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Research Article

Ductile–Brittle Transition Temperature of Epoxy Asphalt Concrete of Steel Bridge Deck Pavement Based on Impact Toughness

Shunxian Zhang[1,2] **Wen Nie**[3,4] **Aimin Sha**[1] **Weixiong Li**[3,4] **and Wei Jiang**[1]

[1]*Chang'an University, South 2nd Ring, Beilin District, Xi'an 710054, China*
[2]*Poly Changda Engineering Co. Ltd., Guangzhou Avenue, Tianhe District, Guangzhou 510641, China*
[3]*School of Civil Engineering and Transportation, South China University of Technology, Wushan Road, Tianhe District, Guangzhou 510641, China*
[4]*Guangzhou Xiaoning Roadway Engineering Technology Research Institute Co. Ltd., Wushan Road, Tianhe District, Guangzhou 510641, China*

Correspondence should be addressed to Shunxian Zhang; shunxian22@126.com and Wen Nie; 202010101505@mail.scut.edu.cn

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To solve the common low-temperature cracking problem of epoxy asphalt concrete pavement on the steel bridge deck, based on the principle of fracture mechanics and energy method, this paper puts forward the impact toughness as the evaluation index of crack resistance of epoxy asphalt concrete and verifies the feasibility of this index through theoretical analysis and experiment. At the same time, based on the study of impact toughness, the ductile–brittle transition temperature of epoxy asphalt concrete was explored, and the working state of epoxy asphalt concrete at different temperatures was mastered. The results show that the impact toughness is closely related to the J integral, which can better evaluate the crack resistance of epoxy asphalt mixture. The Boltzmann function can accurately reflect the relationship between impact toughness and temperature and can determine the ductile–brittle transition temperature and transition interval of epoxy asphalt concrete. Impact toughness and ductile–brittle transition temperature can be used as the evaluation index of crack resistance of epoxy asphalt concrete, which provides a new design idea for the study of crack resistance of epoxy asphalt concrete and the scope of engineering application.

1. Introduction

Epoxy asphalt concrete is widely used in large-span steel bridge decks due to its good high-temperature performance, fatigue performance, corrosion resistance, and other road performance [1–3]. The Golden Gate Bridge in the USA, the West Gate Bridge in Australia, the Zhanjiang Bay Bridge in Guangdong, the Sutong Bridge, the Fumin Bridge in Tianjin, the West Third Ring Bridge in Beijing, and the Baling River Bridge in Guizhou all used epoxy asphalt concrete as a paving layer. Investigations have shown that some of the epoxy asphalt concrete paving layers are susceptible to cracking under prolonged alternating stresses, especially at low temperatures [4–6], which makes it necessary for researchers to rethink the source of the problem. Among the causes of the above problems, in addition to the bridge structure itself force factors, epoxy asphalt concrete cracking resistance design methods, and engineering application temperature on its performance are also particularly important; however, few studies have been conducted at this stage for this aspect. Das et al. [7] used a thermal fracture model to investigate the fracture resistance of epoxy asphalt mixtures, but did not consider the effect of different service temperatures on the fracture performance of the mixes. Braham and Mudford [8] proposed the use of fracture curves (R-curves) to describe the fracture characteristics of asphalt mixtures and to elaborate on the relationship between accumulated energy and crack width, but the ductile–brittle

Table 1: Performance and technical specifications of TAF main agents.

Physical properties	Value	Technical specifications	Test methods
Viscosity (23°C)	1605	1000~5000	ASTM D 445
Specific gravity (23°C)	1.132	1.00~1.20	ASTM D 1475
Epoxy equivalent	203	190~210	ASTM D 1652
Flash point	240	≥230	ASTM D 92

Table 2: Properties and technical specifications of TAF curing agents.

