008) showed that the  
 56 rheological characteristics of synthetic binders are comparable to those of traditional asphalt.  
 57 However, the high cost of synthetic binders, and the lack of infrastructure to produce these products  
 58 on a large scale have limited their application to date. Therefore, it is necessary to develop a new  
 59 generation of asphalt binders that not only have better rheological characteristics than traditional and  
 60 modified binders, but can also be produced and tested using current technologies. Epoxy asphalt  
 61 technology can fulfill these requirements. There are different types of epoxy glues with a wide variety  
 62 of applications from repairing shoes to machine manufacturing, construction materials, shipbuilding,  
 63 electronic, electrical, and the aircraft industry. The binding property of epoxy together with asphalt  
 64 can make a durable material to adhere to aggregate particles in the asphalt mixture because both are  
 65 glues. Epoxy asphalt binder (EAB) as a multi-phase material is one of the reactive polymer-modified  
 66 binders, in which thermosetting epoxy resin is mixed with a thermoplastic asphalt binder. Since there  
 67 are many types of epoxy, different binders with the required properties can be produced. It is  
 68 necessary to understand the rheological characteristics of EAB as well as the laboratory and field  
 69 performance of the epoxy asphalt mix (EAM). This state-of-the-art study attempts to promote  
 70 understanding of the epoxy asphalt binder rheology and analysis of mixture laboratory performance,  
 71 which will support the development and wider application of the technology in academic research and  
 72 industry practice. Field and functional performance of EAM were out of scope of this study.

## 73 2. Chemical Structure of Epoxy Resin

74 The most common used epoxy resins are products of epichlorohydrin polycondensation with phenols  
 75 (diglycidylether of bisphenol A) (Vyrozhemskyi *et al.* 2017). Adding sodium hydroxide (Na(OH)<sub>2</sub>)  
 76 catalyses the formation of hydrochloride intermediates which performs as dehydrohalogens to  
 77 neutralize the hydrochloric acid (HCl) (Xiang and Xiao 2020). This chemical reaction happens when  
 78 the temperature is 110°C over 16 h. The final organic matters are separated, dried with sodium sulfate  
 79 (NaSO<sub>4</sub>), and then slightly distilled in a vacuum environment (Hsieh *et al.* 2020, Raquez *et al.* 2010).  
 80 The common chemical structure of the epoxy resin can be expressed as linear polyether with epoxy  
 81 groups and the hydroxyl groups in Figure 1. Table 1 shows 6 main typical types of epoxy resin  
 82 categorized by ASTM D1763.

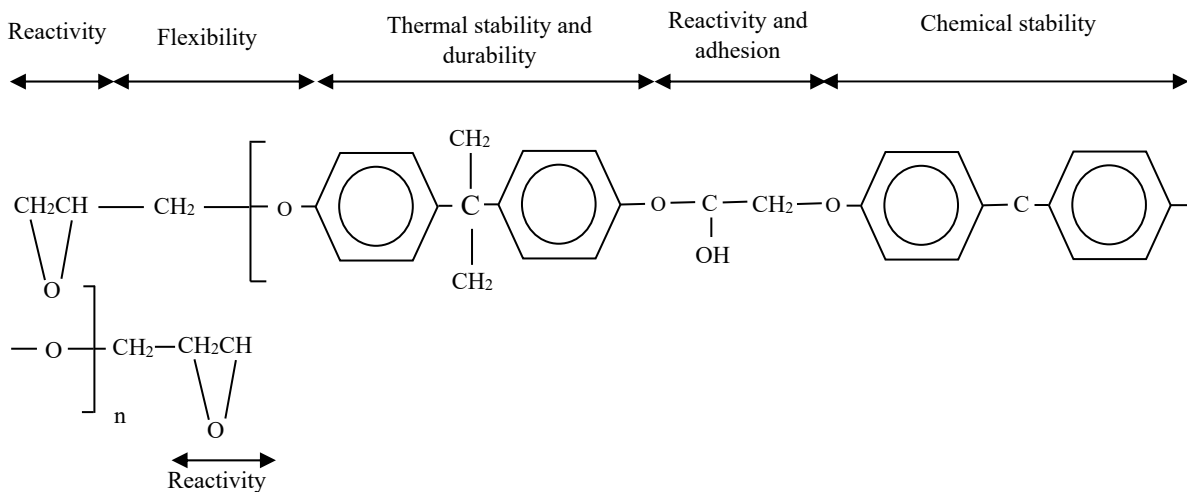


Figure 1: The typically chemical structure of epoxy resin (Osumi 1987).

