FRACTURE RESISTANCE AND SELF-HEALING POTENTIAL OF VERY THIN ASPHALT OVERLAY ENHANCED BY MICROWAVE HEATING

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Keywords

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SCB test

Abstract

Very-thin asphalt overlay mixtures require a careful balance of competing demands, such as enhancing skid resistance, reducing noise, and improving rutting resistance, due to their reduced thickness. Achieving this balance involves reducing the nominal maximum aggregate size (NMAS) and incorporating coarser aggregate gradations. This design complexity is particularly critical for semi-dense graded very-thin overlays, which are more susceptible to cracking. In this context, investigating the healing potential of very-thin asphalt overlays through microwave heating offers a promising opportunity to extend pavement life while minimizing economic and environmental impacts. This study investigates and compares the cracking resistance and self-healing capabilities of two mixtures by applying Fracture–Healing–Fracture (FHF) cycles using Semi-Circular Bending (SCB) testing under microwave heating. The mixtures examined include a semi-dense aggregate gradation (BBTM8) designed for very-thin overlays, and a dense-graded aggregate mixture (ACL 16+) intended for binder courses and containing 50% reclaimed asphalt pavement (RAP). As a result, the ACL mixture exhibited a fracture toughness (KIC) value of 37.1 $N/mm^{3/2}$, attributed to its denser gradation, larger NMAS, higher stiffness, and greater RAP content. In contrast, the initial KIC value of the BBTM8 mixture was 18.4 $N/mm^{3/2}$. However, following microwave heating, the KIC value of the BBTM8 mixture increased significantly and approached that of the ACL mixture, aided by its higher air void content. The FHF cycle results revealed that the BBTM8 mixture demonstrated higher fracture resistance and more efficient recovery performance than the ACL mixture.

MİKRODALGA ISITMA İLE GELİŞTİRİLEN ÇOK İNCE ASFALT KAPLAMANIN KIRILMA DİRENCİ VE KENDİ KENDİNİ İYİLEŞTİRME POTANSİYELİ

Anahtar Kelimeler

Kendi kendini iyileştirme
Kırılma direnci
Mikrodalga ısıtma
Çok ince asfalt kaplama
SCB testi

Öz

Çok ince asfalt kaplamalar, azaltılmış kalınlıkları nedeniyle kayma direncinin artırılması, gürültünün azaltılması ve tekerlek izi direncinin iyileştirilmesi gibi birbiriyle çelişen ihtiyaçların dikkatli bir şekilde dengelenmesini gerektirir. Bu dengenin sağlanması, nominal maksimum agrega boyutunun (NMAS) küçültülmesini ve daha kaba agrega derecelendirmelerinin kullanılmasını içerir. Bu tasarım karmaşıklığı, çatlamaya daha yatkın olan yarı yoğun dereceli çok ince kaplamalar için özellikle kritik öneme sahiptir. Bu bağlamda, çok ince asfalt kaplamaların mikrodalga ısıtma yoluyla iyileşme potansiyelinin araştırılması, ekonomik ve çevresel etkileri en aza indirirken kaplama ömrünü uzatmak için umut verici bir fırsat sunmaktadır. Bu çalışma, mikrodalga ısıtma altında Yarım Dairesel Eğilme (SCB) testi kullanılarak uygulanan Kırılma–İyileşme–Kırılma (FHF) döngüleri aracılığıyla iki farklı karışımın çatlama direnci ve kendi kendini iyileştirme yeteneklerini incelemekte ve karşılaştırmaktadır. İncelenen karışımlar; çok ince kaplamalar için tasarlanmış yarı yoğun agrega derecelendirmesi (BBTM8) ve %50 geri kazanılmış asfalt kaplama (RAP) içeren, bağlayıcı tabaka için kullanılan yoğun dereceli agrega karışımıdır (ACL 16+). Sonuç olarak, ACL karışımı daha yoğun derecelendirme yapısı, daha büyük NMAS değeri, daha *yüksek sertliği ve daha fazla RAP içeriği sayesinde 37,1 N/mm$^{3/2}$ değerinde kırılma tokluğu (KIC) sergilemiştir. Buna karşılık, BBTM8 karışımının başlangıçtaki KIC değeri 18,4 N/mm$^{3/2}$ olarak ölçülmüştür. Ancak mikrodalga ısıtma sonrasında, daha yüksek hava boşluğu içeriğinin de katkısıyla BBTM8 karışımının KIC değeri önemli ölçüde artarak ACL karışımının seviyesine yaklaşmıştır. FHF döngüsü sonuçları, BBTM8 karışımının ACL karışımına kıyasla daha yüksek kırılma direnci ve daha etkin bir iyileşme performansı gösterdiğini ortaya koymuştur.*

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1. Introduction

Concerns about climate change problems caused by greenhouse gas (GHG) emissions have gained importance as awareness about the impact of human activities on the environment has grown. Research conducted by the World Bank revealed that emissions from the transportation sector account for 14% of the global total, with 72% of these emissions generated by road construction, maintenance, rehabilitation, and operation (World Bank, 2010). Road construction, production of raw materials, road operation, maintenance during the service life, and rehabilitation all result in significant GHG emissions, as noted by (Fernández-Sánchez et al., 2015). In the USA, road construction, maintenance, and rehabilitation contribute to 28% of GHG emissions (Melanta et al., 2013). Maintenance is the second largest source of GHG emissions (Stripple, 2001). Therefore, using more sustainable techniques, such as microwave heating to trigger asphalt mix self-healing ability, can reduce gas emissions by minimizing maintenance and rehabilitation activities.

The self-healing mechanism needs activation energy to wet the crack interface, with the energy provided, the necessary molecular diffusion takes place to close the cracks. The most widely recognized molecular diffusion model for polymer materials was introduced by Wool and O'connor (1981). Subsequently, based on this model, researchers have further investigated the two-stage self-healing process of bitumen (D. Sun et al., 2017; G. Sun et al., 2020):

- The first stage is wetting, that is, molecular diffusion, which is expressed as the closure of the microcrack formed in the asphalt pavement.
- The second stage is the recovery of asphalt pavement strength due to diffusion and random distribution of bitumen molecules from one crack surface to the other.

The macroscopic healing observed at a specific temperature T and time t includes the instantaneous strength gain dependent on temperature and the rate of strength recovery that varies with temperature. Healing temperature is one of the most effective parameters on the healing ability of asphalt. However, determining the optimum healing temperature to ensure the healing ability of bituminous binder and asphalt mixture is a difficult and complex task (Tang et al., 2016).

