

Article

Evaluation Methods and Influence Factors of Blisters Disease in Concrete Composite Bridges

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Abstract: The decks of steel–concrete composite bridges are constantly exposed to severe environmental conditions, which frequently give rise to significant issues, including cracks and holes. These problems occur due to the formation of blisters under the paving layer with waterproofing membranes. This paper aims to delve into the characteristics of blisters during their expansion and propagation stages. Additionally, it proposes a rating index and a simplified calculation formula to assess the interface propagation performance of bridge deck pavement. To achieve this, the research group developed a simulated blister test device and employed the digital image correlation (DIC) technique. The study investigated the impact of pavement structure, waterproofing layer, and air voids on blister propagation behavior. It was discovered that the pavement blister test encompassed two distinct stages: expansion and propagation. Furthermore, the SMA-13 asphalt mixture exhibited slightly superior resistance to blistering compared to AC-13. It was also observed that when the mixture void ratio is less than 3.5%, it becomes more susceptible to blistering deformation, ultimately leading to debonding damage. Among the waterproofing materials tested, SBS-modified emulsified asphalt demonstrated the weakest adhesion to cement concrete substrates, while SBS-modified asphalt performed slightly better than rubberized asphalt.

Keywords: concrete bridge deck pavement; blister test; asphalt blistering; asphalt deflection; evaluation of blister propagation

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1. Introduction

Blistering commonly occurs on bridge decks, and it is primarily caused by the accumulation of air and water vapor pressure beneath the pavement of steel–concrete composite bridge [1–6]. The existence of blister will change the stress state of the pavement, leading to the redistribution of the stress field. Cracks, breakages, and even holes in the pavement caused by blisters under traffic load can significantly impact the service life and safety of bridge structures [7,8]. Generally, blisters can be treated through post-processing methods such as drilling drainage and slotting drainage, among others. Although these methods have a mitigating effect, they cannot fundamentally solve the problem. Numerous studies have been conducted on the formation mechanism of blisters [9,10], while there is a lack of research on the propagation mechanism of blisters. Therefore, it is urgent to determine the propagation criterion and influencing factors of blisters in order to implement effective measures and minimize or eliminate problems related to asphalt overlays.

Dannenberg [11] initially introduced the idea of the blister tests to assess the bonding strength between organic coatings and metals. They have also found significant application in studying the propagation of debonding, particularly the separation of a thin layer of adhesive from the substrate [12]. Several researchers have contributed valuable insights and techniques in this field. Steven [13] utilized the Hencky series equation to examine blister propagation. Utilizing an atomic force microscope (AFM), the shape of bulged graphene

membranes at the nanoscale could be precisely measured, with the maximum deflection serving as a crucial parameter in such analyses. Kaimin [14] emphasized that adhesive interactions are encompassed within an energy balance equation, which considers both strain and adhesion energies. This provides a comprehensive understanding of the forces governing debonding processes. In assessing blister propagation, Liao [15] implemented a displacement sensor that accurately measured the expansion of blisters. This enabled the quantification and analysis of blister behavior over time. Furthermore, the blister test holds the potential to simulate crack propagation along the interface between the paving layer and substrate. By subjecting these systems to blister tests, researchers gain insights into the dynamics of crack propagation and the underlying mechanisms. Harvey [16] established a mechanical model for the adhesion toughness of monolayer films under pressure load and point load, namely mode I and II. Williams [17] developed a linear elastic fracture mechanics model to analyze a blistering plate under bending. Jensen further enhanced the model by considering stress intensity factors. Cotterell and Chen [18] solved the Von Karman equation to study blistering films with a wide range of thicknesses. They calculated the constitutive relation and derived the fracture energy (G) through an energy balance. Tan [19] utilized digital speckle correlation techniques to explore the tensile strain rate of asphalt beams across varying stress levels, revealing their deformation patterns over time. In 2013, Yuan [20] combined these techniques with four-point bending fatigue tests, providing a microscopic view of asphalt mixture fatigue deformation. Then, in 2015, Xing Yongming [21] applied the same methods to semi-circular bending tests on UV-aged and modified asphalt mixtures, offering insights into crack initiation and propagation patterns.

In this paper, we will outline the criteria for blister propagation by deriving the fracture energy (G) through a comprehensive analysis of energy balance from first principles. The procedure is detailed in the following steps: (1) In the first section, the preparation process of the investigated sample and the experimental device is introduced. (2) Then, the deformation of the blister is presented and its failure pattern is described. (3) Consequently, the propagation criteria based on energy change are proposed and the expansion mechanism is analyzed. (4) Finally, the influence of pavement structure, waterproofing layer and air voids on blister propagation is discussed.

2. Materials and Methods

2.1. Investigated Samples

The main objective of this article was to determine the propagation behavior of blistering. Six different types of deck pavement were used for this investigation (see Table 1). Considering that the common blister disease of bridge deck pavement is mainly caused by asphalt mixtures with low air voids, AC-13 (optimal asphalt content is 5.0%) and SMA-13 (optimal asphalt content is 6.15%) were used in the experiment.

Table 1. Different types of blister test samples.