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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

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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

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

### 113 3.Epoxy Asphalt Technology

#### 114 3.1. Phase 1: EAB Production

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

124  
125 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 $87 \pm 5$ °C; Step 2: Preheat the component B to $128 \pm 5$ °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

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

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

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

### 136 **3.2. Phase 2: Curing Process of EAB**

137 Curing plays a pivotal role in the toughening or hardening of EAB. The mechanism of curing is  
138 complex and depends on several variables such as temperature, time, and the chemical components of  
139 the curing agent, asphalt binder properties, and aggregate gradation. Curing begins when the epoxy  
140 (component A) and blend of the asphalt binder and the curing agent (component B) are mixed  
141 together. The particle size of the asphalt binder increases as the chemicals cure. Consequently, a  
142 stable cross-linking network is formed between the asphalt binder and the epoxy resin (Yu *et al.*  
143 2009a, Cong *et al.* 2010, 2019, Huang *et al.* 2010). The epoxy network structure can improve various  
144 properties of the binder (Dong and Li 2015). The epoxy resin forms a three-dimensional network that  
145 wraps around the asphalt particles (Ai *et al.* 2016). This network constrains the flow of the binder  
146 particles at elevated temperatures and makes the EAB flexible. The molecular structure obtained after  
147 curing is of a linear and straight-chain type. However, its rigidity and recovery can be compared to  
148 that of the resins (Takahashi *et al.* 2010). Both the epoxy material and asphalt are glues, and when the  
149 two are blended together, they can bind the particles and become stronger over time as well as absorb  
150 heat (thermosetting characteristics). Therefore, the thermosetting nature of epoxy improves the  
151 stability of EAB against high temperature deformation, thermal cracking, moisture, and resistance to  
152 solvents such as fuel (Alabaster *et al.* 2008, Chen, 2009, Cong *et al.* 2011, Mo *et al.* 2012, Sun *et al.*  
153 2021).

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

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

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

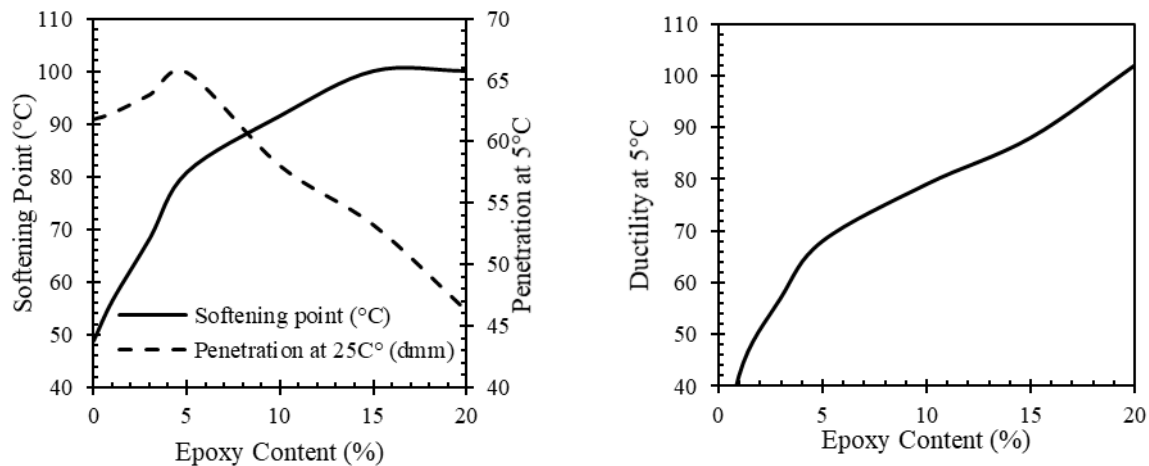
183 another study, Xu *et al.* (2021a) reported that the open traffic time from 21 h decreases to 6 h when  
184 the ambient temperature raised from 25 °C to 35 °C. It means that the waiting time to open the  
185 pavement to the traffic decreased by approximately 70% when the ambient temperature increased by  
186 40%. It should be noted that aggregate packing plays key role in curing (Min *et al.* 2020).  
187 Additionally, other environmental factors influence curing in the field. For example, when the wind  
188 speed is higher than 10 m/s, the air is foggy, or there is dew, or relative humidity is more than 90%,  
189 laying EAM is not permitted (Zhu 2013). The reason is that that the EAB is a thermosetting material,  
190 any type of moisture, due to humidity, fog and dew, can absorb thermal energy of EAB which results  
191 in reduction of temperature. Any temperature loss delays curing which results in lack of stiffness.  
192 To simulate curing in the laboratory, the samples were cured for 50 min at 120 °C prior compaction,  
193 and then the samples were cured for an additional 5 h at 120 °C after compaction (Qian *et al.* 2013,  
194 Chen *et al.* 2018b). The EAM supplier recommended 121 °C as the mixing and compaction  
195 temperature (Luo *et al.* 2015). Additionally, Chen *et al.* (2012a) recommended 5 hours at 130 °C as  
196 the optimum laboratory curing conditioning of EAM.  
197 When the surface is paved with EAM, the mix temperature drops to the ambient temperature. This can  
198 result in a delay in curing. Therefore, it is better to pave the surface during the hot season because  
199 EAM has the heat-storing capacity. For example, the heat-storing capacity of EAM used in the  
200 pavement of the 2nd and 3rd bridge of the Yangtze river was 45 days in the summer (Zhang 2007, Liu  
201 *et al.* 2010). Furthermore, curing of epoxy depends on the base or chemical compounds of the agent  
202 (Zhou *et al.* 2017). As an example, to quickly open the pavement to traffic using an acid-based EAM  
203 in cold temperatures in DaGuang Ming, China, 3000 sheets of electric blankets were applied for 13  
204 days, called in-situ curing technique (Yan *et al.* 2013, Apostolidis *et al.* 2019a). To overcome such  
205 shortcomings, amine-based curing agents are often recommended (Liu *et al.* 2010, Yin *et al.* 2014,  
206 Kang *et al.* 2016). Amine-curing agents are more expensive than acid-curing agents, which increases  
207 the total price of EAM (Song *et al.* 2017). Therefore, the best approach to achieve a satisfying curing  
208 is selection of appropriate curing agent based on environmental factors and chemical characteristics of  
209 epoxy resin.  
210 If EAB as a three-component system (unmodified binder, epoxy resin, and curing agent) is compared  
211 with traditional polymer-modified binder (PMB), as a two-component system (unmodified binder +  
212 reactive copolymers such as polyurethanes and unmodified binder + reactive elastomeric terpolymer  
213 (RET)), role of curing agent is the same as accelerators and activator exist in the polymers and  
214 reactive copolymers. In other words, catalyst in EAB production is a separate material added in the  
215 production, while the catalysts and reactive substance are incorporated in the chemical structure of  
216 polymer materials. Furthermore, the catalyst can be added in the binder during modification process.  
217 For example, polyphosphoric acid is added in the binder containing RET pills which leads to  
218 crosslinking in the binder. As polyphosphoric acid is used in the bitumen–polymer mixture, the  
219 amount of polymer needed for the modification is reduced (Jasso *et al.* 2015, Polacco *et al.* 2015).  
220 Interaction between the catalyst and polymer improves binder rheological and chemical properties.  
221 Selection of appropriate reactive polymer in PMB or curing agent in EAB is an effective approach to  
222 add functional groups for obtaining specific functions of the resultant binder (Functionalization). It  
223 should be noted that functionalization can improve rheological characteristics and chemical properties  
224 of the binder (Zhu *et al.* 2014). Obviously, the rheological properties and quality of the base binder  
225 play pivotal in the rheological properties of the PMB and EAB.