To determine the best self-healing temperature for bitumen, the viscosity-frequency scanning test was performed in the Dynamic Shear Rheometer (DSR) (Tang et al., 2016). The study found that the optimal self-healing temperature was the softening point of the bitumen, based on the results from a Fatigue-Healing-Fatigue test. However, Xiang et al. (2019) conducted a Fatigue-Healing-Fatigue test using the time sweep mode of DSR and determined the optimal healing temperature for PEN70 matrix base bitumen to be 47.6 °C, which is a little higher than the softening point. D. Sun et al. (2018) also found that the self-healing ability of bitumen was higher at the phase transition temperature, where the molecular diffusion rate and range were more prominent. Based on the Fatigue-Healing-Fatigue and Differential Scanning Calorimetry results of these studies, the optimal healing temperature range is between 40.3 °C and 48.7 °C. He et al. (2022) reported that healing time decreases as temperature increases, particularly when it comes closer the glass transition temperature of 300 K (27 °C). For example, Xiang et al. (2019) found that the optimal healing temperature for base bitumen was 47.6 °C, while the optimal temperature for 4.5% linear styrene-butadiene-styrene (SBS) modified bitumen was 76.7 °C. Yoo et al. (2019) investigated the effect of carbon-based materials on the self-healing properties of asphalt pavement, and determined the optimal heating temperatures for carbon fiber, carbon nanotube, and graphite nanofiber to be 108 °C, 105 °C, and 104 °C, respectively. Although various suggestions exist regarding healing temperatures in studies on bituminous binders, there is a general consensus on the optimal healing temperature in research focused on the self-healing ability of asphalt mixtures. The widely accepted view is that asphalt mixtures exhibit the best healing performance at 85 °C

(Liu, Schlangen, van de Ven, et al., 2012; Liu, Schlangen, and Van De Ven, 2012; W. Liu et al., 2024). Finally, we should keep the heating temperature as low as possible to prevent bitumen aging acceleration.

Self-healing studies on asphalt mixtures have gained significant attention in recent years, particularly due to their potential to enhance the service life and performance of pavement structures. These studies utilize various heating methods, such as induction heating and microwave heating, based on the Fracture-Healing-Fracture (FHF) test cycle and semi-circular bending (SCB) tests. Research indicates that the fracture resistance and recovery ability of asphalt mixtures can vary significantly depending on the types and gradations of aggregates used. This highlights the need for a comprehensive understanding of how different materials interact within the mixture. For instance, Wang et al. (2022) investigated the microwave heating-based self-healing ability of asphalt mixtures that incorporated both basalt and limestone aggregates using the FHF test. Their findings revealed that microwave heating not only enhanced flexural strength by at least 65% but also improved fatigue resistance by 23%. These improvements underscore the effectiveness of microwave heating as a viable method for enhancing the mechanical properties of asphalt mixtures. Furthermore, the study indicated that both the type and size of the aggregate significantly influenced the microwave heating rate, suggesting that material selection is crucial for optimizing healing performance. In addition to aggregate properties, other factors such as temperature and nominal maximum aggregate size (NMAS) also play a critical role in the healing process. Atakan and Yıldız (2024) observed that a higher degree of aggregate damage during fracture corresponded with a lower healing rate. They explained that the extent of healing is influenced by the increase in cohesive damage and a decrease in adhesive damage as the temperature rises during fracture. Garcia-Gil et al. (2019) further noted that a larger NMAS contributes to increased aggregate damage, emphasizing the importance of careful design in asphalt mixtures.

Very-thin overlay is widely used as a wearing course in various regions, including the EU, China, and the USA, either as a reinforcement layer or as a surface course to mitigate noise. The layer thickness prescribed for the very-thin overlay in the ČSN 73 6121:2023 national technical standard used in the Czech Republic is 20-30 mm. However, very-thin overlay presents unique challenges; it requires a reduction in NMAS while necessitating a coarser grading to enhance skid resistance, noise reduction, and rutting resistance. This conflicting requirement complicates the design process, particularly since open-graded or semi-open-graded very-thin overlays are more susceptible to cracking compared to dense-graded overlays. Recent studies, such as the work of Eren et al. (2024), have investigated the fracture resistance of waste steel fiber (WSF) reinforced very thin overlay through SCB tests and explored their healing ability via induction heating. Their research highlighted that the healing potential, measured in terms of fracture toughness, diminishes as the stiffness modulus of WSF increases. Yu et al. (2024) investigated the cracking resistance of the designed cold asphalt mixture for basalt fiber reinforced ultra thin overlay according to the SCB test. However, the investigation of fracture resistance and microwave healing ability of ultra-thin overlay is a new and current topic in the literature and further research is needed in this area (Guo et al., 2024).

The self-healing capabilities of asphalt mixtures have been widely studied in the literature, focusing on factors such as the type and content of modifiers, aggregate type and gradation, and heating methods like microwave and induction heating. Despite the advantages of very-thin wearing courses, such as noise reduction and extending the service life of asphalt roads, their limited durability remains a significant challenge within the sustainability framework. To address this, examining and enhancing the self-healing capabilities of very-thin wearing courses has become increasingly important. Developing policies aimed at improving their performance and durability is essential for overcoming these challenges and maximizing their potential benefits. This study investigates and compares the fracture resistance and microwave healing ability of two asphalt mixtures: one with a semi-dense aggregate gradation designed for thin overlays and another with a dense aggregate gradation containing 50% reclaimed asphalt (RA) material used as binder layer in asphalt pavements. The findings aim to provide valuable insights into how different aggregate types and mixture designs especially very-thin-wearing courses influence the self-healing capabilities of asphalt pavements, contributing to more sustainable and durable road infrastructure.

In the following section, a detailed explanation of the materials and production processes utilized in the asphalt mixtures developed for this study is provided. Additionally, the FHF test procedure, which is based on the SCB test used in this research, is outlined to clarify the experimental framework. Experimental results from the SCB tests and FHF cycles are then discussed in relation to the fracture resistance and self-healing potential of the asphalt mixtures, supported by relevant literature. Consequently, the study's key findings are clearly presented in the conclusion section.