Physical properties	Value	Technical specifications	Test methods
Viscosity (23°C)	178	100~800	ASTM D 445
Specific gravity (23°C)	0.857	0.80~1.00	ASTM D 1475
Acid value (mg, KOH/g)	170	150~200	ASTM D664
Flash point (°C)	176	≥145	ASTM D 92

transition of asphalt concrete at different temperatures was not described. Ge et al. [9] used the strain energy method to evaluate the low-temperature crack resistance of asphalt mixtures, and considered the ultimate bending and tensile strains and bending strength to evaluate the crack resistance of the mixes, but did not include the effect of temperature on the crack resistance of the mixes. Zhang et al. [10] compared the effects of asphalt type, asphalt aggregate ratio, and temperature on the cracking resistance of asphalt mixture using three indices: fracture energy based on the cohesion model, *J* integral based on elastic-plastic fracture mechanics theory, and breaking strain based on elastic damage theory, and analyzed the sensitivity of these three indices to the above-influencing factors using statistical methods, but there was a lack of research on the ductile–brittle transition temperature of asphalt mixtures.

However, most of the studies on the tough-brittle transition temperature of materials have focused on the tough-brittle transition temperature of raw materials such as steel and asphalt [11–13], and the tough-brittle transition temperature of epoxy asphalt mixture has not been studied. Besides, throughout the research results, at this stage epoxy asphalt mixture cracking resistance design theory is not perfect, and the research tools need to be further improved. Some research results design the epoxy asphalt mixture cracking resistance is not ideal, and the actual engineering use of a certain difference. Based on the principle of fracture mechanics and energy method, this paper puts forward the method of impact toughness to evaluate the crack resistance of epoxy asphalt mixture and studies the ductile–brittle transition temperature of epoxy asphalt mixture by means of mathematical simulation and experimental calibration, which provides a reference for the study of low-temperature resistance of epoxy asphalt mixture and the scope of engineering application.

2. Epoxy Asphalt Mixture Material Selection

2.1. Epoxy Asphalt Binder. The asphalt binder used in this research is TAF epoxy asphalt produced by Taiyo Corporation of Japan. The epoxy asphalt consists of three parts: the main agent, the curing agent, and the base asphalt, and the base asphalt is Tepco AH-70 base asphalt, which complies with Chinese standards the Technical Specification for Construction of Asphalt Pavements on Highways (JTG F40-2004). The properties and technical specifications of the epoxy main agent and curing agent are shown in Tables 1–4.

2.2. Aggregate. The stone used in this paper is granite, respectively 5~10 mm crushed stone, 3~5 mm crushed stone, 0~3 mm stone chips, and ordinary limestone mineral powder, and the indicators are in line with the "Technical Specification for Construction of Asphalt Pavement on H." The test results of the aggregates are shown in Tables 5 and 6.

2.3. Grading Options. The current stage of epoxy asphalt mixture grade composition design mainly uses continuous dense grade form, but in the process of use found that the use of the grading design of epoxy asphalt mixture antislip performance and fatigue resistance is poor [14, 15]. To improve the road performance of epoxy asphalt mixtures, this paper uses the Course Aggregate Void Filling (CAVF) method, which has been proven to have good road performance, to design an epoxy asphalt mixture [14, 16, 17]. The design grade of the mixture is shown in Figure 1. It can be seen from Figure 1 that the epoxy asphalt mixture designed by the CAVF method has broken grading characteristics.

3. Impact Toughness Research

3.1. Theoretical Foundations of Impact Toughness. Impact toughness refers to the ability of a material to absorb deformation work and fracture work under impact loading, which is an important indicator for evaluating the toughness of materials [18]. When a material is subjected to an external load, a certain amount of stress is generated within the material itself and leads to a corresponding strain, which in turn results in a loss of energy. When the yield strength of the external loading action is greater than the fracture strength of the object itself, the object will be damaged within a short period. The *J* integral theory, based on the energy principle, can quantitatively describe the strength of the stress-strain field generated when a body fractures. *J* integral theory is not only applicable to elastomers but also to elastoplastic with small deformations [19–21]. The schematic diagram of the J integral is shown in Figure 2 and the *J* formula is shown in the following equation:

$$J = \int_{\Gamma} \left(W\mathrm{d}y - \overrightarrow{T \frac{\partial \vec{U}}{\partial x} \mathrm{d}s} \right), \tag{1}$$

Table 3: Performance of TAF epoxy resins after recuperative curing.