#### 226 **4. Rheological Characteristics of EAB**

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

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

234 Advanced tests, using a dynamic shear rheometer, rotational viscometer, and bending beam rheometer,  
 235 and testing direct tensile strength not only provide more information about the structural response of  
 236 binder at various temperature ranges but is also useful for asphalt producers, material technologists,  
 237 and researchers for the evaluation of mix performance. Both empirical and advanced tests of EAB are  
 238 helpful. In this section, results of both the tests are evaluated. Figure 2(a) shows that the softening  
 239 point of EAB decreases as the epoxy content increases, which is consistent with results yielded by Yu  
 240 *et al.* (2009b), Huang and Huang (2011), and EI Rahman *et al.* (2012). Additionally, the penetration  
 241 (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).

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



263 characterize the effects of various epoxy types and curing agents on the viscoelastic characteristics of  
 264 EAB through master curves, black and Cole-Cole diagrams. As an instance, Huang *et al.* (2019)  
 265 developed some master curves for characterization of creep compliance of epoxy asphalt.  
 266 The optimum rheological design of EAB depends on the appropriate selection of curing time, asphalt  
 267 type, and epoxy type and content, and also, the optimum epoxy content depends on temperature and  
 268 the frequency test (Dong and Li 2015). Therefore, pavement service conditions, including the  
 269 environmental ambient temperature and frequency of traffic loading, should be well understood for an  
 270 optimum design of EAB. The curing method can affect the rheological characteristics of EAB. Figure  
 271 4 shows the difference in elongation and tensile strength due to curing methods. From the figure, it is  
 272 observed that the elongation and tensile strength of microwave-cured EAB is 7.6% higher than the  
 273 conventionally cured EAB. The tensile strength of microwave-cured EAB is also observed to be lower  
 274 than its conventionally cured counterparts (Figure 4(b)). In addition, use of modifier may change  
 275 curing rate and mechanism. To find optimized conditions for curing, more chemical and  
 276 microstructural tests are essential (Li *et al.* 2021).  
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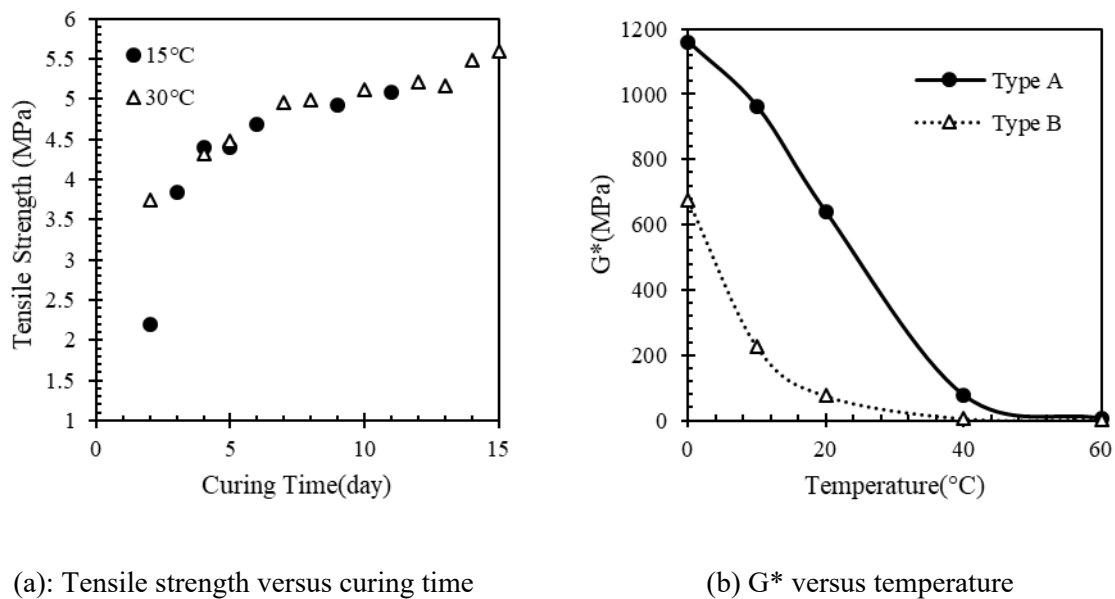