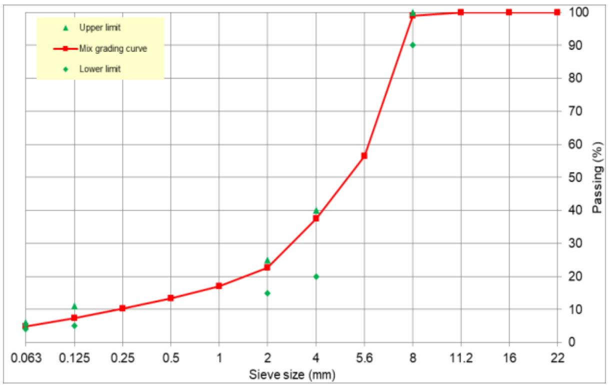
2. Materials and Methods

2.1. Materials

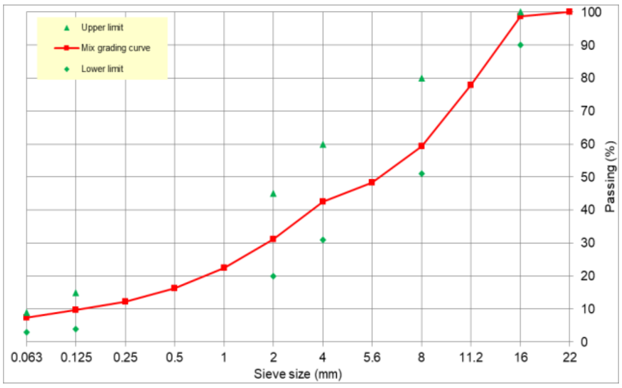
In this study, two different hot mix asphalt (HMA) were prepared according to the BBTM8 mixture type and ACL16+50RA mixture type according to the ČSN 73 6121:2023. To do so, the Marshall Design method specified in the EN 12697-30 standard was followed in the preparation of asphalt mix samples. For each mix type, 3 Marshall test specimens were prepared for the Marshall Stability test, 6 for the Stiffness Modulus test from which 3 (equivalent to 6 semi-circular specimens) were used for the SCB test.

- BBTM8: for the very-thin wearing layer, a bituminous binder with a penetration grade of 50/70 was obtained from the Litvinov refinery in the Czech Republic. The aggregates used in the mixture were sourced from the Brant quarry, also located in the Czech Republic.
- ACL16+50RA: for the binder layer, a bituminous binder with a penetration grade of 70/100 was sourced from the Litvinov refinery in the Czech Republic. The aggregates used in this mixture were obtained from the Bělice quarry, also in the Czech Republic. Additionally, the binder layer contains 50% RAP.

Figures 1(a) and Figure 1(b) show the grading curves of the mixtures BBTM8 and ACL16+50RA, respectively.



(a)



(b)

Figure 1. Aggregate Gradations Used in the Study (a) BBTM8 (b) ACL16+50RA

2.2. Determination of volumetric and mechanical properties by production of samples

In this study, asphalt mixtures were prepared by compacting specimens with 2x50 blows according to EN 12697-30 standard. The volumetric and mechanical properties of the prepared asphalt mixtures were determined and are presented in Table 1.

Table 1. Detailed of the Volumetric and Mechanical Properties of Asphalt Mixtures

	ACL16+ 50RA	BBTM8	Standard
Bitumen content (%)	4.2	5.2	ČSN 73 6121:2023
Maximum density (g/cm^3)	2.549	2.544	EN 12697-5
Bulk density (g/cm^3)	2.400	2.178	EN 12697-6
Air void (%)	5.8 (3%- 10%)	14.4 (11%- 15%)	ČSN 73 6121:2023
Marshall Stability (kN)	17.4	6.2	EN 12697-30
Stiffness modulus (MPa)	16093	7974	EN 12697-26

2.3. Semi-circle bending (SCB) test

The SCB test, as standardized in EN 12697-44:2019, is widely recognized for its effectiveness in evaluating the fracture resistance of asphalt pavements under real-world conditions. While the standard specifies conducting the test on 150 mm specimens, previous studies have proposed a modified SCB test suitable for standard Marshall specimens. Based on the procedures outlined in EN 12697-44:2019, this modified protocol is designed to assess the resistance of asphalt mixtures to crack propagation and evaluate their fracture behavior under various conditions (Vackova and Valentin, 2022). Details of the modified test method are provided in Table 2. The principle of this method is the three-point bending of a semi-circular test specimen with a 10 mm notch at the bottom. As shown in Figure 2, a typical SCB sample has a diameter of 100 mm, a notch width of 0.90 ± 0.20 mm, and a notch length of 10 mm. The modified SCB test can be performed at loading speeds of 2.5 mm/min at test temperatures of 0°C, 15°C, and 27°C. In this study, samples were subjected to SCB testing at 15 °C in FHF test cycles and their cracking behavior and healing abilities were investigated at medium temperatures. Bui and Saleh (2021) performed SCB tests on mixtures including thin wear samples of 150 mm and 100 mm sizes with different loading conditions and test temperatures and showed that the results were consistent and convertible with each other.

Table 2. Modified SCB Test Procedure

Conditions	Modified SCB test
Test temperature	0 °C, 15°C and 27°C
Specimen dimensions	100x50x50 mm
Notch height	10 mm
Loading rate	2.5 mm/min

Figure 2. Typical SCB Specimen with 100 mm Length

After the SCB test, the load-deformation curve is obtained. According to the obtained load-deformation curve, the fracture parameters are determined. The fracture parameters can be listed as fracture toughness (K_{IC}), fracture work (W_f), fracture energy (G_f) and flexibility index (FI) and are calculated using the equations given in Equations (1)-(5), respectively (Vackova and Valentin, 2022).

$$K_{IC} = \sigma_{max} Y_1 \sqrt{\pi a} \tag{1}$$

$$\sigma_{max} = \frac{F_{max}}{2rt} \tag{2}$$

$$Y_1 = 4{,}782 - 1{,}219 \left(\frac{a}{r}\right) + 0{,}063\, exp\left(7{,}045 \left(\frac{a}{r}\right)\right) \tag{3}$$

K is the fracture toughness ($N/mm^{1.5}$); σ_{max} is the maximum applied stress (N/mm^2); F_{max} is the maximum applied load (N); a is the notch length (mm); r is the radius of the sample; t is the sample thickness. Y_1 represents the normalized K parameter.

$$G_f = \frac{W_f}{A_{lig}} \tag{4}$$

$$FI = A \times \frac{G_f}{|m|} \tag{5}$$

The fracture work W_f is defined as the area under the load-deformation curve. The fracture energy G_f is calculated by dividing the fracture work by the ligament area A_{lig}. The flexibility index (FI) is an index based on the fracture energy G_f divided by the absolute value $|m|$ of the slope of a load-displacement curve at the inflection point of crack propagation phase (post-peak, after F_{max}). A is a scaling factor.