Sample	Mixture	Waterproofing Layer	Bottom Plate
1	AC-13	SBS-modified asphalt	Cement concrete substrate
2	AC-13	Asphalt rubber	Cement concrete substrate
3	AC-13	SBS-modified emulsion asphalt	Cement concrete substrate
4	SMA-13	SBS-modified asphalt	Cement concrete substrate
5	SMA-13	Asphalt rubber	Cement concrete substrate
6	SMA-13	SBS-modified emulsion asphalt	Cement concrete substrate

The sample preparation process is as follows:

- Cement concrete plates with dimensions of 300 mm width, 300 mm length, and 50 mm height were prepared as substrates. Each plate included a centrally positioned hole with a diameter of 10 mm that serves as a hydraulic inlet at the bottom. The orifice (filled with fine sand) in the substrate is sealed using asphalt release agent on the surface.

- The waterproofing membrane was set in an interlayer between the concrete and the asphalt mixture to prevent water intrusion and increase the interfacial bonding force.
- Next, 5 cm thick asphalt mixture was laid over the substrates, and the total test mold was rolled into shape under the wheel mill.
- Finally, the well-formed specimen was conditioned at room temperature for 48 h before removing the mold. Figure 1a shows the prepared sample.
- To facilitate the observation of blister behavior in experiments, a paint spray technique was employed on the asphalt mixture, resulting in a spackle-like pattern as illustrated in Figure 1b. Subsequently, a layer of white primer was applied and allowed to thoroughly dry. To ensure clear visibility and enhance contrast, black spots were manually sprayed onto the surface, creating a distinct gray differentiation.

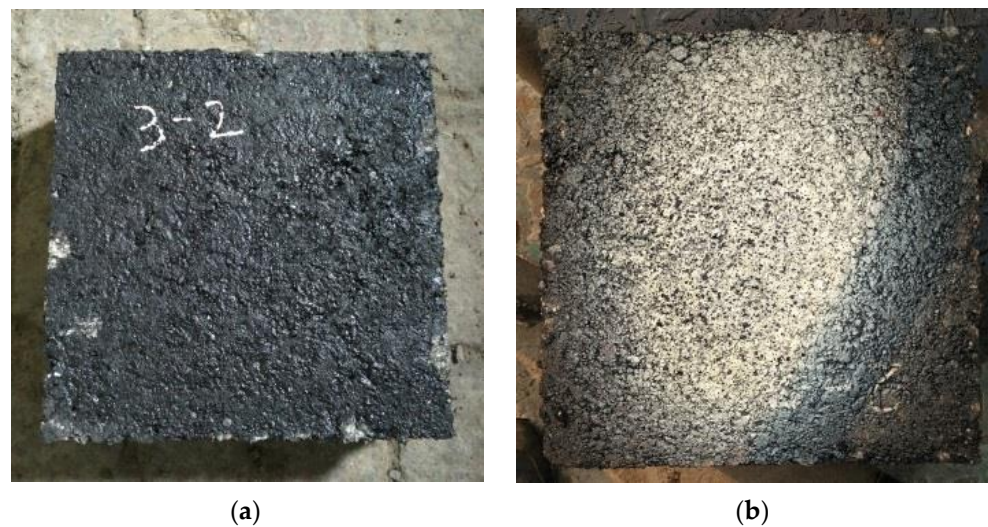


Figure 1. (a) The virgin sample and (b) the speckled sample.

2.2. Blister Test

The blister loading device and data acquisition device used in this experiment are mainly composed of a hydraulic loading system, a sample bearing platform, a sample fixing device, an environment box developed by the research group and an MTI-3D non-contact displacement measurement system. The blister test method uses an electro-hydraulic servo fatigue machine to control the flow rate of injected oil.

The sample bearing platform is a high-strength steel plate (80 cm × 80 cm × 1 cm) with a stainless-steel bolt at each corner (for sample securing), as is shown in Figure 2a. The platform contains a central hole with a size of 1 cm diameter as oil pressure inlet from the hydraulic oil chamber below. In order to prevent the hydraulic oil from leaking from the bottom of the sample during the loading process, three O-shaped rubber seal ring are arranged on the outside of the orifice, as presented in Figure 2b.

To ensure the sample was in close contact with the O-ring seal and no slippage occurred under liquid pressure, a sample fixing device was designed as indicated in Figure 3. The device is a high-strength steel plate of thickness 1 cm with a central hole size of 28 cm × 28 cm. The device is tightened on the sample bearing platform by bolts to form a fixed reaction frame. Therefore, it not only ensures the sealing, measuring precision, but also convenient handling and simple operation.

The transparent environmental box was connected to the bearing platform, which was used to control the test temperature and humidity. As shown in Figure 4, the environment box consisted of a heating and humidifying system, temperature and humidity control system, lighting, and other components. The four sides of the environmental box were made up of stainless-steel plate and an insulation layer to ensure the constant temperature and humidity of the internal gas. The top of it was made of low-refractive-index toughened

glass, which is convenient for the non-contact displacement measurement system for observing blister behavior.