Physical properties	Value	Technical performance	Test methods
Weight ratio (main agent/curing agent)	56/44	56/44	—
Tensile strength (23°C, MPa)	3.62	≥3.0	JIS K 7113
Damage elongation (23°C, %)	319	≥100	JIS K 7113

Table 4: Technical specifications of TAF epoxy bitumen after extended curing.

Physical properties	Standard values	Test methods
Weight ratio (matrix bitumen/epoxy resin)	50/50	—
Specific gravity (23°C)	1.05	JTJ 0603-1993
Needle penetration (25°C, 0.1 mm)	5~20	JIS K 2207
Softening point (°C)	≥100	JIS K 2207
Tensile strength (23°C, MPa)	≥2.0	JIS K 7113
Damage elongation (23°C, %)	≥100	JIS K 7113

Table 5: Main technical specifications of aggregates.

Name of material	Apparent relative density (g/cm^3)	Surface dry relative density (g/cm^3)	Gross bulk density (g/cm^3)	Crushing value (%)	Content less than 0.075 (%)	Water absorption (%)
5~10 mm crushed stone	2.744	2.709	2.690	12.5	0.6	0.63
3~5 mm crushed stone	2.742	2.703	2.681	—	0.4	0.73
0~3 mm stone chips	2.737	2.705	2.687	—	8.9	0.59
Mineral powder	2.751	—	—	—	—	—

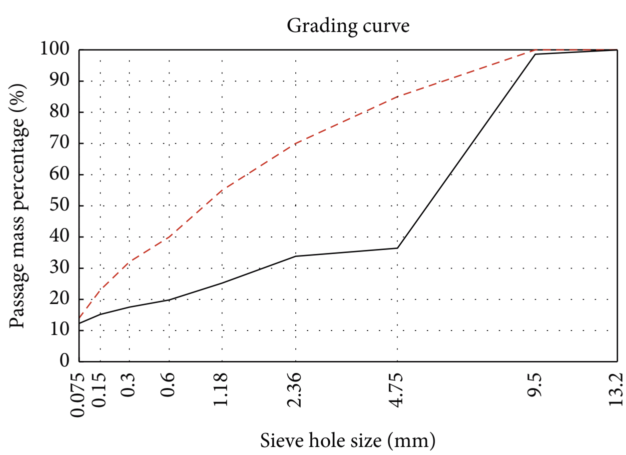

Figure 1: Epoxy asphalt mixture grading design.

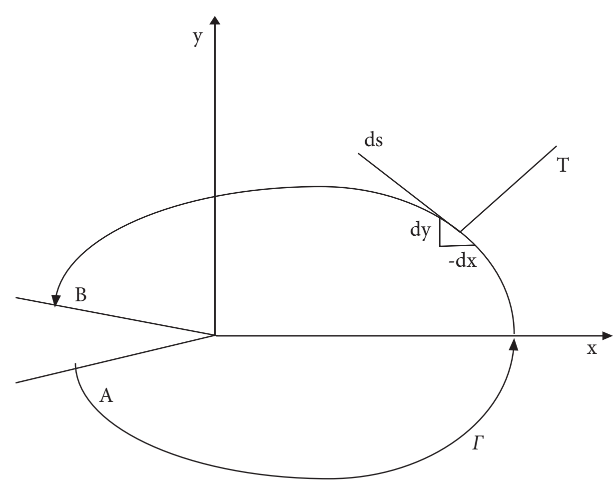

Figure 2: Schematic diagram of J integral.

where W: the strain energy density of the plate; $\overrightarrow{T}$: the vector of external forces acting on the integral loop Γ arc element ds; $\overrightarrow{U}$: the displacement vector on the loop Γ.