Figure 3: Trends of tensile strength and G\*; plotted based on data reported by Xiao *et al.* (2011).

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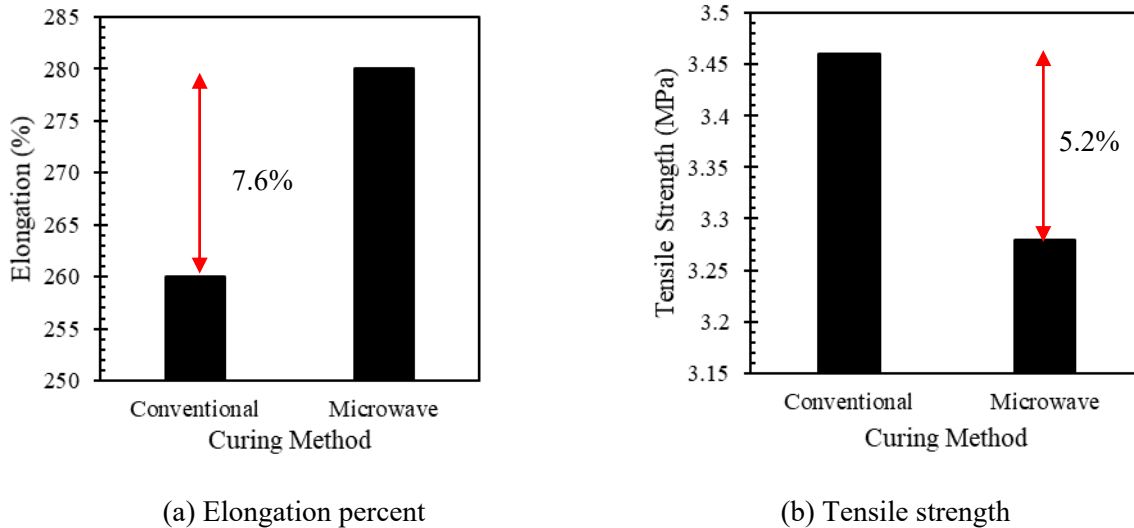


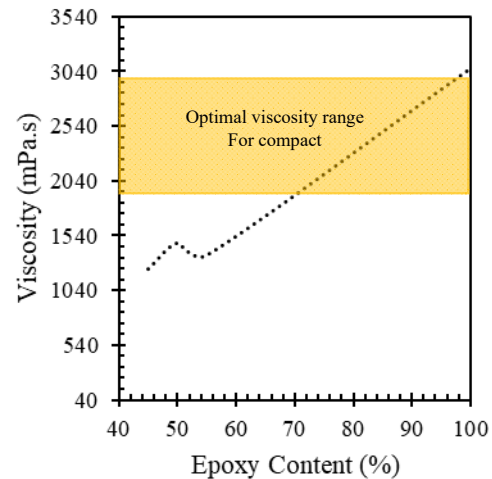
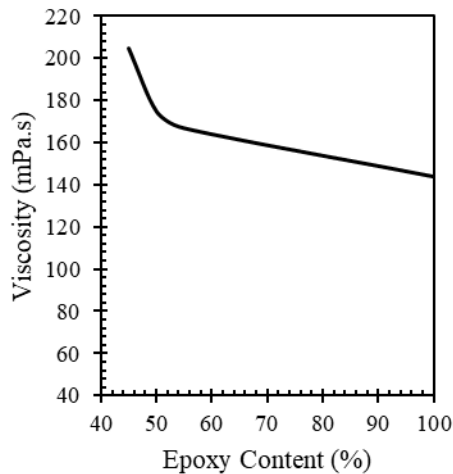
Figure 4: Effect of different curing methods on the engineering properties of EAB; plotted based on data reported by Ai *et al.* (2016).

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285 Figure 5 shows the rotational viscosity of EAB containing various epoxies at various curing times at  
 286 160 °C. The viscosity of pure epoxy (100%) is less than the viscosity of EAB immediately after the  
 287 materials are mixed (Figure 5a). However, the viscosity increases significantly after 2.5 h after mixing  
 288 (Figure 5b), indicating that curing increases the viscosity, which is consistent with the results reported  
 289 by Fuhaid *et al.* (2018) and Zhang *et al.* (2021). The incremental epoxy molecular weight results in  
 290 higher viscosity due to curing (Liu *et al.* 2017a). For example, Wang *et al.* (2021) showed that the  
 291 viscosity of the EAM increases at the higher temperatures due to the continuous cross-linking reaction  
 292 occurs during curing.