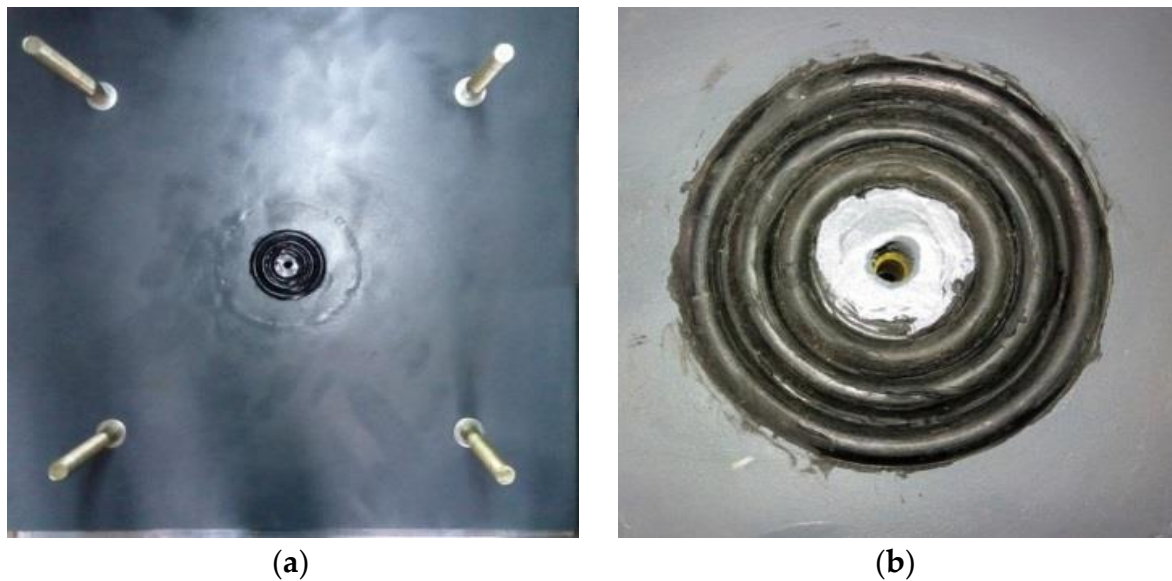
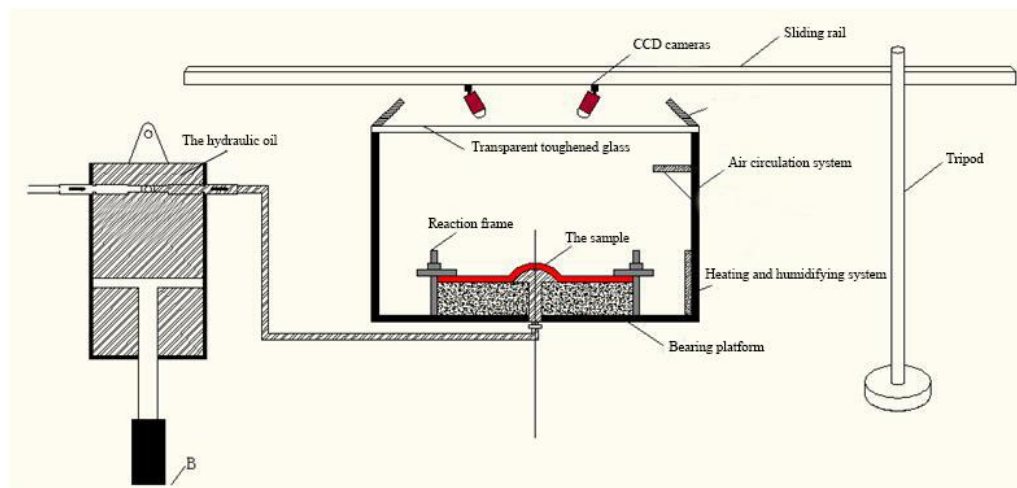


Figure 2. (a) The sample bearing platform and (b) the seal ring.

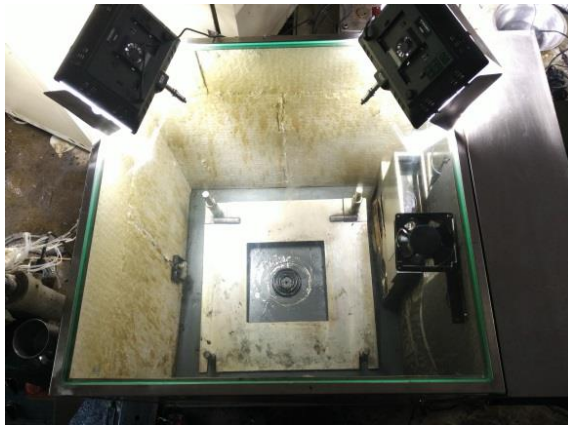


Figure 3. The sample fixing device.

In order to overcome the limitations of a traditional deformation measurement device, such as single point realization testing, complicated optical path testing and difficult equipment control, etc., the Digital Speckle Correlation Method (DSCM) was used to collect the deformation data of blister in this paper. The evolution of the blisters was documented by the MTI-3D structural deformation analysis system, comprising both hardware and software components. The hardware subsystem included two high-precision industrial CCD cameras, two high-performance lenses with a focal length of 25 mm and 50 mm, respectively, a signal synchronous collector, a lighting system, and a workstation. The MTI-3D analysis calculation flow is shown in Figure 5. The pressure simulation test was carried out at 60 °C until the specimen was damaged.



