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A Comparative Study on Fatigue and Cracking Performance for HMA, SMA, and Gussasphalt Mixtures

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ABSTRACT

The primary goal of this study was to evaluate the fatigue and cracking resistance of Gussaphalt (GA), stone mastic asphalt (SMA), and hot mix asphalt (HMA) mixtures. The fatigue and fracture behaviors of these mixtures were examined using the Superpave indirect tension (IDT) strength test and the four-point bending beam fatigue test. Digital cameras were installed to monitor crack development on both faces of the specimens during the IDT strength tests. The length and width of the cracks were measured using the captured digital images. The test findings show that GA mixtures have much greater IDT strength, toughness, and fatigue life than HMA and SMA mixtures. The SMA exhibited the weakest resistance to fracture initiation, with an IDT toughness of only 2.0 kPa, which is 48% lower than that of the HMA and 60% lower than that of the GA. The GA exhibits the highest average IDT strength, exceeding that of HMA by 15% and that of SMA by 47%, while HMA remains 38% higher than SMA. The crack length and crack width of GA mixtures are significantly lower than those of SMA and HMA mixtures. This indicates that GA has an advantage in delaying crack initiation and propagation under indirect tensile loading. For fatigue life, at 1,000 $\mu\varepsilon$ and 50% stiffness, the GA lasts over 60 times longer than the HMA and nearly 120 times longer than the SMA before cracking. The study's findings indicate that asphalt mixtures with dense aggregate gradation exhibit superior fatigue performance compared to those with gap-graded aggregates.

Keywords: Fatigue cracking resistance, HMA, SMA, Gussaphalt, Crack length, Crack width.

INTRODUCTION

When exposed to repetitive traffic loads, fatigue cracking in asphalt concrete pavements is considered a serious form of pavement distress. Asphalt pavement may experience a shorter service life when cracks appear, as water can seep through the surface into the underlying layers (Teltayev et al., 2019; Le, 2021). Fatigue cracking refers to the progressive structural degradation associated with the initiation and propagation of macro-cracks. Air voids, binder content, aggregate gradation, binder properties, environmental conditions, loading mode, stress state, and aging are among the variables that influence an asphalt mixture's susceptibility to cracking (Rezaei et al., 2024; Yuniarti et al., 2024; Murana et al., 2024). While mixtures with low asphalt content are more prone to fatigue cracking, those with high asphalt content are more susceptible to rutting (Lotfi Omran et al., 2022; Khan et al., 2023). As a result, asphalt mixtures should possess strong stress relaxation capacity and good flexibility to minimize the risk of cracking under repeated traffic loads (Le, 2024).

As a gap-graded mix with a high concentration of coarse aggregate, the SMA optimizes stone-to-stone contact and provides an effective load distribution network (Brown et al., 1998). It was originally developed in Germany in the 1960s (Chegenizadeh et al., 2021). According to most studies, the use of SMA mixtures can enhance asphalt pavement resistance to rutting and reflective cracking (Brown et al., 1999; Cooley et al., 2004; Fomin et al., 2023; Kumar et al., 2023). The behavior of SMA mixtures has not been thoroughly evaluated, particularly with regard to their fatigue cracking performance. The SMA differs from the HMA in that it has a gap-graded aggregate structure with a high proportion of coarse aggregates, forming a stone-on-stone contact pattern. When combined with a dense mortar of binder and filler, typically containing fibers, this structure significantly enhances the mixture’s resistance to rutting and fatigue cracking. The fibrous ingredients help bond the mixture, reducing crack initiation and propagation. However, due to its stiffer matrix and higher binder content, the SMA may be more susceptible to low-temperature thermal cracking than the HMA. This susceptibility depends on binder modification and local environmental conditions (Yin & West, 2018).