293 EAM is typically mixed at approximately 110 °C to 120 °C that allows 57 to 94 min of hauling (Lu  
 294 and Bors 2015). Furthermore, Cong *et al.* (2011) recommended 2,000 to 3,000 mPa.s as the optimal  
 295 viscosity range of EAB for compaction (Figure 5 (b)), which is consistent with ranges recommended  
 296 by Gallagher and Vermillion (1997) and Chen *et al.* (2012a). From Figure 5(b), the viscosities of the  
 297 binders containing 45%, 50%, and 55% epoxy are 1,234; 1,473; and 1,360 mPa.s, respectively, which  
 298 are much lower values than the recommended 2,000 mPa.s. Additionally, the time to reach 2,000  
 299 mPa.s at the curing temperature of 110 to 130 °C varies from 48 min to 70 min (Yu *et al.* 2009b). In  
 300 another similar study, Li *et al.* (2014) recommended that the viscosity should be equal to or less than  
 301 1,000 mPa.s 50 min after mixing. Therefore, by knowing the target viscosity for compaction, a  
 302 combination of curing time and epoxy content can be selected. The time until the epoxy reaches 1,000  
 303 mPa.s is an indicator of haul time and operational window or reserve time. Beyond that amount of  
 304 time, the workability of mix decreases, which may result in poor EAM. For example, Takahashi *et al.*  
 305 (2010) found that the degree of compaction of EAM proportionally decreases over time.

306



(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).

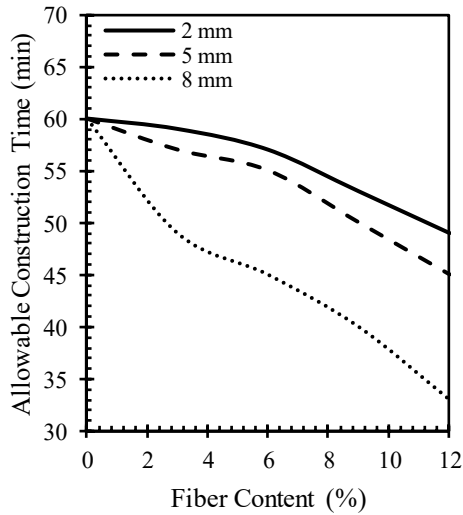
307

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

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

321 In another study, Liu *et al.* (2017b) reported that the incorporation of ethylene vinyl acetate (EVA)  
 322 copolymer in EAM decreases the construction time from 56 min (for the control EAM or 0% EVA) to  
 323 38 min (for 4% by weight of EVA). To extend the operational window, different methodologies can  
 324 be used. For example, the use of a natural fibrous nanoclay, namely attapulgite (chemical formula  
 325  $\text{Si}_8\text{O}_{20}\text{Mg}_5(\text{Al})(\text{OH})_2(\text{H}_2\text{O})_4 \cdot 4\text{H}_2\text{O}$  with a 2:1 phyllosilicate structure) (Bradley 1940), in EAB  
 326 decreases the viscosity because of the hindrance impact of fibrous nanoclays on the molecular  
 327 movement of epoxy monomers, curing agents, and asphalt binder particles (Esmizadeh *et al.* 2016).  
 328 The analysis by a rotational viscometer of different percentages of attapulgite, from 0% (control) to  
 329 5%, shows that the viscosity decreases with the increased percentage (Sun *et al.* 2015, 2018).  
 330 Therefore, the higher percentages of attapulgite extend the paving window, and the attapulgite  
 331 performance as a viscosity-reducing agent can be compared with the warm-mix additives.  
 332 Consequently, the characteristics of modifiers play a key role in the trend of EAB viscosity. For  
 333 instance, the incorporation of mineral fibers increases the EAB viscosity, depending on fiber content  
 334 and length of the fibers (Xue and Qian, 2016).

335



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

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 ( $R^2=94\%$ )

336

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

366 Additionally, the complex interaction between the epoxy resin, binder, modifiers, and additives  
367 increases the uncertainty of the conventional thermo-rheological constitute models, such as the  
368 fractional linear solid (FLS) model and the Huet-Sayegh (HS) model (Wu *et al.* 2018). The  
369 uncertainty is due to the complicated synergistic effects of the resin, binder, additive, temperature, and  
370 intermolecular forces. Consequently, there are no highly accepted models to predict the rheological  
371 properties of EAB. Thus, it is recommended that the rheological behaviors of EAB are modeled by a  
372 set of micromodels valid for a specific temperature and frequency range.  
373 Additionally, it is necessary for the compatibility between the asphalt binder and the epoxy resin to be  
374 evaluated. Compatibility is an essential indicator for selection of binder type and epoxy material (Min  
375 2011). Although the higher toughness of EAB reduces temperature susceptibility, it can lead to low  
376 temperature cracking. To improve the compatibility and toughness of EAM at a low temperature,  
377 three different methods are proposed:

- 379 • To add natural rubber, SBS, styrene isoprene styrene block copolymers (SIS), or other elastic  
380 materials, which effectively improve the toughness of EAB (Jiang *et al.* 2018, Cong *et al.*  
381 2016, Yin *et al.* 2014, Kang *et al.* 2010). However, the shortcoming is that the viscosity of the  
382 modified EAB increases substantially. The lack of compatibility between the modifier and the  
383 epoxy can be problematic.
- 384 • To use cis-butenedioic anhydride and maleic acid as an asphalt modifier (Herrington *et al.*  
385 1999). Although cis-butenedioic anhydride improves the viscoelastic properties of asphalt  
386 binder, the higher viscosity and cost limit its application in epoxy asphalt technology  
387 (Zher'akova and Kochkan'an 1990).
- 388 • To use curing agents with a long-chain fatty acid or anhydride that have a high compatibility  
389 with both the asphalt binder and epoxy material (Li *et al.* 2014, Zhang *et al.* 2010, Araki *et al.*  
390 2008). This method can be consistent with epoxy asphalt technology.
- 391 • To use polyethylene glycol (PEG) in EAM. The PEG with number-average molecular weight  
392 (Mn) of 400-800 g/mol could improve the toughness of epoxy asphalt (Min *et al.* 2021a). As  
393 the Mn of PEG increases, the low-temperature resistance, toughness, and hydrophilicity of  
394 asphalt binder improve. However, PEG chains may slightly decrease high temperature  
395 characteristics of the asphalt.

396

## 397 **5. Engineering Properties of EAM**

### 398 **5.1. Marshall Stability and Flow**

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

413 components for EAM production (Table 4). The effect of aggregate and filler properties should be  
 414 considered in analysis of Marshall Stability of EAM. In this regard, Xu *et al.*, (2021b) evaluated effect  
 415 of two types of filler on the Marshal Stability of EAM. The results showed that the Marshall Stability  
 416 of EAM containing filler dust was 73% higher than the mixtures with mineral filler.  
 417

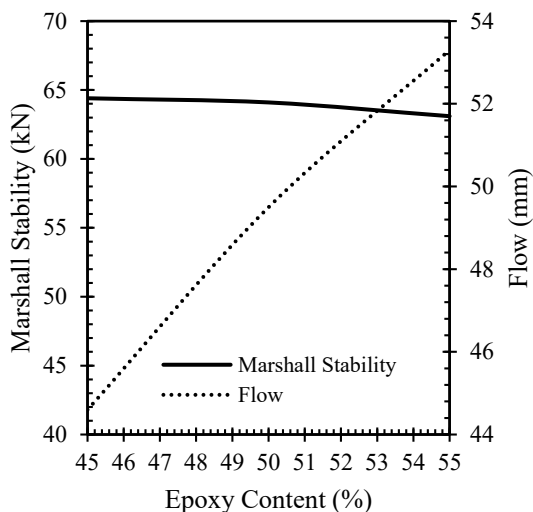


Figure 7: Marshall Stability and flow as a function of epoxy content; plotted based on data reported by Yin *et al.* (2015).

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

418  
 419  
 420 Figure 8 illustrates the effect of different blending methods on the Marshall stabilities and volumetric  
 421 properties of EAM. From the Figure, the maximum Marshall Stability can be achieved from the  
 422 method I, while the air void and voids in the mineral aggregate (VMA) of EAM in all the methods are  
 423 almost identical. As a result, selection of the blending method may play a key role to quality control  
 424 and mix design of EAM. It should be noted that every epoxy material supplier will provide  
 425 instructions and guidelines to blends of the components and aggregate that should be followed  
 426 carefully.  
 427 EAM can also be produced with other waste materials and binder modifiers (Figure 9). For example,  
 428 Figure 9(a) shows that the Marshall stability of the EAM samples is much higher than the PMB,  
 429 indicating the higher structural performance. Furthermore, the Marshall stability of the PMB samples  
 430 decrease as the glass content increases, but the Marshall Stability of the EAM samples do not change.  
 431 The trend of the flow for both mixes are also similar; however, the flow of EAM are higher than those  
 432 of PMB. The Marshall Stability of EAM is consequently less sensitive to the glass content.