(a)



(b)



(c)

Figure 4. The environmental box (Note: (a) the schematic diagram of test equipment; (b) the top of the environmental box; (c) data acquisition device).

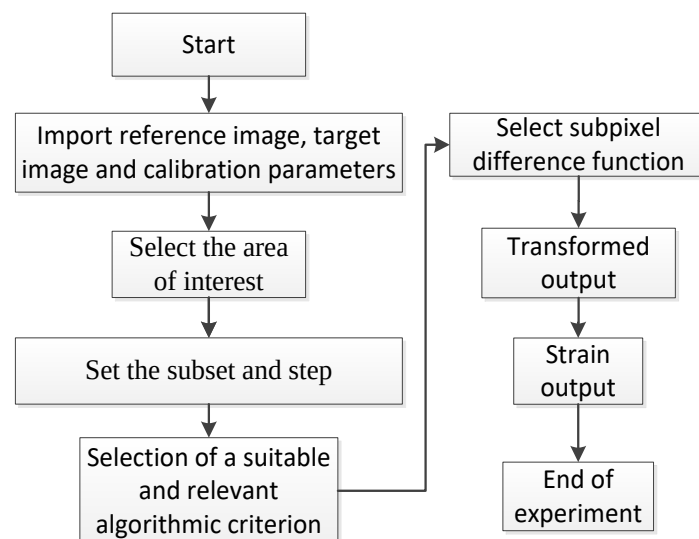


Figure 5. MIT-3D calculation flowchart.

3. Results and Discussion

3.1. The Blister Propagation and Failure Patterns

Under uniform load, the failure surface of the blister on asphalt mixture pavement is not regular. The deflection at middle points of blister is relatively large (about 4.5 mm). This irregular deformation is mainly due to the uneven paving layer. The final failure of the blister is caused by the interfacial debonding between the asphalt mixture paving layer and the cement concrete substrates with the increasing pressure. Meanwhile, the pressurized liquid seeps from the side of the sample. The expansion of the blister along the bonding interface indicates that the bonding surface between the deck pavement and the concrete plates is its area of weakness.

It is found that the deformation of the blister is divided into two stages: expansion and propagation. In the expansion stage, the obvious deflection occurs after the load reaches a certain value due to the high rigidity of the pavement layer, and increases sharply with the load (see Figure 6a). Afterwards, the blister begins to propagate and the deflection decreases when the load reaches the critical load of blister expansion (see Figure 6b). This observation suggests that the crack initiation and propagation of blister may be the reason for the decrease in the overall stiffness of the sample, which will affect the mechanical behavior of the material under the load.

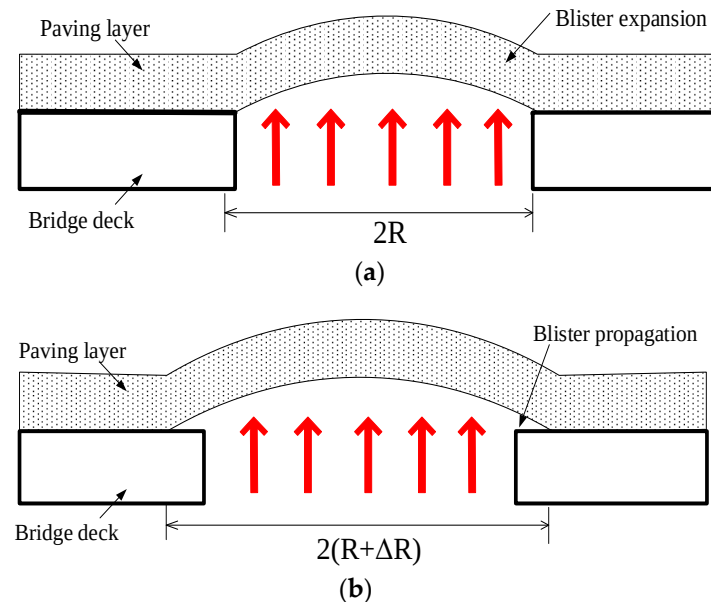


Figure 6. A pressurized circular blister (a) the expansion stage and (b) the propagation stage.

3.2. The Propagation Criteria of Blister

The center deflection ω of the paving layer changes with the pressure P . Because the edge of the paving layer is clamped on substrate, the boundary conditions are:

$$\begin{aligned} \omega &= 0 \text{ and } \frac{d\omega}{dr} = 0, \text{ for } r = R \\ \omega &= \omega_0 \text{ and } \frac{d\omega}{dr} = 0, \text{ for } r = 0 \end{aligned} \quad (1)$$

If residual stress in a paving layer can be ignored, the relationship between pressure and deflection can be written as

$$\omega(r) = \frac{P}{64D} (R^2 - r^2)^2 = \frac{P}{64D} a^2 \quad (2)$$

where the stiffness D is determined by the following expression:

$$D = \frac{Eh^2}{12(1-v^2)} \quad (3)$$

where a is the radius of a blister at propagation and h is the pavement thickness, P is the critical pressure at propagation, E is the elastic modulus, ω is the largest deflection of the blister center, and v is the Poisson ratio.