The GA was first used in European countries in the 1960s to improve the fatigue resistance of bridge decks (Luo et al., 2017). The GA has a higher binder content than traditional deck-pavement mixtures, resulting in improved flexural strength (Wenjun et al., 2014). The mixture is produced and laid at high temperatures, effectively eliminating internal air voids (Ren et al., 2024). The GA is a dense, gap-graded, self-compacting asphalt mixture with a thick binder film that offers excellent fatigue resistance and durability under repeated heavy loads, making it ideal for bridge decks and heavily trafficked pavements. However, excessive binder content can reduce flexibility, increasing susceptibility to thermal stresses and temperature-induced cracking if the binder grade is not properly adjusted (Zou et al., 2020).

The HMA provides balanced performance. However, if it is not properly designed, it becomes more susceptible to fatigue and thermal cracking. The coarse aggregate skeleton and fiber reinforcement of SMA improve fatigue resistance and rutting control. However, binder modification may be required to enhance its resistance to thermal cracking. Ban et al. (2025) conducted a comparative analysis of SMA and HMA mixtures modified with crumb rubber (CR). According to the findings of Ban et al. (2025), gap-graded mixtures are more sensitive to variations in the amount of crumb rubber (CR) modified binder than dense-graded mixtures, particularly in terms of air void content. Additionally, the gap-graded mixtures exhibited slightly better mechanical properties than the CR-modified mixtures. The GA exhibits excellent fatigue resistance and durability; however, its stiffness and high binder content require careful thermal crack mitigation measures (Ban et al., 2025). Nevertheless, the fatigue and cracking behaviors of HMA, SMA, and GA mixtures must be thoroughly investigated, as different asphalt mixtures exhibit distinct fatigue and fracture characteristics.

In this study, the fatigue and fracture behaviors of asphalt mixtures with three distinct gradations for HMA, SMA, and GA were examined and compared using four-point bending beam fatigue test and Superpave IDT strength test. Furthermore, the crack length and width measured from specimen photographs were used to evaluate the crack growth rates of the different mixtures.

EXPERIMENTAL PROGRAM

Materials and Processing of Specimens

In this research, laboratory tests were conducted on three different types of asphalt mixtures. Aggregate gradations used for these mixtures are presented in Figure 1. In addition, a conventional binder (PG64-22) was used for all three asphalt mixtures. For the gap-graded aggregate mixtures (SMA) and the dense-graded aggregate mixtures (HMA), the target air void contents were 3.0 ± 0.5% and 4.0 ± 0.5%, respectively. For the HMA mixture, the binder content was 5.0 %, whereas for the SMA mixture, it was 6.5%. Furthermore, Trinidad Lake Asphalt (TLA) was incorporated into the GA mixture at 30% by weight, while the asphalt binder accounted for 8.5% of the mixture. The air void content of GA is nearly zero.

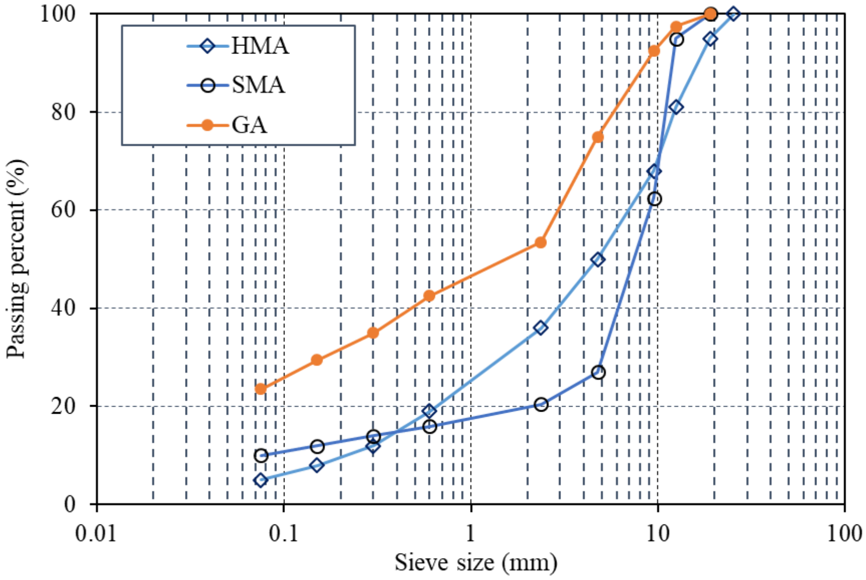

Figure 1. Aggregate gradation for HMA, SMA, and GA mixtures

Cylindrical specimens measuring 150 mm in diameter and 175 mm in height were prepared using a Superpave gyratory compactor. The compacted specimens were cut into two parts to obtain the required 50 mm thick specimens for the IDT testing. Furthermore, a beam specimen of roughly 50.8 mm in height, 63.5 mm in width, and 380 mm in length was used for the flexural beam fatigue test.