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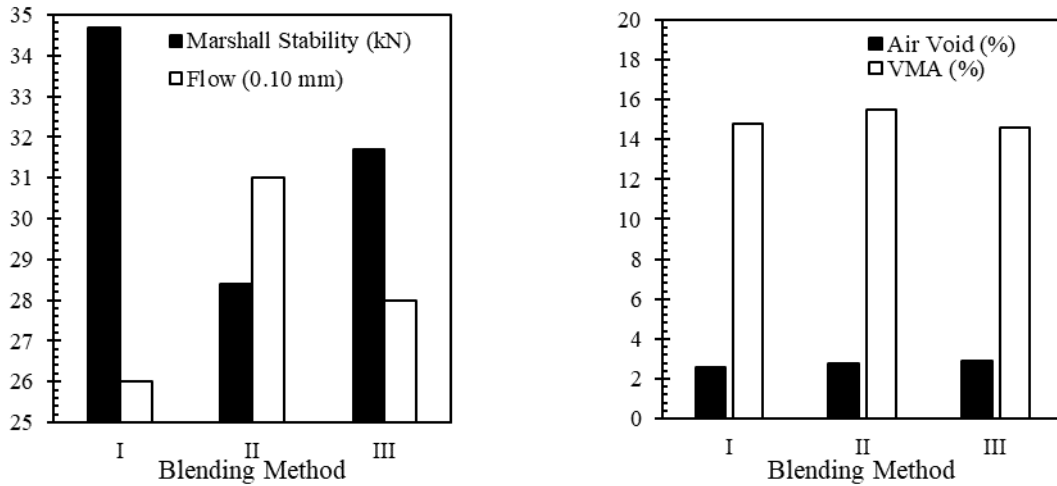
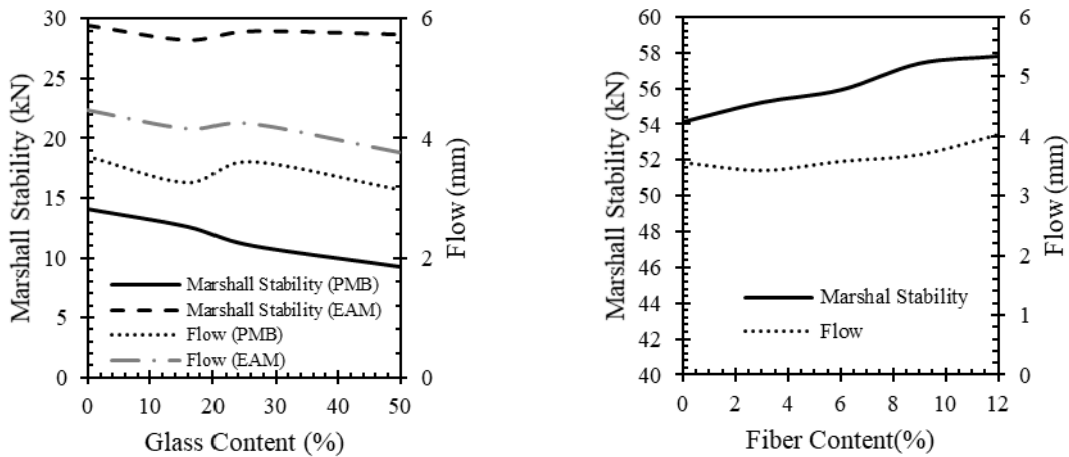


Figure 8: Effect of different blending methods on the Marshall Stability and volumetric properties of EAM, plotted based on data reported by Cong (2009).

443



(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.

444

445 Figure 9(b) also shows that the Marshall Stability of EAM modified by mineral fibers increases. The  
 446 reason is that the fiber increases the binder viscosity and bridge the microcracks formed in the mix  
 447 during the loading. Consequently, the structural performance of EAM can be improved by adding  
 448 waste glass and mineral fiber. However, the OBC may be different because of the absorption of the  
 449 modifiers or additives. For example, the waste glass particles do not absorb the binder because of their  
 450 hydrophobic nature, while the mineral fibers are hydrophilic materials. Therefore, it is expected that  
 451 the OBC in EAM increases by adding higher percentages of fiber. Moreover, the compatibility of  
 452 EAM and fiber or any modifiers/alternative materials needs further investigation. It should be noted  
 453 that adding fiber requires facilities in the production line of EAM which incurs initial costs. In  
 454 addition, workability of EAM containing fiber is matter of concern. Also, the long-term performance  
 455 of the fiber-modified EAM in terms of field aging and durability should be addressed in the life cycle  
 456 of mixture. As a result, all the uncertainty and risks in the performance EAB should be analyzed.  
 457 Other industrial by-products that can be used as an asphalt modifier are sulfur or sulfur-derived  
 458 polymers, resulting from the bulk polymerization reaction between sulfur and dicyclopentadiene  
 459 above the melting point of sulfur (Salman *et al.* 2016, Adam *et al.* 2003). Additionally, the melting

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

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

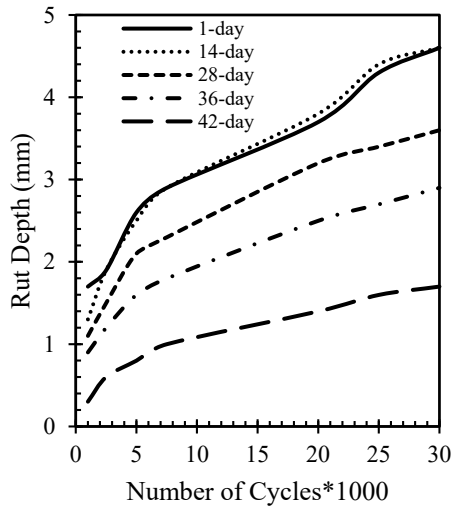
## 477 **5.2. Rutting**

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

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

494





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

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 Vyrozhemskiy *et al.* (2017). Note: 1-day rutting results for the control asphalt mix, but the other samples are EAM.