The elastic modulus can be quantitatively determined from the deflection of the blister and the applied pressure, and given by Equation (4)

$$E = \frac{p}{w} \left[\frac{(1-v^2)a^4}{5.3h^3} + \frac{(1+v)a^2}{1.7h} \right] \quad (4)$$

Equation (2) indicates that the blister deflection is related to the pressure, the radius of debonding, the pavement thickness and the stiffness modulus. Under certain deflection, the applied force of the blister is inversely proportional to the debonding radius, which is proportional to the stiffness modulus and pavement thickness. Therefore, the choice of the appropriate loading radius is critical for the effective acquisition of blister cracking loads.

Propagation criterion is a basis for determining whether a crack will expand and in which direction it will expand. The initial crack direction for a blister was predicted using the maximum energy release rate criterion in this study.

From the perspective of fault theory, crack expansion occurs because the strain energy is greater than the energy required for the material to resist crack development. Thus, the critical condition of blister propagation is expressed as:

$$G = G_{cr} \quad (5)$$

The energy release rate, denoted as G , represents the force required to detach the membrane from the substrate. G is calculated per unit width situated along the elliptical failure boundary separating the asphalt paving layer and the underlying concrete. It is expressed in $\text{N} \cdot \text{m}^{-1}$, as illustrated in Equation (6).

$$G = \frac{\Delta W - \Delta W_2}{2\pi R \Delta R} = \frac{q(V|_{R+\Delta R} - V|_R) - \Delta W_2}{2\pi R \Delta R} = \frac{3q^2 R^4 (1-v^2)}{32Eh^3} + \frac{3q^2 R^2 (1+v)}{10Eh} \quad (6)$$

The cumulative energy involved in the spread of the adhesive blister is composed of two components: the potential energy resulting from an externally applied load and the elastic strain energy stored within the membrane. The magnitude of this energy is influenced by the geometry of the adhesive failure region [22,23], as described by Equation (7).

$$\begin{aligned} \Delta W &= \Delta W_1 + \Delta W_2; \Delta W = q\Delta V = q(V|_{R+\Delta R} - V|_R) = q\left(\frac{\partial V}{\partial R}\right)_q \Delta R \\ \Delta W_1 &= 2\pi R G \Delta R; \\ \Delta W_2 &= \int \sigma d\epsilon|_{R+\Delta R} - \int \sigma d\epsilon|_R \end{aligned} \quad (7)$$

where ΔW is the blister propagation energy, ΔW_1 is the energy consumed for blister propagation and ΔW_2 is the elastic strain energy, and q is the uniform load.

The critical pressure p_{cr} required for a blister to expand from an initially flat state to a certain height can be determined when the strain energy release rate G reaches the critical release rate G_{cr} , as shown in Equations (8) and (9).

$$p_{cr} = \sqrt{\frac{512Eh^3 G_{cr}}{3(1-v)}} \times \frac{1}{(2R)^2} = \frac{k_1}{(2R)^2} \quad (8)$$

$$k_1 = \sqrt{\frac{512Eh^3 G_{cr}}{3(1-v)}} \quad (9)$$

3.3. The Mechanism of Blister Propagation

A specimen was placed in the test setup, and the pressure inside the blister was gradually increased until it reached its highest point, resulting in the separation of the blister. Each sample had three parallel groups. The changes in the radius and deflection of the blister over time are illustrated in Figure 7. Within the initial 60 s of loading, the blister started to bulge without any change in its radius, while its height increased proportionally to the pressure, as shown in Figure 7a. The deflection of the blister increased after 20 s and expanded rapidly after 60 s (see Figure 7b). Finally, the radius of the blister stabilized at 80 s, and its deflection showed the tendency to decrease slightly first and then increase gradually. This was the generation phase of the next blister propagation. Subsequently, the specimen experienced a cycle of unloading and reloading. This process was repeated until the asphalt paving layer completely separated from the substrate.