The relationship between the J integral and the deformation work, the boundary load or stress vector, and the displacement vector can also be expressed as follows [21]:

$$J = -\frac{\mathrm{d}U}{\mathrm{d}a} + \int_{c_t} t_i \frac{\mathrm{d}u_i}{\mathrm{d}a}\,\mathrm{d}_s, \tag{2}$$

where C_1 is the boundary range perimeter of the specimen. In the fracture impact test, a concentrated load P is applied such that the displacement at the loading point $u_i = 0, u_2 = \delta$, then $\int_{c_1} t_i \mathrm{d}u_i/\mathrm{d}a\mathrm{d}_s = P\mathrm{d}\delta/\mathrm{d}a$, equation (2) can then be simplified to

$$J = -\frac{dU}{da} + \frac{Pd\delta}{da}. \tag{3}$$

From which we have that $J = -(\partial\Pi/\partial a)_p, J = -(\partial U/\partial a)_\delta$. According to the principle of conservation of energy, the work of deformation or strain energy received by the specimen is equal to the work done by the applied load through the displacement of the point of application $\Pi = U - P\delta$ and $U =$

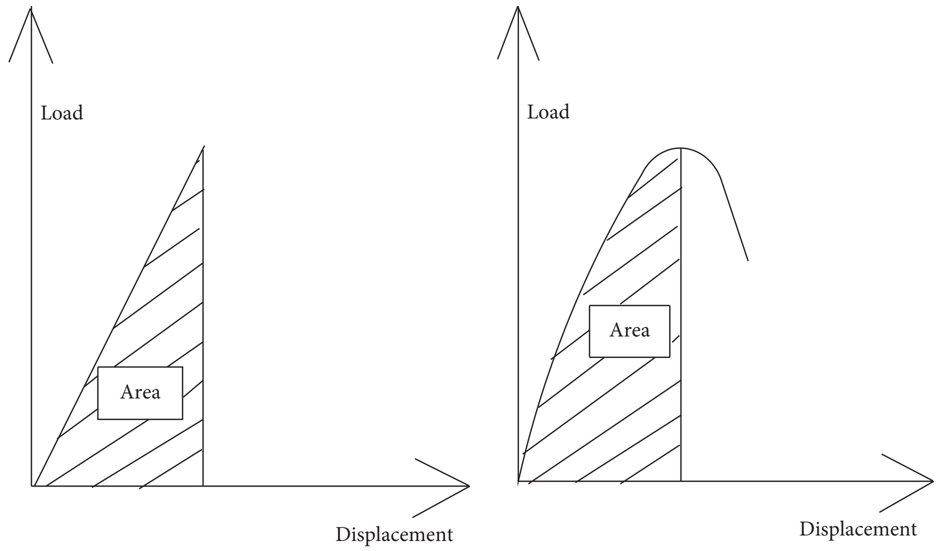

Figure 3: Load displacement diagram: (a) brittle damage; (b) yield damage.

(a) (b)

Figure 4: Impact toughness test: (a) specimens after cutting; (b) MTS testing machine.

$\int_0^{\delta} P\mathrm{d}_{\delta}$; Therefore, we have that $J = \int_0^{\delta} (-\partial P/\partial a)_{\delta}\mathrm{d}_{\delta}$ and equation (3) can then be simplified to

$$J = \int_0^{P} \left(-\frac{\partial \delta}{\partial a}\right)_P \mathrm{d}_P. \quad (4)$$

In this way, the macroscopic load-displacement curve is linked to the J integral. In an elastoplastic body, a certain stress-strain field is generated at the crack when the specimen is deformed by the applied load, and the J integral can quantify the strength of this field. Bagley and Landes established the J integral criterion based on extensive experiments that the J integral was appropriate as a covariate measure of crack cracking [21]. When the J integral around the crack tip reaches a critical value of JC (plane stress) or JIC (plane strain), the crack begins to expand and JC or JIC is made the J integral fracture toughness, representing the crack resistance of the material. As the toughness of JIC can be expressed in terms of the potential energy equation, the J integral fracture toughness of an asphalt mixture can be obtained according to the following equation:

$$J_{IC} = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2}\right)\frac{1}{a_2 - a_1}, \quad (5)$$

where U: load work, i.e. area under the load-displacement curve; specimen thickness (mm); and crack length (mm).