495

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

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

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

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

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

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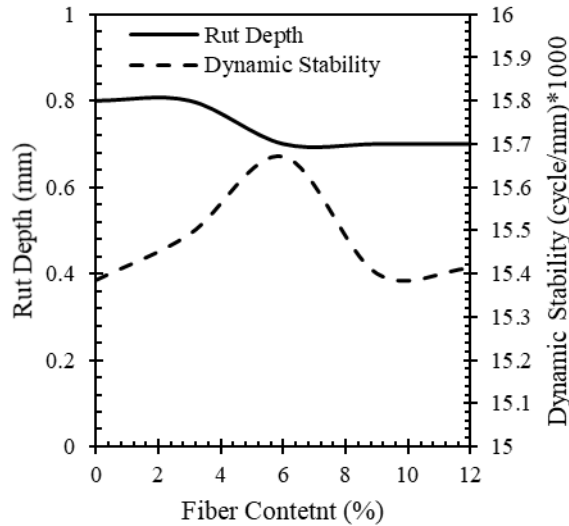


Figure 11: Effect of fiber content on the rut depth and dynamic stability of EAM; plotted based on results reported by Xue and Qian (2016).

### 525 **5.3. Crack Resistance**

526 Indirect tensile strength (ITS) is a parameter used to evaluate the potential of cracking in asphalt  
 527 concrete mixtures. Laboratory results showed that EAM has a higher stiffness in terms of ITS  
 528 compared with the other modified mixtures (Zhu *et al.* 2004, Apostolidis *et al.* 2019b) because of the  
 529 high stiffness of EAB (Chen *et al.* 2018a, Wang *et al.* 2013). Additionally, oxidative aging of samples  
 530 increased the ITS of EAM. For example, Herrington and Alabaster (2008) showed that the ITS of  
 531 porous EAM are higher than for the traditional asphalt regardless of oxidation time. Furthermore, they  
 532 found that the ITS increases linearly up to 120 h for both pavements. At 186 h, there is an inflection  
 533 point, and then the ITS increases in EAM. The same inflection point is observed for the porous  
 534 control mix. The change in the trend can be related to the stiffening effects of the binders. Although  
 535 both pavements display the same trend, the values are different. It should be noted that aggregate type,  
 536 gradation, epoxy content and binder performance grade play pivotal role in crack resistance of EAM  
 537 (Bahmani *et al.* 2021).

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

552 Additionally, the high ductility of EAB (Figure 2(b)) results in the higher flexural strength in the  
 553 EAM (Figure 12). The flexural strength of EAM is almost three times higher than those of PMB-  
 554 mixtures, which is consistent with results reported by Zhao *et al.* (2019). The similar trend was  
 555 observed in flexural strength of EAM compared to SBS-modified mixtures (Wang *et al.* 2021). Also,  
 556 Xu *et al.* (2019a) found that fatigue life of EAM is two to three times higher than SMA and

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

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

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

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

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

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

585

586 • The fiber dispersed throughout the mixture forms a network that resists crack propagation and  
587 prevents aggregate material from sliding to the pavement surface. Furthermore, the fiber can  
588 evenly distribute stress and strain throughout the matrix of the mix, reducing local micro-  
589 failures. Furthermore, the fiber bridges the cracks, which results in fewer openings. Also, load  
590 transferring does not develop into micro-cracks due to the fibers. Therefore, fiber decelerates  
591 the propagation of cracking, which results in higher fracture strength.

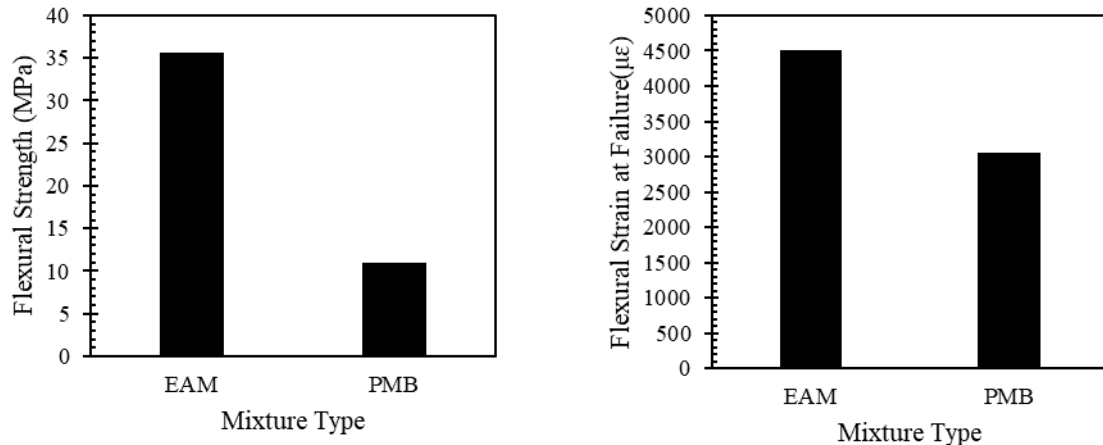
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593 • The fiber performs as a stabilizer in the asphalt binder which decreases asphalt drain down or  
594 binder creep due to the higher viscosity of the asphalt binder. This property is particularly  
595 important for the porous asphalt mix or open-graded friction courses or mixes constructed for  
596 high-temperature service condition.

597

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

605



(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).

606

607 **6. Conclusion**

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

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

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

630

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