Mixture Tests

The Hamburg Wheel Tracking (HWT) test was used to evaluate the deformation properties of asphalt mixtures. Slab specimens measuring 300 × 300 × 50 mm were subjected to a wheel load of 0.7 MPa. The HWT equipped with an environmental chamber was used to maintain the test temperature at 60°C. An MTS servo-hydraulic loading system was used for the IDT strength test, which was conducted at 20°C and a constant displacement rate of 1 mm/min. To quantify horizontal deformations, two extensometers with a gage length of 25.4 mm were attached to the front and rear surfaces of the specimen. Two digital cameras were used to track the fracture propagation during the IDT test. As seen in Figure 2, the cameras were positioned in the front and rear of an IDT specimen.

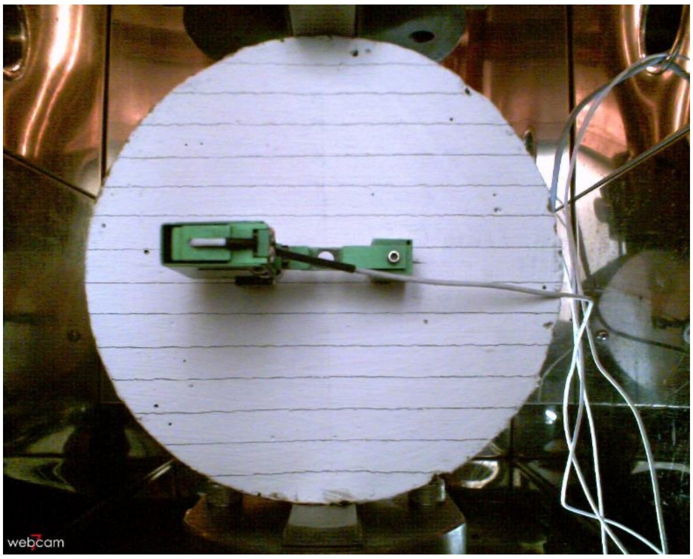

Figure 2. The setup for IDT test and crack images

As shown in Figure 3, the four-point beam fatigue test was performed in strain-controlled mode at 20 °C. A digital servo-controlled pneumatic actuator generated a repetitive haversine load, which was delivered at a frequency of 10 Hz with no rest intervals. Using a linear variable differential transformer (LVDT), the center beam's deflection was measured. At the 50th loading cycle, the initial flexural stiffness of a beam specimen measuring 380 mm in length, 63 mm in width, and 500 mm in height was calculated. The ASTM D7460-10 (2004) testing standard states that the number of loading cycles at 50% initial stiffness drop is the measure of fatigue failure.

Figure 3. The setup for the four-point beam fatigue test

RESULTS AND DISCUSSION

Wheel Tracking Test

Prior to investigating the cracking behavior of HMA, SMA, and GA mixtures, the Hamburg Wheel Tracking test was conducted to characterize the rutting resistance of the asphalt mixtures. Figure 4 shows a comparison of rut depths for HMA, SMA, and GA mixtures. It can be seen from Figure 4 that mixtures with higher asphalt content tend to exhibit poorer rutting performance.