The subscripts 1 and 2 denote the test piece and it can be seen that the material undergoes fracture accompanied by a loss of energy. The energy value can be calculated using the

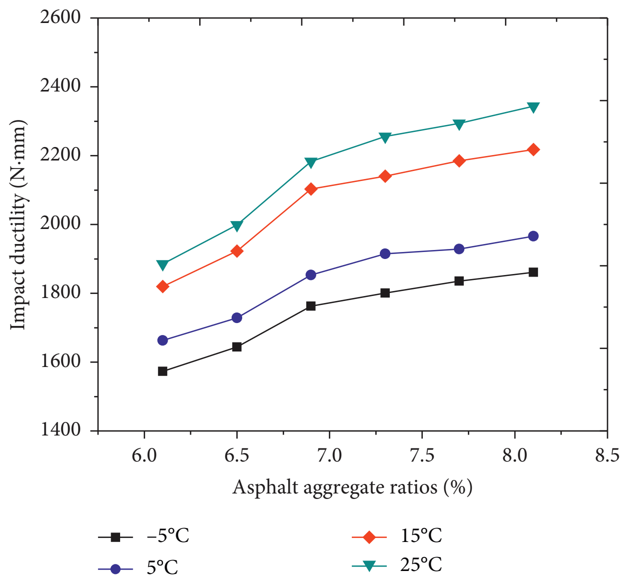

FIGURE 5: Impact toughness test results at different temperatures.

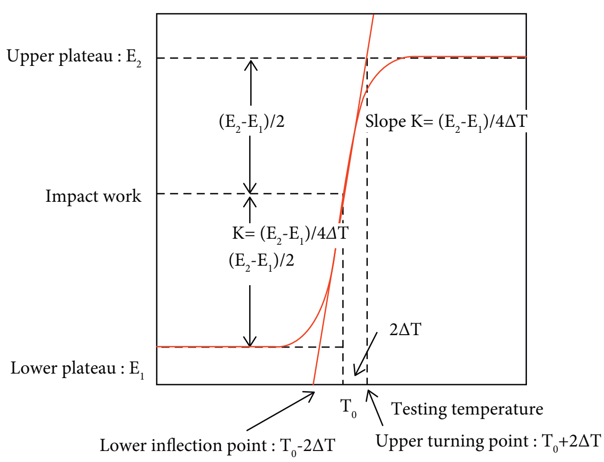

FIGURE 6: Schematic representation of the ductile–brittle transition temperature of an object.

area enclosed by the load-displacement graph. The larger the area enclosed under the test load-displacement curve, the greater the fracture toughness *JIC* and the greater the resistance of the material to damage.

It is well known that brittle and yield damage can occur with varying external temperatures. Figure 3(a) shows a linear relationship between the applied load and the deformation of the specimen, the object is in an elastic state at this stage and the material suddenly fractures when the load is increased to its maximum value, which is typical of brittle fracture damage [22–24]. Figure 3(b) shows that the material does not fracture suddenly when loaded to its maximum load, but continues to deform more and more until it fractures despite gradual unloading [25, 26]. This form of damage is yield damage. In this paper, we define the area of the shaded part of the graph as the impact toughness, which is the work done when the load acts at its maximum [27, 28]. According to formulas (4) and (5) can be seen, impact toughness can reflect the ability of the material to resist fracture damage, combined with Origin software and MATLAB software can calculate the product of the shaded part in Figure 3.

TABLE 6: Sieving results for each grade of aggregate.

	Pass rate (%)			
Sieve hole size	5~10 mm	3~5 mm	0~3 mm	Mineral powder
13.2	100.0	100.0	100.0	100.0
9.5	98.1	100.0	100.0	100.0
4.75	0.0	92.2	100.0	100.0
2.36	0.0	2.2	88.3	100.0
1.18	0.0	0.0	51.4	100.0
0.6	0.0	0.0	30.0	100.0
0.3	0.0	0.0	20.9	100.0
0.15	0.0	0.0	14.1	100.0
0.075	0.0	0.0	8.9	83.0

3.2. Test Procedure. The impact toughness test is to be carried out using small beam prismatic specimens, and the specimen preparation process is as follows:

(1) The specimens were prepared in the form of 300 mm × 300 mm × 50 mm slabs using a wheel mill forming machine for compaction. The prepared specimens were placed in an oven at 60°C for 4 days to allow for rapid curing.