2.4. Fracture Healing Fracture test procedure

Fracture-Healing-Fracture (FHF) test cycles represent a series of testing processes designed to investigate the self-healing capacity of asphalt mixture. The primary objective of this method is to evaluate the effects of repeated heating cycles during the service life and the potential decline in self-healing capacity due to repetitive cracking. To achieve this, a microwave healing procedure is applied after the specimens are fractured using the SCB test. If the nearly separated specimen parts are in contact, the healing is considered successful. Therefore, many studies use wooden, plastic, or steel molds to hold the fractured parts together. Additionally, plastic zip ties are a practical alternative due to their resistance to microwave heating temperatures. In this study, plastic zip ties were used to hold the specimens together.

Based on preliminary laboratory testing, it was determined that the samples needed to be heated for 30 seconds to reach a self-healing temperature 85°C. Therefore, during the FHF test cycles, the samples were heated in the microwave for 30 seconds to heal. Figure 3 shows the process of SCB testing of the FHF test cycle and microwave heating. In this study, the FHF test cycle was conducted five times to assess how aging or service-related damage affects the self-healing capacity of road pavements. Consequently, the microwave healing index (HI) was determined for asphalt mixtures subjected to repeated cracking and healing cycles. The results of the first cycle included both the $HI_1\_G_f$ and $HI_1\_K_{IC}$ values, while the subsequent evaluations focused on $HI_{i.cycle}\_K_{IC}$ over the course of all five cycles. The evaluation parameters were defined Equation (6) and (7) (Zhang et al., 2023).

$$HI_{i.cycle}\_K_{IC} = \frac{K_{IC_{i+1}}}{K_{IC_1}} \quad (i=1,2,3,4,5) \tag{6}$$

Where, K_{IC_i} is the fracture toughness K_{IC} value in the i-th cycle, K_{IC_1} represents the fracture toughness K_{IC} value in the first cycle. $HI_{i.cycle}$ the relative retention of fracture toughness through each cycle, providing insight into the healing efficiency of the asphalt mixtures over multiple cycles. Additionally, $HI_1\_G_f$ represents the healing index of fracture energy in the first cycle, where G_{f_1} the initial fracture energy before the heating and G_{f_2} is second fracture energy after heating in the first cycle.

$$HI_1\_G_f = \frac{G_{f_2}}{G_{f_1}} \tag{7}$$

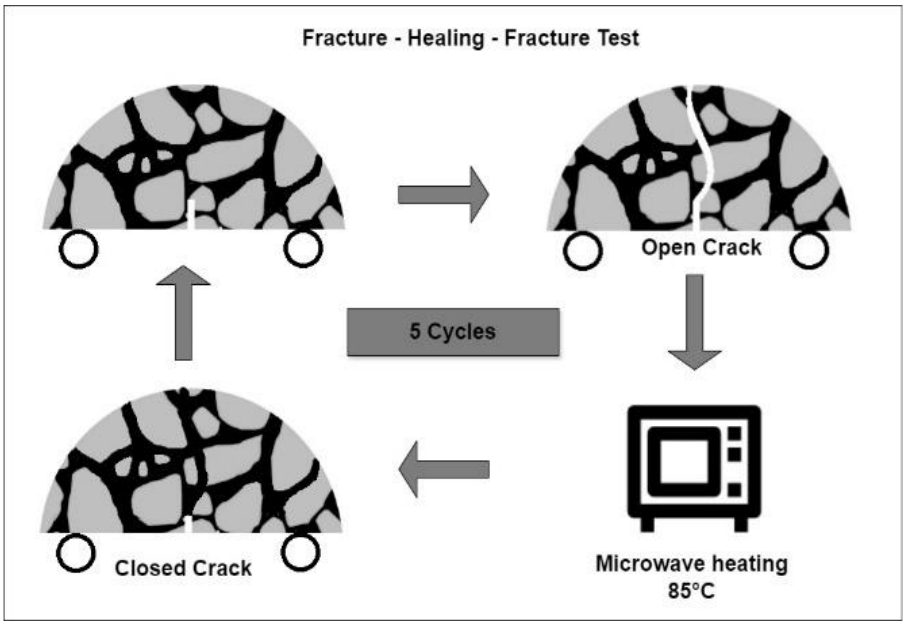


Figure 3. Fracture-Healing-Fracture (FHF) Test Procedure Used in This Study

3. Results and Discussion

3.1. Effect of microwave heating on crack resistance of asphalt mixtures

SCB test was performed to evaluate the crack resistance of asphalt mixtures. An example of the load-displacement curve obtained as a result of the SCB test of ACL16+ and BBTM8 mixtures before and after healing is given in Figure 4.

Before heating, the mixture with semi-dense aggregate gradation and slightly higher bitumen content, designed for the very-fine wearing course, had a significantly lower F_{max}. However, it was observed that this mixture displaced slightly more under load compared to the densely graded ACL16+ mixture with a high RAP content. In addition, before reaching F_{max}, the linear region covering 40-80% of the F_{max}. The linear region represents the elastic deformation of the material. When the slope starts to change, microcracks occur. After Fmax, macrocrack is developed. For the ACL it is less or nearly invisible because of high RAP content and thus, high stiffness.

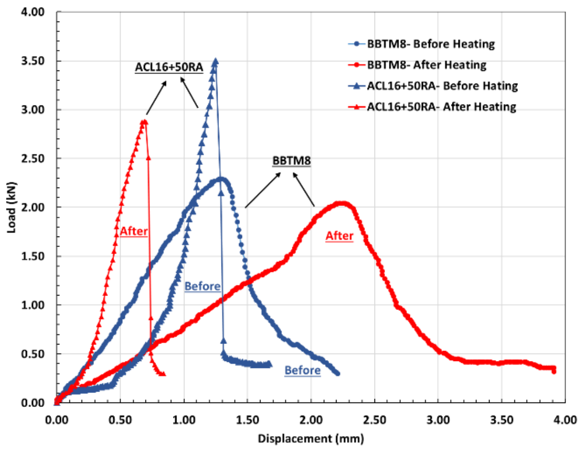


Figure 4. Load-Displacement Curves for Asphalt Mixtures Before and After Microwave Heating

This result indicates the asphalt mixture's effective ability to handle micro cracks. As observed, the ACL16+ mixture exhibits a much more brittle behavior than the BBTM8 mixtures, showing a steep deformation slope under load before the formation of macrocracks. This behavior was further illustrated by the sudden fracture of the ACL16+ mixture blends after reaching F_{max}. Additionally, the ACL mixture reached its maximum deformation capacity much sooner, emphasizing the key difference between the ACL16+ and BBTM8 mixtures. Unlike the ACL16+ mixture, the BBTM8 mixture gradually and steadily reached its maximum deformation capacity under load, despite the propagation of macrocracks that continued to expand. The primary reasons for these results are related to the ACL16+ dense aggregate gradation and high RAP content, enabling them to withstand greater loads but exhibiting more brittle behavior due to aged bitumen and aggregates from the RAP content. Similarly, BBTM8 mixture contains slightly younger and more bitumen than ACL16+ mixture, and their NMAS value is 8 mm, significantly smaller than that of the ACL16+ mixture. Altogether, these factors enable BBTM8 mixtures to better manage the propagation of micro- and macrocracks, as they have high deformation capacity despite achieving lower maximum load.