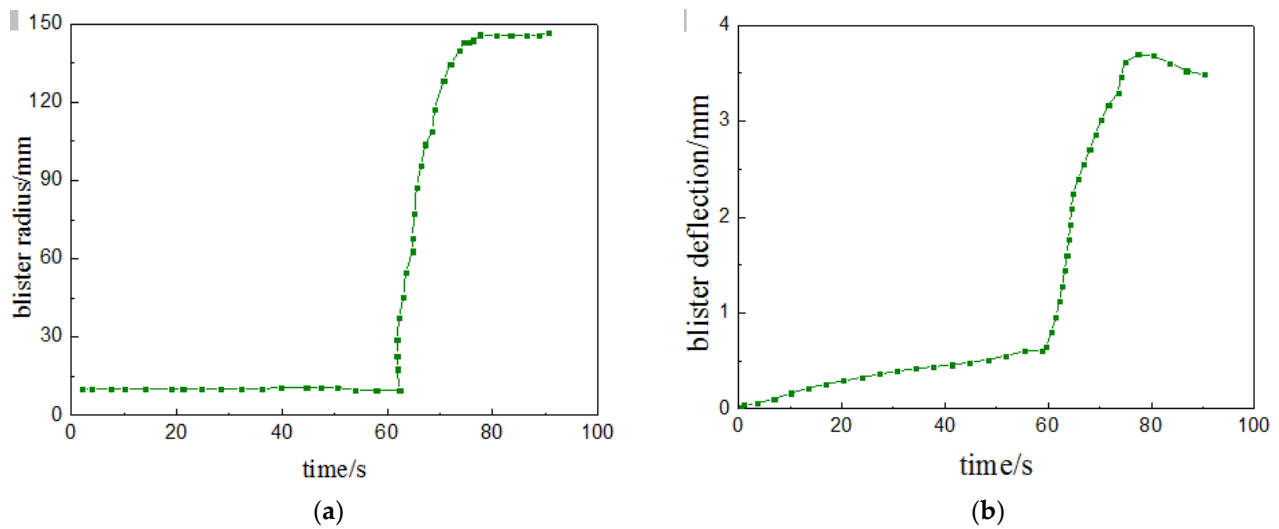


Figure 7. (a) The blister radius with time and (b) measured blister deflection.

Boyle's law can be stated as Equation (10)

$$V\Delta p + p\Delta V = 0 \quad (10)$$

The product of pressure and volume is equal to a constant value, denoted as k . In this equation, P denotes the pressure of the gas, Δp is the variable quantity of the gas, V denotes the volume of the gas, and ΔV is the variable quantity of the volume, which can be written as:

$$V = \int_0^R \omega(r) 2\pi r dr = \frac{\pi q R^6}{192D} \quad (11)$$

$$\Delta V = \frac{\pi R^5 p}{32D} \Delta R \quad (12)$$

When G is equal to G_{cr} , the critical pressure for blister expansion can be calculated from Equations (8) to (12):

$$\Delta p = -\frac{3k_1}{2R^3} \Delta R \quad (13)$$

The above Equation (13) indicates that the blister pressure decreases $\frac{3k_1}{2R^3} \Delta R$ when the blister radius increases gradually from R to $R + \Delta R$ during the propagation process.

Differentiating the above equation in Equation (8) and solving the change in blister radius ΔR to the change in blister critical pressure Δp_{cr} results in

$$\Delta p_{cr} = -\frac{k_1}{2R^3} \Delta R \quad (14)$$

It can be seen from Equations (13) and (14) that the pressure and critical pressure of a blister decreases with the growth of the blister radius. This means that the propagation will stop when the pressure in the blister is reduced to less than the critical pressure. When the blister radius remains stable, the volume of gas in it is unchanged. At this point, the blister pressure increases gradually with the load. Eventually the pressure will be increased to exceed the critical pressure, Δp_{cr} , and an interface separation will occur between the asphalt paving layer and concrete substrate, at which point a new propagation cycle with the growth in blister radius begins until final failure.

3.4. The Influence of Pavement Structure on Blister Propagation

Figure 8 shows the curves indicating the variation in blister deflection with time under different pavement layer structures. Each sample has three parallel groups. Bulging of the blister on AC-13 asphalt pavement was observed after the first 38 s loading period and increased with the load. Then the blister height reached up to 4.5 mm (the maximum) after 77 s and the deflection gradually decreased, while the deflection of SMA-13 occurred 20 s later than that of AC-13. This indicated that the blister propagation of SMA-13 was relatively slow, but the deflection of both pavements was basically the same. Thus, the degree of blister propagation of SMA asphalt pavement is lower than that of AC-13 asphalt pavement.

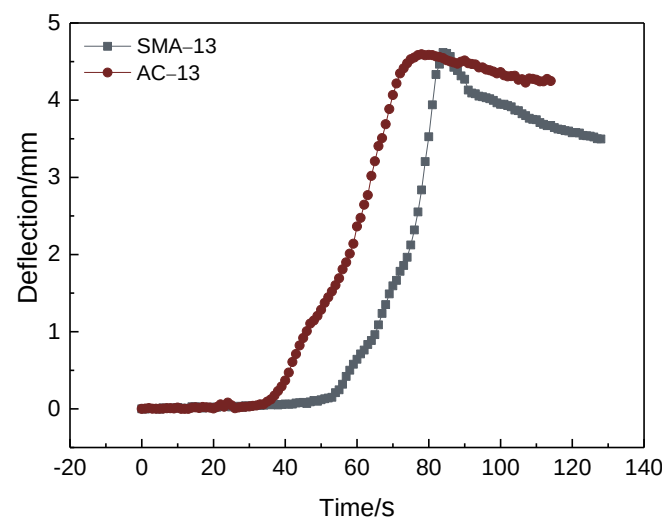


Figure 8. The variation in blister deflection with time under different pavement layer structure.

The blister critical propagation loads and critical propagation deflections of the SMA-13 and AC-13 obtained in the tests were substituted into Equations (4) and (6) to obtain the critical energy release rates G for both SMA-13 and AC-13 samples, as shown in Table 2. The critical propagation load and the critical propagation deflection on the SMA-13 asphalt paving layer are larger than those of AC-13. The results prove that the ability of SMA-13 to resist blister deformation is better than that of AC-13.