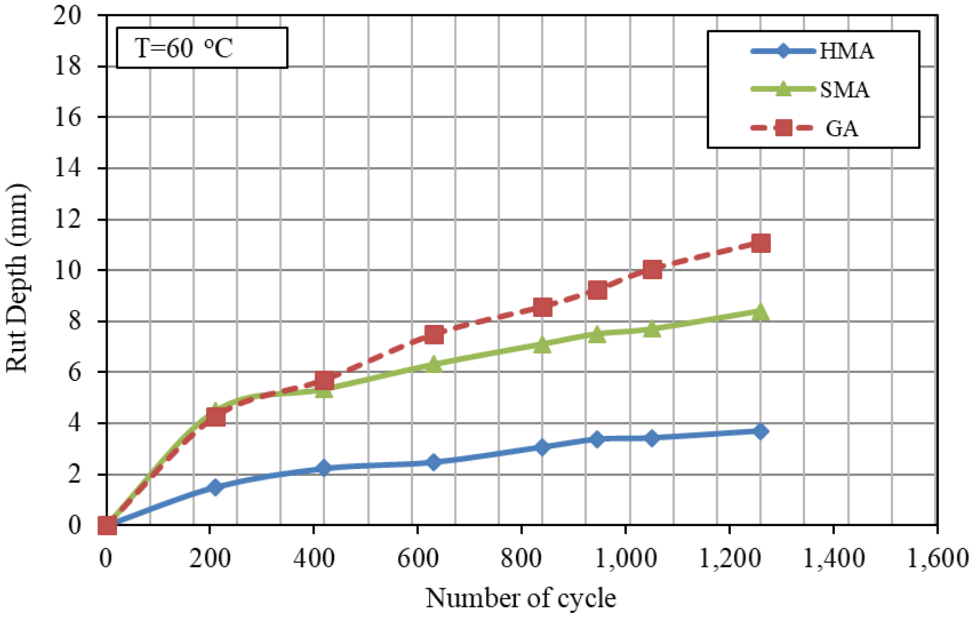

Figure 4. The rut depth *versus* number of cycles for HMA, SMA, and GA mixtures

In addition, the dynamic stability (DS) is computed from the measured rut depth between 45 and 60 minutes in the HWT test at a reference temperature of 60 °C, as follows (Hao and Hachiya, 2004):

$$DS = \frac{42 \times 15}{d_{60} - d_{45}} \qquad (1)$$

where

DS = dynamic stability at a reference temperature of 60 °C (cycles/mm) in dry conditions,

d_{60} = rut depth at 60 minutes under dry conditions at a reference temperature of 60°C (mm), and

d_{45} = rut depth at 45 minutes under dry conditions at a reference temperature of 60°C (mm).

Equation (1) was utilized to compute the DS value. Figure 5 displays the DS results. Depending on the type of asphalt mix used in Korea, mastic asphalt mixtures typically have a minimum dynamic stability of 300 cycles/mm (Kim et al., 2004). As shown in Figure 5, the DS values of asphalt mixtures are 1,930 cycles/mm, 700 cycles/mm, and 340 cycles/mm for HMA, SMA, and GA, respectively. It was noted that the DS value meets the minimum requirement of 300 cycles/mm for mastic asphalt mixtures in accordance with Korea standard (Kim et al., 2004).