(2) A high-precision double-sided saw manufactured in Finland was used to cut the molded cured specimen into prismatic beams of 250 mm ± 2 mm, 30 mm ± 0.5 mm wide, and 35 mm ± 0.5 mm high, with a span of 200 mm 0.5 mm, as shown in Figure 4(a).

(3) The impact toughness test was carried out on an MTS tester as shown in Figure 4(b). The loading rate of this tester can be adjusted as required and the loading rate for this test was 50 mm/min.

(4) The cut test pieces are placed in the COOPER environmental holding tank for insulation. Adjust the control temperature of the COOPER holding tank as required. When a test is to be carried out, the test piece is removed and immediately loaded to avoid changes in test temperature due to the surrounding environment.

4. Ductile–Brittle Transition Temperature Research

4.1. Analysis of the Effect of Temperature on the Impact Toughness of Mixes. Asphalt mixture is a temperature-sensitive material, the temperature of the mixture has a greater impact on the road performance. When the temperature is high, asphalt binder is prone to softening phenomenon, when the temperature is low when the mixture is not flexible enough to occur brittle damage [29–31]. For steel deck pavement, the surface temperature of

Table 7: Fitting parameter for the ductile–brittle transition of epoxy asphalt mixtures.

Parameter name	Parameter value	Standard deviation	Correlation coefficient
E_1	1784.98	38.42	0.9636
E_2	2188.13	21.97	
T_0	7.50	2.13	
ΔT	2.54	1.76	

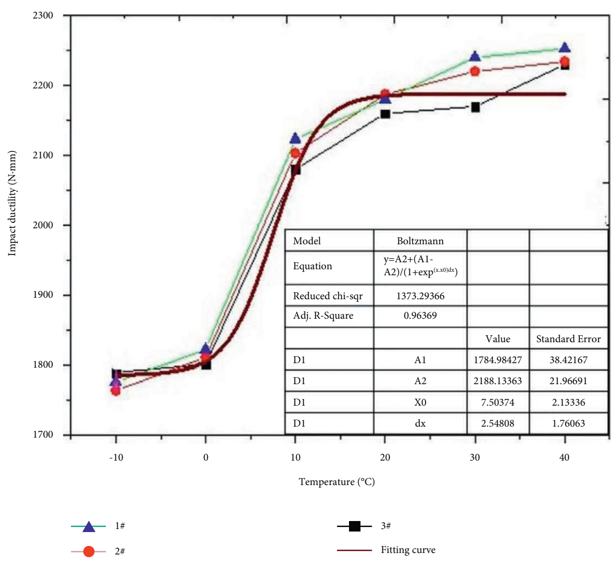

Figure 7: Epoxy asphalt mixture ductile–brittle transition temperature.

the pavement is low due to the dramatic drop in winter temperatures and is susceptible to bending damage under traffic loads. To understand the effect of temperature variation on the flexural performance of the paving layer, impact toughness tests were carried out at different temperatures (−5°C, 5°C, 15°C, and 25°C) and different asphalt aggregate ratios (6.1%, 6.5%, 6.9%, 7.3%, 7.7%, and 8.1%) according to test method 3.2, and the test results are shown in Figure 5.