According to the load-displacement curves for the mixtures healed through microwave heating, the F_{max} values decreased in both the ACL and BBTM8 mixtures. While the F_{max} required for macrocrack formation decreased for both mixtures, the maximum deformation of BBTM8 mixtures approximately doubled after healing. This indicates that BBTM8 blends exhibit a higher recovery ability in fracture work and energy after healing. In contrast, the deformation capacity of ACL16+ mixture decreased by approximately 50%, showing a much more brittle behavior post-healing due to the reduced deformation capacity. Since fracture toughness is a fracture parameter influenced by F_{max} and the geometric properties of the specimen, a decrease in fracture toughness values is expected in both mixture types following healing as shown in Figure 5.

The pre-healing fracture toughness of the BBTM8 mixture was determined to be 18.4 N/mm$^{3/2}$, while for the ACL16+ mixture, it was measured at 37.1 N/mm$^{3/2}$. The dense gradation, high NMAS value, and the presence of RAP in the ACL16+ mixture led to achieving a higher F_{max}, resulting in greater fracture toughness. On the other hand, due to the high air void content of the BBTM8 mixture, the observed F_{max} decreased, leading to a decrease in fracture toughness. However, when examining the HI_K_{IC} values of samples self-healed by microwave, the healing rate for BBTM8 mixtures was found to be 50.63%, whereas, for ACL16+50RA mixtures, it was 19.73%. It can be concluded that the high air voids content in BBTM8 mixtures due to gradation and higher binder content enhances the healing capability. Gómez-Meijide et al. (2016) also demonstrated that porous asphalt, characterized by a higher air void content, exhibits significantly better healing abilities compared to dense asphalt.

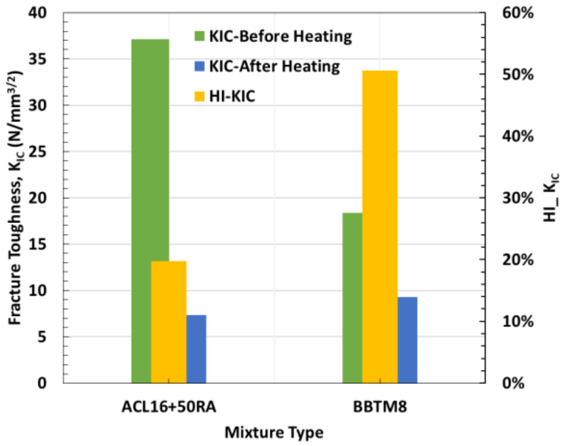


Figure 5. HI_K_{IC} Values of Asphalt Mixtures

To determine the fracture energy, it is first necessary to measure the fracture work. Fracture work represents the area under the load-displacement curve and can be defined as fracture work until F_{max} and total fracture work, measured in Joules (J). The fracture works up to F_{max} and the total fracture work of the BBTM8 mixture, which has a high deformation capacity, are higher than those of the ACL16+ mixture both before and after healing, as clearly shown in Figure 6. As a result, it was determined that the increase in the fracture work with microwave heating after F_{max} was greater than before F_{max} for both ACL16+ and BBTM8 mixtures.

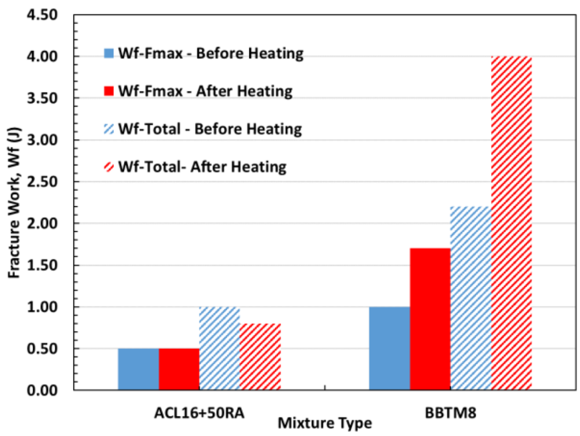


Figure 6. Fracture Work (W_f) of Asphalt Mixtures

Fracture energy results are illustrated in Figure 7 and presented in detail in Figure 8. Fracture energy represents the amount of energy required to create a fracture surface per square meter (Bui and Saleh, 2021). It was found that BBTM8 mixtures had three times the fracture energy of ACL16+ mixture before healing. Similarly, after healing, the recovery in fracture energy was seven times higher in BBTM8 mixture.

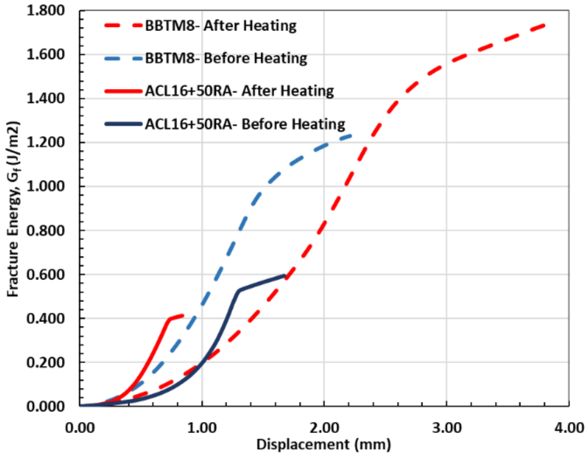


Figure 7. Fracture Energy (Gf) of Asphalt Mixtures

This accounts for the mixture's increased resistance to crack propagation. Therefore, it was concluded that with microwave heating, the fracture energy recovery ability of BBTM8 mixture was significantly higher than that of ACL16+ mixture. As a result, it was determined that more improvement could be observed if healing was performed by microwave heating after the occurrence of macro cracks in very-thin asphalt pavements with semi-dense aggregate gradation.