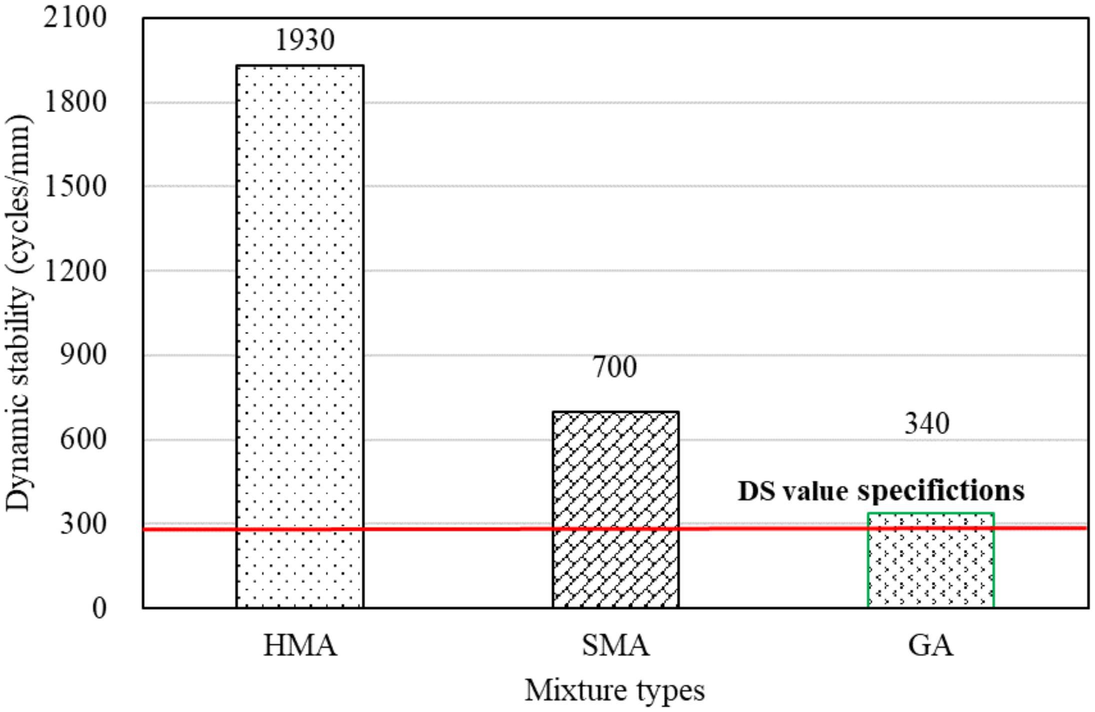

Figure 5. Comparison of DS values for HMA, SMA, and GA mixtures

Indirect Test of Tensile Strength

Crack Initiation

The tensile stress and strain at the center of the specimen can be obtained using the following equations (Buttlar & Roque, 1994; Kim et al., 2002):

$$\sigma_x = \frac{2P}{\pi d \delta} C_{\sigma x} \qquad (2)$$

$$\varepsilon_x = H \frac{C_1 + C_2 \nu}{C_3 + C_4 \nu} C_{\varepsilon x} \qquad (3)$$

where

σ_x = tensile stress at the center of the specimen (kPa),

ε_x = tensile strain at the center of the specimen (με),

P = amplitude of an applied vertical load (N),

d and δ = diameter and thickness of the specimen (mm).

$C_{\varepsilon x}$, and $C_{\sigma x}$ = correction factors to consider the bulging effects proposed by Buttlar and Roque (1994), as follows:

$$C_{\varepsilon x} = 1.03 - 0.189\left(\frac{\delta}{d}\right) - 0.08\upsilon + 0.089\left(\frac{\delta}{d}\right)^2 \qquad (4)$$

$$C_{\sigma x} = 0.948 - 0.01114\left(\frac{\delta}{d}\right) - 0.269\upsilon + 1.436\left(\frac{\delta}{d}\right)\nu \quad (5)$$

C_1, C_2, C_3, and C_4 = geometry coefficients related to specimen diameter and gauge length. C_1=8.4121, C_2=24.9981, C_3=0.2041, C_4=0.6235 provided by Kim et al. (2002).

H = amplitude of horizontal deformation, and

ν = Poisson's ratio, ν = 0.35 was used in this study.

The results of tensile stress and strain for HMA, SMA, and GA mixtures are shown in Figure 6. In addition, the average maximum IDT strength values for HMA, SMA, and GA mixtures was calculated, as shown in Figure 7. The HMA mixture has an average maximum IDT strength value significantly higher than that of the SMA mixture. The HMA mixture exhibited an average maximum IDT strength of 535 kPa, representing a 38% increase compared to that of the SMA mixture (328 kPa). This is because dense-graded HMA mixtures make the mixture stiffer than gap-graded SMA mixtures. Meanwhile, the average maximum IDT strength of the GA mixture was 630 kPa, which is 15% and 47% higher than that of the HMA and SMA mixtures, respectively.