Table 2. The blister propagation energy release rate G under different pavement layer structure.

Mixture	Waterproofing Layer	Load (at Peak) /N	Deflection (at Peak) /mm	Propagation Time /s	Critical Energy Release Rate/ $\text{N}\cdot\text{m}^{-1}$
SMA-13	SBS-modified asphalt	1550	4.65	85	179
AC-13	SBS-modified asphalt	1432	4.58	77	163

3.5. The Influence of Waterproofing Layer on Blister Propagation

For comparing and ranking the influence of membranes on blister propagation, the deflection of blister with SBS-modified asphalt, asphalt rubber and SBS-modified emulsion

asphalt waterproofing membranes were determined in a blister test. The results of each blister central deflection are shown in Figure 9. Blister tests were performed at 60 °C, increasing the pressure for 140 s during blister growth.

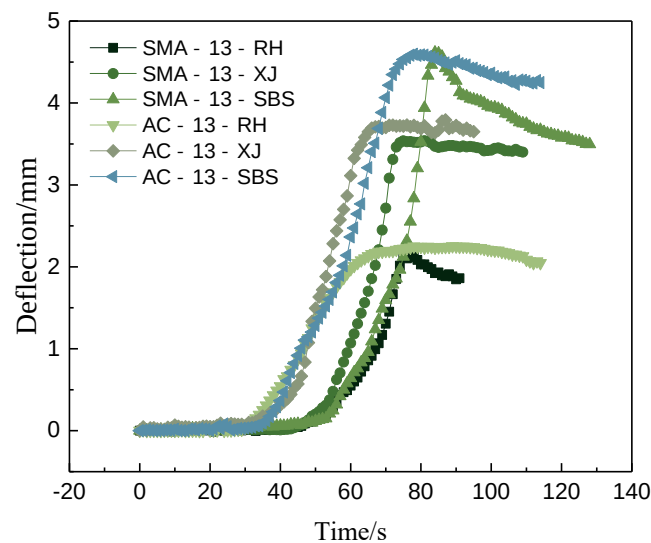


Figure 9. Deflection curves of the blister with different waterproofing layers. (Note: SBS—SBS-modified asphalt; XJ—asphalt rubber; RH—SBS-modified emulsion asphalt).

When comparing the deflection results of blister tests for the SBS (SBS-modified asphalt), XJ (asphalt rubber), and RH (SBS-modified emulsion asphalt) membranes in the same pavement structure, it can be observed that the SBS membrane has a greater deflection value compared to the other types. For the same paving layer, the bulging of the blister on the AC-13 pavement (waterproofing adhesive is SBS-modified asphalt) was observed earliest (at 73 s), with a maximum deflection of 4.6 mm; the bulging of the blister on the AC-13 pavement (waterproofing adhesive is SBS-modified emulsion asphalt) was observed earliest (at 62 s), with a maximum deflection of 3.7 mm; the bulging of the blister on the AC-13 pavement (waterproofing adhesive is asphalt rubber) was observed earliest (at 57 s), with a maximum deflection of 2.0 mm. It can be seen that SBS-modified emulsified asphalt has the worst adhesion to cement concrete bridge deck decks, rubber asphalt is better, and SBS-modified asphalt is the best. The reason for the difference in blister propagation time can be attributed to the different membranes' properties.

For the same waterproofing layer, the AC-13 pavement structure has lower deflection and a shorter propagation time compared to SMA-13. For example, the bulging of the blister on SMA-13 pavement (waterproofing adhesive is SBS-modified asphalt) was detected at the latest time point, at about 85 s, with a maximum deflection of 4.7 mm. In contrast, the bulging of the blister on AC-13 pavement (waterproofing adhesive is SBS-modified asphalt) was observed at the earliest time point (at 73 s), with a maximum deflection of 4.6 mm. This shows that the SMA-13 asphalt mixture bulge deformation is smaller under the same load level condition.

3.6. The Influence of Air Voids on Blister Propagation

The influence of air voids on blister propagation behavior was investigated in this paper. The samples were obtained by coring from the central debonding site. Prior to the experiments, the bottom cement concrete of the samples was removed. In order to avoid the influence of the speckle on the air voids, the sample surfaces were polished. Then they were dried to a stable weight by putting them in a drying oven. Each sample had three parallel groups. Finally, their air voids were measured, as shown in Figure 10.