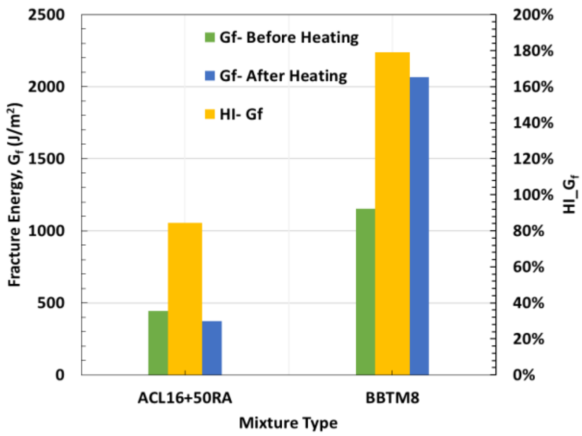


Figure 8. HI_Gf Values of Asphalt Mixtures

Another recently proposed fracture energy-based index for evaluating the cracking resistance of asphalt mixtures is the FI value. A high FI value indicates greater resistance to cracking, reflecting the mixture's fracture behavior during crack propagation. Jiang et al. (2022) demonstrated that FI offers a more effective approach than fracture energy, especially for mixtures containing RAP. They also highlighted that the post-peak FI is strongly influenced by binder properties. As illustrated in Figure 9, the FI value of the BBTM8 mixture increased after healing, whereas it decreased for the ACL16+ mixture. Furthermore, the FI results revealed that the BBTM8 mixture exhibited significantly higher resistance to fracture propagation than the ACL16+ mixture, both before and after healing.

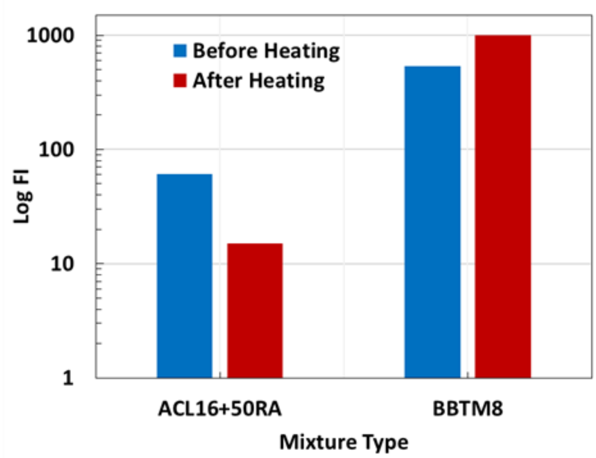


Figure 9. FI Values of Asphalt Mixtures

3.2. Results of the Fracture-Heating-Fracture test cycle

The FHF test is a test cycle consisting of the first fracture with SCB, then self-healing with microwave heating, and a second fracture with SCB. Figure 10 shows images of ACL16+ and BBTM8 samples before and after healing. Figure 11 illustrates the $HI_i\_K_{IC}$ after the FHF test cycles. In addition, error bars in the Figure 11 indicate the standard error calculated from six independent measurements of the same sample. In BBTM8 mixtures, the healing capacity decreased by 8.94% after five healing cycles. A primary factor contributing to this decline in fracture toughness is the formation of microcracks within the asphalt structure due to repeated fracture cycles, as noted by Chen and Solaimanian (2019). These microcracks weaken the material, making it more susceptible to fracture under mechanical stresses. Thus, it is generally expected that the healing capacity will progressively decrease over successive heating and healing cycles.

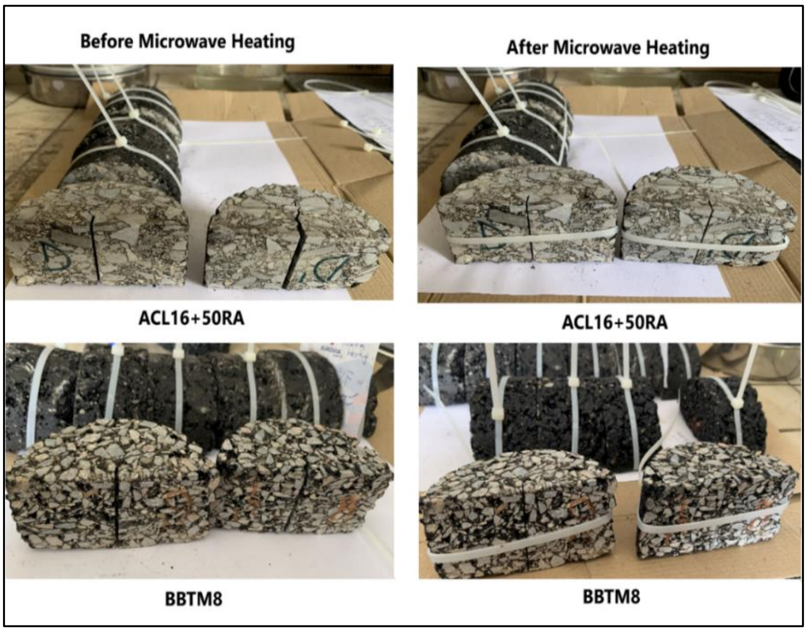
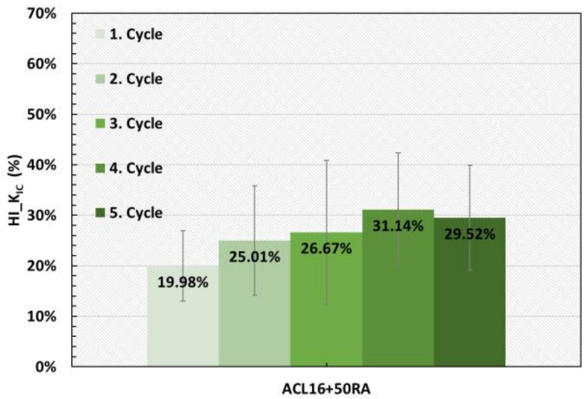
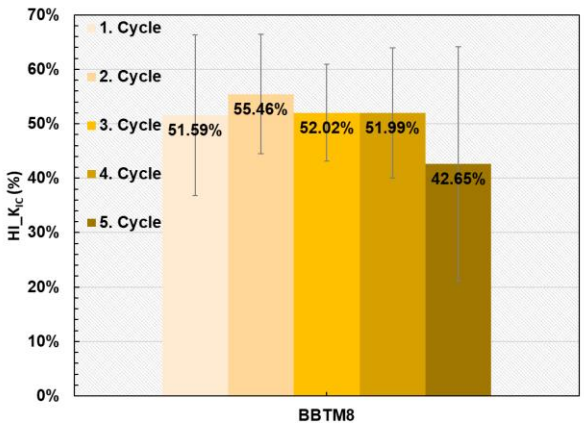