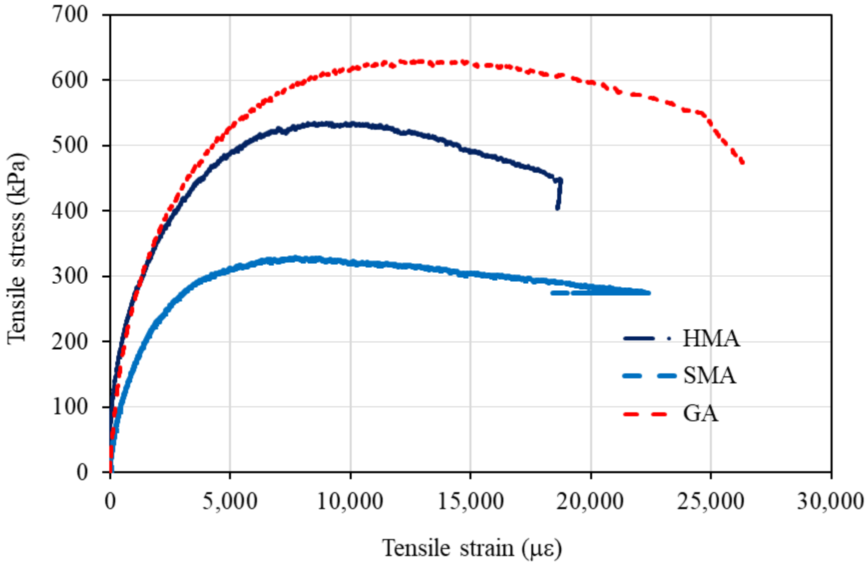

Figure 6. The IDT strength test results for HMA, SMA, and GA mixtures

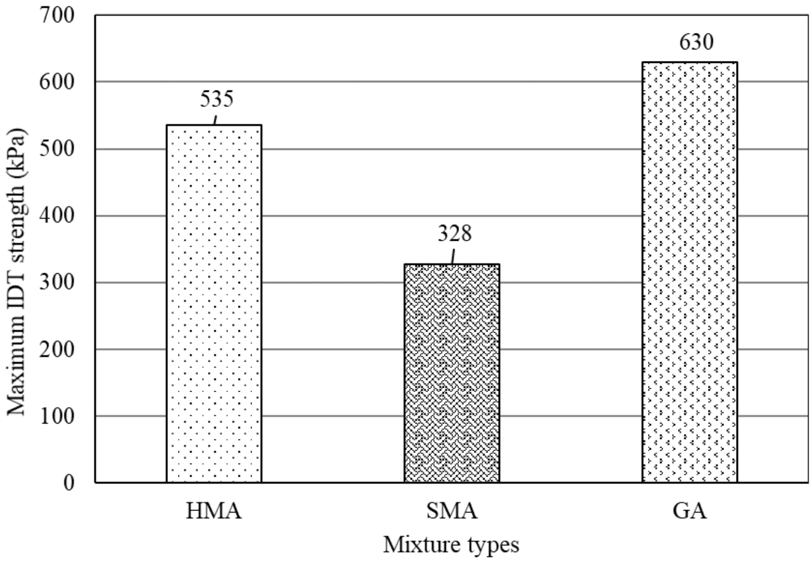

Figure 7. The maximum IDT strength for HMA, SMA, and GA mixtures

Moreover, the IDT toughness was calculated based on the area under the tensile stress–strain curve up to the maximum IDT strength, as shown in Figure 8. It was found that the toughness values were 3.9 kPa, 2.0 kPa, and 6.5 kPa for HMA, SMA, and GA mixtures, respectively. The toughness of the SMA mixture was 48% and 60% lower than that of the HMA and GA mixtures, respectively. Therefore, the SMA mixture was less effective than the HMA and GA mixtures in preventing initial cracking.