As can be seen from Figure 5, the impact toughness of the epoxy asphalt mixture gradually increased as the test temperature increased, mainly due to the dependence of the epoxy asphalt properties on temperature which dictated that the asphalt mixture properties were also significantly affected by temperature. As the test temperature increases, the epoxy asphalt mixture changes from a glassy brittle solid to a viscoelastic body and the damage state of the mixture changes from brittle damage to yield damage. Also, a small viscoelastic deformation occurs within the epoxy asphalt mixture, which increases the area of the load-displacement curve, i.e. the impact toughness gradually increases, indicating that the toughness of the epoxy asphalt mixture gradually increases with the increase in temperature, and the crack resistance of the epoxy asphalt mixture gradually increases. As can be seen from Figure 5, the asphalt aggregate ratio has a greater impact on the impact toughness of the mix, with the increase in the asphalt aggregate ratio; the impact toughness of the epoxy asphalt mixture gradually increases. When the asphalt aggregate ratio is less than 6.9%, the slope of the curve increases faster and the impact toughness changes more; when the asphalt aggregate ratio is greater than 6.9%, the slope of the curve changes less and the impact toughness grows slowly. This is mainly because epoxy bitumen is a curing material and the source of its strength depends mainly on the combined action of the epoxy resin and the curing agent. When the asphalt aggregate ratio is small, the thickness of the asphalt film wrapped around the aggregate is thin, the bond between the aggregates is small, the resistance to deformation is poor, and the impact toughness is small. When the asphalt aggregate ratio is large, the thickness of the structural asphalt wrapped around the aggregate reaches saturation. With the increase of the asphalt aggregate ratio, the thickness of the structural asphalt layers no longer changes and the impact toughness changes less. Therefore there is a threshold point for the amount of bitumen (asphalt aggregate ratio) which controls the magnitude of the impact toughness variation of the mix. Based on the above analysis, the threshold for the asphalt aggregate ratio of epoxy bitumen designed in this paper is 6.9%.

4.2. Determination of the Ductile–Brittle Transition Temperature. At this stage, there are many ways to study the ductile–brittle transition temperature of objects. Kim et al. [32] used a small beam impact work method to determine the ductile–brittle transition temperature of RPV vessels. Contreras et al. [33] and Tiwari and Paul [34] studied the ductile–brittle transition temperature of steel structures and polymers, respectively, and analyzed the various factors affecting the ductile–brittle transition temperature. Zhong et al. [35] applied the mathematical model ($T = T_c - 1/b \ln (Y_{max} - Y_{min}/Y - Y_{min} - 1)$) to predict the ductile–brittle transition temperature of steel. Luo et al. [36] adopted Origin software to evaluate the ductile–brittle transition temperature and gave the physical significance of the Boltzmann function. In this paper, the Boltzmann function is used to evaluate the ductile–brittle transition temperature of epoxy asphalt mixtures. Due to unpredictable factors, it is unlikely that the impact work at the set temperature in the test will reach exactly the ductile–brittle transition value of the object. Therefore, curve fitting and interpolation methods are usually used to determine this. The Boltzmann function expression is as follows:

$$E = \frac{E_1 - E_2}{1 + \exp^{(T - T_0)/\Delta T}} + E_2. \quad (6)$$

The parameters of the Boltzmann function according to equation (6) and in combination with Figure 6, when the test temperature $T \longrightarrow -\infty$, $E \longrightarrow E_1$, E_1 represents the lower plateau value of the material; when the test temperature

Table 8: Bending test results for small beams at the ductile–brittle transition temperature.

Specimen no	Maximum load at the damage (N)	Max. deflection at the damage (mm)	Extreme tensile strain (10^{-6})	Modulus of bending stiffness (MPa)
1	2844.70	0.68	3640.22	6349.00
2	2839.90	0.72	3857.16	6149.71
3	2887.00	0.48	2526.82	9630.96
4	2857.80	0.64	3375.56	7151.76
	Average		3350	7320.36

$T \longrightarrow +\infty$, $E \longrightarrow E_2$, E_2 represents the upper plateau value of the material, $T_0 = (E_1 + E_2)/2$ represents the ductile–brittle transition temperature. $T_1 = T_0 - 2\Delta T$ represents the lower transition temperature of the material. $T_2 = T_0 + 2\Delta T$ represents the inflection point transition temperature on the material, the entire temperature transition interval is $4\Delta T$, the narrower the temperature range spanned by the transition temperature interval, the easier it is for the material to transition from a plastic to a brittle state.