Figure 10. Before and After Microwave Heating



(a)



(b)

Figure 11. HI_KIC Values of Asphalt Mixtures During FHF Cycles (a) ACL16+50RA (b) BBTM8

However, in the ACL16+ mixture, an increase of 9.54% in the healing rate of fracture toughness was observed after repeated cycles. In a study by Yıldız et al. (2020), the FHF test cycle was repeated three times, and samples with significant crack damage showed an increase in fracture toughness alongside aging. This phenomenon was explained by the possible enhancement of the mechanical strength of the asphalt concrete due to changes in the distribution of air voids within the asphalt samples during the microwave heating and healing process. Additionally, it is thought that the aged binder in the ACL16+ mixture may harden further through FHF cycles, potentially providing a marginal contribution to fracture toughness. On the other hand, as the number of FHF test cycles increases, a gradual decline in the healing index in fracture toughness is projected. After the 5th cycle, significantly pronounced reduction is anticipated. Similarly, Wan et al. (2018) conducted four FHF cycles to investigate the healing abilities of ultra-thin asphalt mixtures containing steel slag and steel fibers. The AC-5 mixture, which included steel slag and 3% steel fibers, achieved a HI_K_{IC} of 80% at the end of the first cycle. However, this value decreased to approximately 35% by the end of the fourth cycle.

During the repeated microwave heating process in FHF cycles, the self-healing of asphalt pavements is facilitated by reducing the viscosity of asphalt binders and accelerating capillary flow and molecular diffusion (Gallego et al., 2013). In field applications, microwave heating technology is preferred for both self-healing and deicing processes due to its advantages over traditional methods, including high efficiency, low pollution, energy savings, and ease of control (Huang et al., 2021; Zhang et al., 2023). However, significant temperature differences may occur within the pavement due to variations in the microwave absorption capacity and heat transfer ability of the aggregate and bitumen components (X. Liu et al., 2024; Zhang et al., 2023). The healing of micro-cracks in asphalt specimens during repeated cycles may vary as a result of these temperature differences. This can be attributed to the substantial influence of temperature on the healing process.

Overall, the healing capacity of BBTM8 mixtures is, on average, 24.28% higher than that of ACL16+ samples across all test cycles. However, based on the experimental work conducted during the FHF test cycles, it is worth noting that the heating temperature of 85°C may be too high for mixtures produced for very-thin wearing courses. In repeated tests, some of the BBTM8 samples heated to 85°C broke down and were discarded. In contrast, this problem was not observed in the ACL16+ samples.

4. Conclusion

Cracking behavior is a significant research topic in fracture mechanics, with the SCB test playing a crucial role in analyzing the fracture properties of asphalt pavements. In this study, SCB test-based FHF test procedure was applied in the scope of the study for the comparative analysis of the fracture behavior and microwave healing ability of very-thin asphalt overlay. In asphalt pavements with increased crack damage over time through FHF test cycles, the damage level of cracks in asphalt pavement directly affects the pavement's healing ability. As the damage level increases, cracks in the asphalt expand and multiply, which can lead to stripping and the formation of deep potholes under repeated loading and adverse environmental conditions. In very-thin asphalt pavements, where stability issues are expected under repeated loading, microwave heating of cracks has the potential to extend pavement life and reduce the use of bituminous binder in asphalt mixtures. This approach could enhance the economic and environmental benefits of very-thin asphalt pavements.

The key conclusions and overall assessment of the research are summarized below.

- The pre-healing fracture toughness of the BBTM8 mixture was measured at 18.4 N/mm$^{3/2}$, while the ACL16+ mixture exhibited a significantly higher value of 37.1 N/mm$^{3/2}$.
- The ACL16+ mixture achieved a higher F_{max} due to its dense gradation, higher NMAS, and the presence of RAP, resulting in increased fracture toughness compared to the BBTM8 mixture.
- Microwave healing improved the HI_K_{IC} of the BBTM8 mixture by 50.63%, while the ACL16+ mixture resulted in only 19.73% improvement, indicating higher healing efficiency in BBTM8.
- Due to its high air void content (14.4%), the BBTM8 mixture demonstrated greater healing potential, as the voids enhance microwave heating's effectiveness in healing cracks.
- Before and after healing, the fracture work for the BBTM8 mixture, which has high deformation capacity, was consistently higher than for the ACL16+ mixture.
- The BBTM8 mixture had three times the fracture energy of the ACL16+ mixture before healing and achieved seven times the recovery after healing, indicating greater crack propagation stability. Its lower stiffness modulus, higher bitumen content and air voids resulted in a HI_G_f of over 100%.
- The FI value, which measures cracking resistance, increased for the BBTM8 mixture after healing but decreased for the ACL16+ mixture, highlighting BBTM8's higher post-healing crack resistance.
- During FHF testing, BBTM8's healing capacity decreased by 8.94% over five cycles due to microcrack formation, while ACL16+ exhibited a 9.54% increase in fracture toughness, potentially due to changes in air void distribution.
- The average healing capacity of BBTM8 mixtures across FHF test cycles was 24.28% higher than that of ACL16+ mixtures.
- Microwave heating to 85°C caused some BBTM8 samples to break down, while no problems were observed in ACL16+ samples, indicating potential limitations for very-thin asphalt pavements.

Moreover, the results of the study indicate that microwave heating can enhance the healing capacity of asphalt mixtures. This finding highlights the potential benefits of applying microwave heating methods to repair cracks in pavement layers in field applications. During the application of microwave heating, it is essential to establish proper energy sources and connections for microwave generators. Additionally, the heating duration and energy intensity must be carefully adjusted based on the surface type, damage level, and desired temperature. Although this study observed that very-thin asphalt pavements should not be subjected to high temperatures for healing, further research is necessary to better understand this limitation. Future studies could explore topics such as the long-term effects of microwave heating methods or the impact of climate conditions on the performance and durability of very-thin-wearing courses.

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Author Contributions

Ezgi EREN contributed to the experimental design, data collection, and manuscript writing. Jan VALENTIN was involved in the implementation, data analysis, and manuscript revision. Peter GALLO contributed to the laboratory work, data analysis, writing, and editing. Perviz AHMEDZADE contributed to the experimental design, supervised the study, and provided critical feedback and revisions.

Conflict of interest

No conflict of interest was declared by the authors.

References

Atakan, M., and Yıldız, K. (2024). Effect of aggregate damage on self-healing characteristics of asphalt concrete: An image processing-based method. Construction Building Materials, 425, 135924.