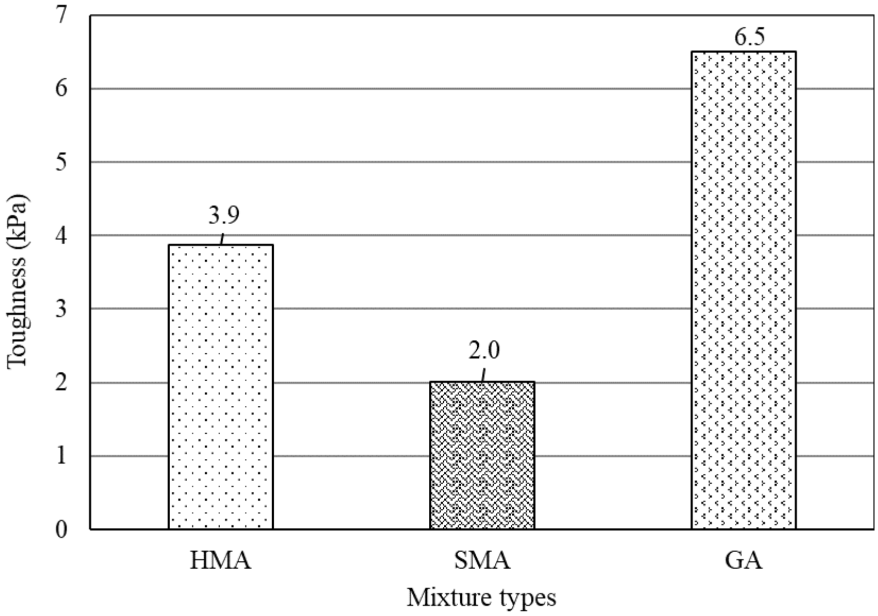

Figure 8. The IDT toughness for HMA, SMA, and GA mixtures

Crack Growth

Crack images for HMA, SMA, and GA mixtures during a loading period of 110 s are displayed in Figure 9. The HMA and SMA mixtures showed an evident crack through the centerline of the prescribed region, but the GA mixture showed no crack at all. The GA mixture distributes fatigue damage over a wider area, reducing stress concentration and improving fatigue crack resistance.

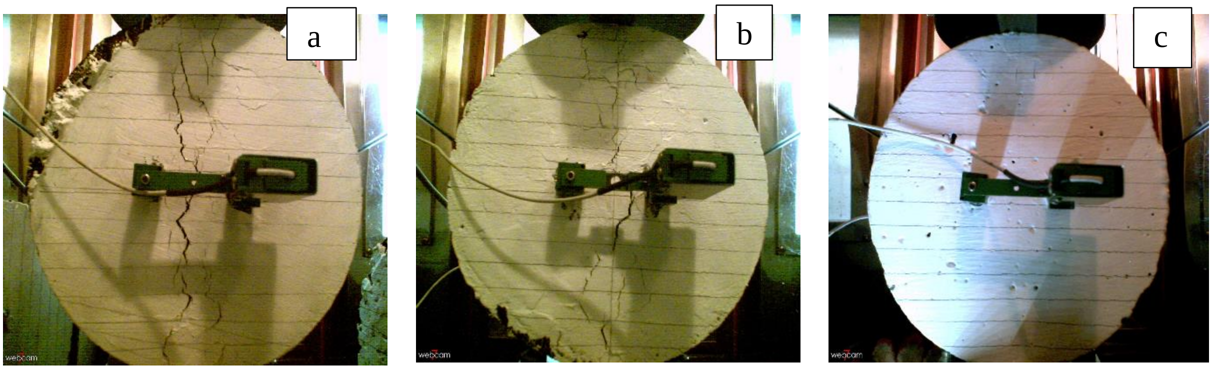

Figure 9. The crack propagation images of 1280x1024 pixel: a) HMA, b) SMA, and c) GA at loading time of 110s

Crack propagation was investigated by analyzing images obtained from three specimens to measure crack length and width. Figure 10 presents the variations in fracture length and crack width with loading time for all asphalt mixtures. The crack length corresponds to the total length of all visible cracks formed in the prescribed area, while the crack width was estimated from the position of the maximum width along each fracture path observed in the crack image near failure. As shown in Figure 10, there is no significant difference in crack length or crack width between the HMA and SMA mixtures. On the other hand, the GA mixture has significantly lower crack length and crack width than the SMA and HMA mixtures. Therefore, under indirect tensile loading, the GA mixture provides a clear advantage in delaying initial fracture and subsequent crack propagation.