Taking into account the physical properties of the epoxy asphalt mixture and the performance of the roadway in different areas of the bridge deck at this stage, based on the optimal asphalt-aggregate ratio of 6.9% determined above, the impact toughness tests at −10°C, 0°C, 10°C, 20°C, 30°C and 40°C were carried out respectively. Three tests were carried out at each temperature, numbered 1#, 2#, and 3# respectively. Based on the impact toughness test data, the Boltzmann function was fitted using Origin and Matlab software. The test results and numerical fitting results are shown in Table 7 and Figure 7.

The fit was carried out according to the Boltzmann function expression $E = E_1 - E_2/1 + \exp^{(T-T_0)/\Delta T} + E_2$ and the result was $E = -403.15/1 + \exp^{(T-7.50)/2.54} + 2188.13$ a correlation coefficient $R2 = 0.9636$. Based on the fitted results, the ductile–brittle transition temperature T_0 of the epoxy asphalt mixture is 7.5°C. The ductile–brittle transition interval $4\Delta T$ is 10.16°C. The smaller the ΔT narrower the temperature range spanned by the transition temperature interval, indicating that the epoxy asphalt mixture is more likely to change from a plastic to a brittle state. The Boltzmann function is therefore a good description of the relationship between impact toughness and temperature and can determine the ductile–brittle transition temperature of the mix more accurately. To further understand the mechanical properties of the epoxy asphalt mixture at the ductile–brittle transition temperature, the bending test of the epoxy asphalt mixture at the ductile–brittle transition temperature (7.5°C) was conducted in this paper, and the test results are shown in Table 8.

As can be seen from Table 8, the ultimate tensile strain of the epoxy bitumen mix at the ductile–brittle transition temperature is 3350 $\mu\varepsilon$ and the bending stiffness modulus is 7320.36 MPa. When the surrounding temperature of the entity project is lower than the ductile–brittle transformation temperature, the impact toughness of the epoxy asphalt mixture can be seen by the test results in Figure 7, there will be a substantial reduction in the mixture of crack resistance, and then will produce low-temperature bending damage phenomenon.

The ductile–brittle transition temperature is an important indicator of the tendency of epoxy asphalt mixtures to change from brittle to elastic-plastic. It determines the range of applications of epoxy asphalt concrete and can better explain the susceptibility of epoxy asphalt concrete paving to cracking under low-temperature conditions. Therefore, the ductile–brittle transition temperature can be used as an important criterion to prevent the fracture of epoxy asphalt concrete. Understanding the ductile–brittle transition temperature of epoxy bitumen is important for predicting its low-temperature fracture behavior and can provide a basis for the paving application range of epoxy bitumen concrete steel bridge decks.

5. Conclusions

(1) The cracking resistance of epoxy asphalt mixture is influenced by temperature and asphalt aggregate ratio. As the test temperature increases, the impact toughness of the mixture gradually increases and the anticracking properties are gradually enhanced.

(2) According to the epoxy asphalt material and grading used in this paper, the threshold point of the asphalt aggregate ratio of epoxy asphalt mixture is 6.9%. When it is less than 6.9%, the impact toughness increases faster and the crack resistance is enhanced. When greater than 6.9%, the impact toughness changes less and the cracking resistance is not significant. From the perspective of cost-effectiveness, it is recommended that the asphalt aggregate ratio of epoxy asphalt should be taken as a threshold value.

(3) The Boltzmann function is a good description of the relationship between impact toughness and temperature. The physical significance of the parameters of the function is clear and, when combined with impact toughness testing, can predict the toughness transition temperature of epoxy asphalt mixtures more accurately.

(4) Based on the fitted results, the ductile–brittle transition temperature T_0 of the epoxy asphalt mixture designed in this paper is 7.5°C; the ductile–brittle transition interval is 10.16°C. The determination of

the ductile–brittle transition temperature of the epoxy asphalt mixture can qualitatively be used as an important criterion to prevent the fracture of the epoxy asphalt mixture, which can determine the scope of application of the epoxy asphalt mixture.

Data Availability

The (DATA TYPE) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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