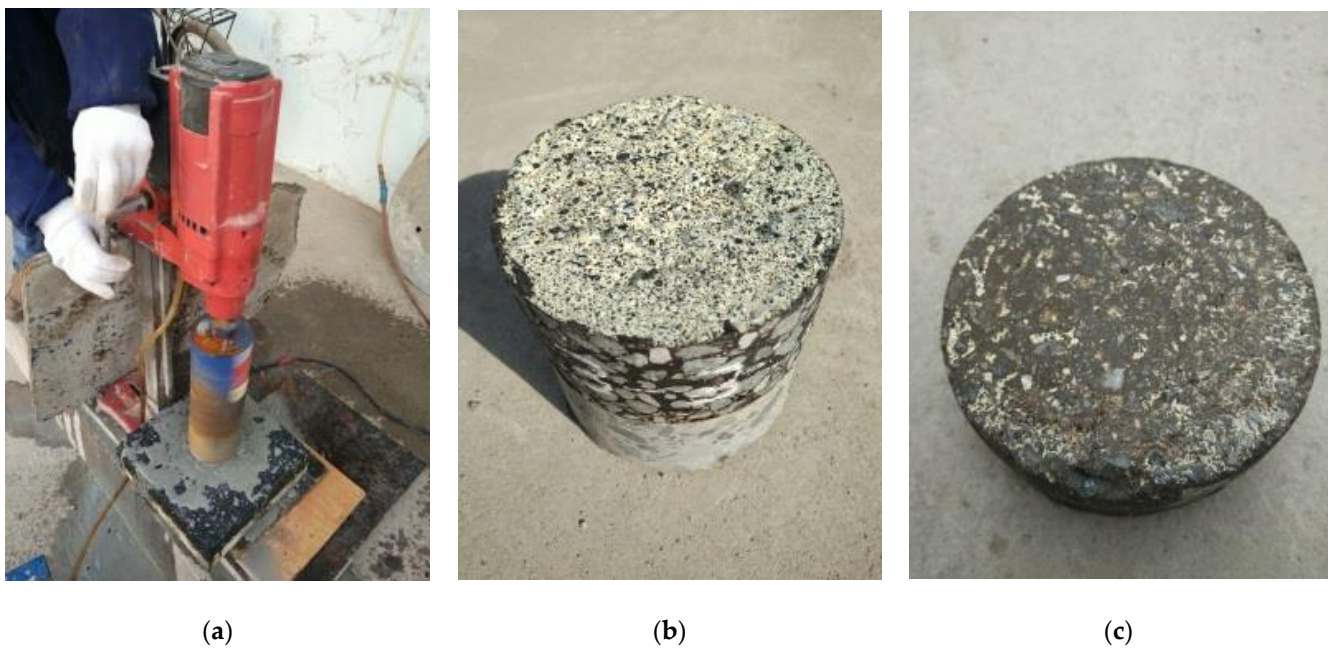


Figure 10. The sample with different air voids (a) coring sample (b) original core sample (c) polished sample.

It is possible to use the energy release rate as an index of blister propagation to evaluate the propagation behavior. As shown in Table 3, the critical energy release rate of the blister decreased as the air voids increased. The failure mode of the pavement layer changed from debonding to the seepage of the asphalt mixture. For the sample with an air void of less than 3.5%, the blister occurred under uniform pressure and eventually experienced propagation to destruction. However, for the sample with an air void greater than 3.5%, the hydraulic oil flowed through the micro voids under uniform pressure. When the internal pressure of a sample is greater than the oil seepage pressure, the hydraulic oil will eventually penetrate the surface of the mixture; the reason for this can be the increasing connectivity of micro voids from a higher air void, which decreases the oil seepage pressure. Therefore, the low air voids of asphalt mixture are an important cause of blisters in bridge deck pavement.

Table 3. The blister propagation energy release rate G under different air voids.

Mixture	Waterproofing Layer	Air Voids/%	Load (at Peak) /N	Deflection (at Peak) /mm	Critical Energy Release Rate/ $\text{N}\cdot\text{m}^{-1}$	Failure Pattern
AC-13	SBS-modified asphalt	3.21	1135.2	2.71	90.6	Asphalt mixture seepage + bonding course destruction
AC-13	SBS-modified asphalt	3.44	1035.3	2.53	77.1	Asphalt mixture seepage + bonding course destruction
AC-13	SBS-modified asphalt	4.67	878.9	1.59	41.5	Asphalt mixture seepage

4. Conclusions

In this study, blister propagation in concrete bridge deck pavement was investigated. A detailed analysis of the factors influencing propagation behavior, such as pavement structure and air voids, was conducted by calculating the critical energy release rate. The following conclusions were drawn from this study.

- (1) Blister deformation is divided into an expansion phase and a propagation phase. In the expansion phase, the blister radius remains stable, and the deflection of the pavement layer gradually increases; in the propagation phase, the blister radius increases and the deflection rate of pavement layer also increases. This is because

- propagation leads to a decrease in the overall stiffness of the specimen. Furthermore, catastrophic debonding often occurs once a critical pressure is reached.
- (2) For the same waterproof bonding layer, a blister in the AC-13 pavement structure is more likely to propagate than one in the SMA-13 pavement structure. For the same pavement structure, pavement with SBS-modified asphalt membranes is the most difficult to propagate, followed by asphalt rubber. Blister propagation on pavement with SBS-modified emulsified asphalt membranes is the most likely. In addition to this, the low air voids of asphalt mixture are a crucial reason for blisters forming in bridge deck pavement.
 - (3) In this study, using the critical energy release rate as an evaluation index for the interface expansion performance of bridge deck pavement is recommended.

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Conflicts of Interest: Author C.Y. was employed by First Highway Consultants Co., Ltd., Engineering and Technology Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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