Bui, H. H., and Saleh, M. J. E. F. M. (2021). Effects of specimen size and loading conditions on the fracture behaviour of asphalt concretes in the SCB test. 242, 107452.

Chen, X., and Solaimanian, M. (2019). Effect of long-term aging on fracture properties of virgin and recycled asphalt concrete. Advances in Civil Engineering Materials, 8(1), 527-543.

Eren, E., Valentin, J., and Ahmedzade, P. (2024). Assessment of the Effects of Induction Heating Induced-Healing on the Fracture Properties of Very Thin Asphalt Concrete. Paper presented at the International Conference on Maintenance and Rehabilitation of Pavements.

Fernández-Sánchez, G., Berzosa, Á., Barandica, J. M., Cornejo, E., and Serrano, J. M. (2015). Opportunities for GHG emissions reduction in road projects: a comparative evaluation of emissions scenarios using CO2NSTRUCT. Journal of Cleaner Production, 104, 156-167.

Gallego, J., del Val, M. A., Contreras, V., Páez, A. J. C., and Materials, B. (2013). Heating asphalt mixtures with microwaves to promote self-healing. 42, 1-4.

Garcia-Gil, L., Miró, R., and Pérez-Jiménez, F. E. J. A. S. (2019). Evaluating the role of aggregate gradation on cracking performance of asphalt concrete for thin overlays. 9(4), 628.

Gómez-Meijide, B., Ajam, H., Lastra-González, P., Garcia, A. J. C., and Materials, B. (2016). Effect of air voids content on asphalt self-healing via induction and infrared heating. 126, 957-966.

Guo, M., Zhang, R., Du, X., and Liu, P. J. E. (2024). A state-of-the-art review on the functionality of ultra-thin overlays towards a future low carbon road maintenance. 32, 82-98.

He, L., Zhou, Z., Ling, F., Alexiadis, A., Van den Bergh, W., Cannone Falchetto, A., . . . Kowalski, K. J. (2022). A Coarse-Grained Molecular Model for Simulating Self-Healing of Bitumen. Applied Sciences, 12(20), 10360.

Huang, H., Xu, J., Liu, J., and Chen, H. (2021). Comparative Study on Microwave Absorbing Heating Characteristics and Microwave Deicing Performance of Airport Pavement Modified Concrete.

Jiang, J., Chen, H., Bahia, H. U. J. M., and Structures. (2022). Factors controlling pre-and post-peak behavior of asphalt mixtures containing RAP in the SCB test. 55(6), 160.

Liu, Q., Schlangen, E., van de Ven, M., van Bochove, G., van Montfort, J. J. C., and Materials, B. (2012). Evaluation of the induction healing effect of porous asphalt concrete through four point bending fatigue test. 29, 403-409.

Liu, Q., Schlangen, E., and Van De Ven, M. J. T. r. r. (2012). Induction healing of porous asphalt. 2305(1), 95-101.

Liu, W., Wan, P., Wu, S., Liu, Q., Wang, J., Jiang, Q., . . . Materials, B. (2024). Effect of aging level on the healing properties of an induction-heated ultra-thin wearing course and its mechanism. 430, 136506.

Liu, X., Zhao, Y., Wei, D. J. C., and Materials, B. (2024). The effect mechanism of microwave enhanced aggregates on the microwave heating performance of asphalt mixtures. 411, 134314.

Melanta, S., Miller-Hooks, E., and Avetisyan, H. G. (2013). Carbon footprint estimation tool for transportation construction projects. Journal of Construction Engineering Management, 139(5), 547-555.

Stripple, H. (2001). Life cycle assessment of road. A pilot study for inventory analysis. In: IVL Svenska Miljöinstitutet.

Sun, D., Sun, G., Zhu, X., Pang, Q., Yu, F., and Lin, T. (2017). Identification of wetting and molecular diffusion stages during self-healing process of asphalt binder via fluorescence microscope. Construction Building Materials, 132, 230-239.

Sun, D., Sun, G., Zhu, X., Ye, F., and Xu, J. (2018). Intrinsic temperature sensitive self-healing character of asphalt binders based on molecular dynamics simulations. Fuel, 211, 609-620.

Sun, G., Hu, M., Sun, D., Deng, Y., Ma, J., and Lu, T. (2020). Temperature induced self-healing capability transition phenomenon of bitumens. Fuel, 263, 116698.

Tang, J., Liu, Q., Wu, S., Ye, Q., Sun, Y., and Schlangen, E. (2016). Investigation of the optimal self-healing temperatures and healing time of asphalt binders. Construction Building Materials, 113, 1029-1033.

Vackova, P., and Valentin, J. (2022). Semi-circular Bending (SCB) Test—Modified Method and New Test Parameters. Paper presented at the CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure: Proceedings of the 6th International Conference on Geotechnics, Civil Engineering and Structures.

Wan, J., Xiao, Y., Song, W., Chen, C., Pan, P., and Zhang, D. J. M. (2018). Self-healing property of ultra-thin wearing courses by induction heating. 11(8), 1392.

Wang, F., Zhu, H., Shu, B., Li, Y., Gu, D., Gao, Y., . . . Materials, B. (2022). Microwave heating mechanism and self-healing performance of asphalt mixture with basalt and limestone aggregates. 342, 127973.

Wool, R., and O'connor, K. (1981). A theory crack healing in polymers. Journal of applied physics, 52(10), 5953-5963.

World Bank, G. (2010). Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation: A Toolkit for Developing Countries.

Xiang, H., He, Z., Chen, L., Zhu, H., and Wang, Z. (2019). Key factors and optimal conditions for self-healing of bituminous binder. Journal of Materials in Civil Engineering, 31(9), 04019172.

Yıldız, K., Atakan, M. J. C., and Materials, B. (2020). Improving microwave healing characteristic of asphalt concrete by using fly ash as a filler. 262, 120448.

Yoo, D.-Y., Kim, S., Kim, M.-J., Kim, D., and Shin, H.-O. (2019). Self-healing capability of asphalt concrete with carbon-based materials. Journal of Materials Research Technology, 8(1), 827-839.

Yu, J., Feng, Z., Chen, Y., Yu, H., Korolev, E., Obukhova, S., . . . Zhang, Y. (2024). Investigation of cracking resistance of cold asphalt mixture designed for ultra-thin asphalt layer. Construction Building Materials, 414, 134941.

Zhang, L., Zhang, Z., Yu, W., and Miao, Y. J. P. (2023). Review of the application of microwave heating technology in asphalt pavement self-healing and de-icing. 15(7), 1696.