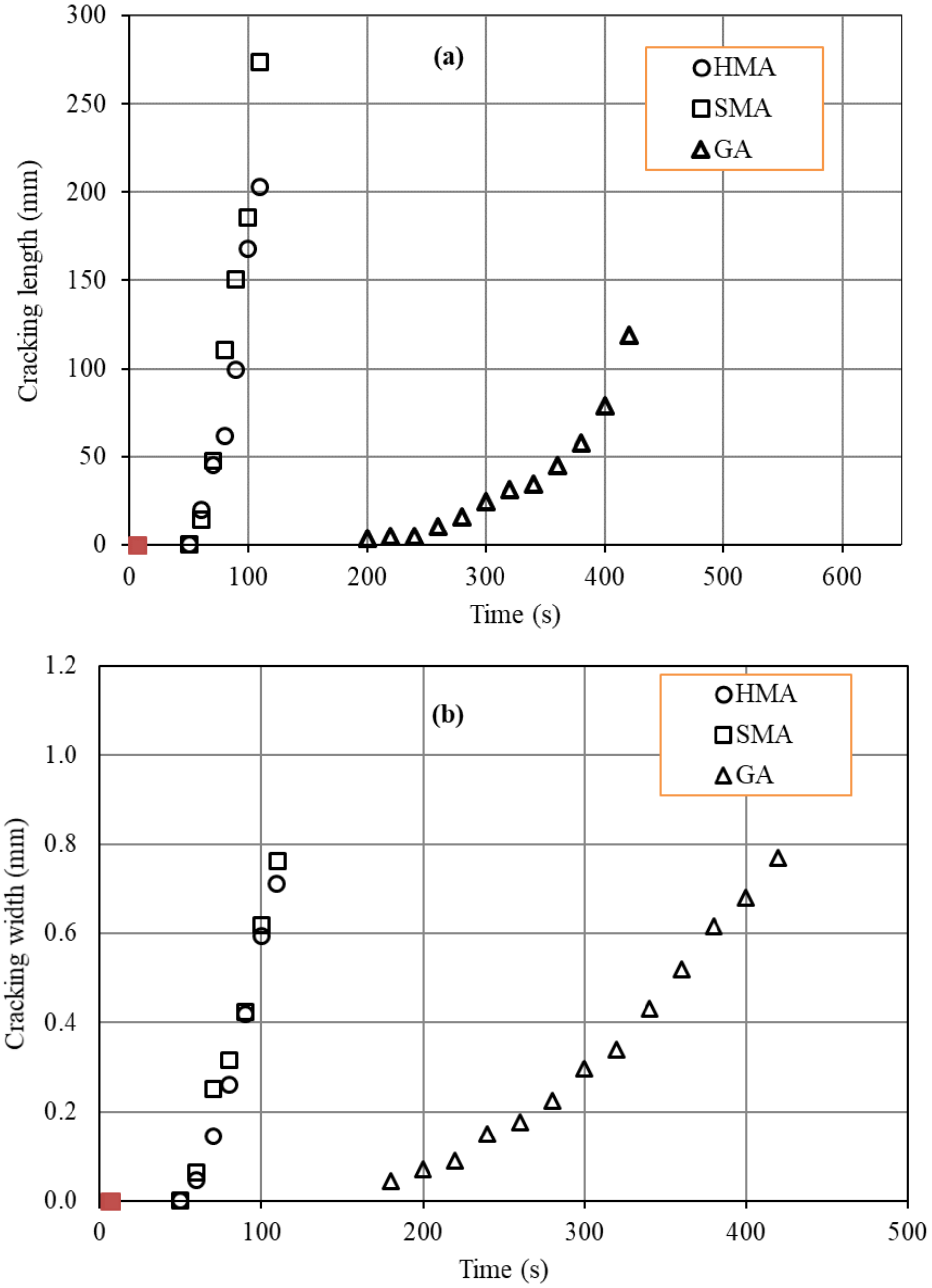

Figure 10. The crack growth with respect to loading time: (a) Crack length and (b) Crack width

Four-point Beam Fatigue Test

In this study, the number of loading cycles to failure (N_f) was determined based on the 50% flexural stiffness reduction criterion. Figure 11 illustrates that the three asphalt mixtures demonstrated clearly different fatigue behaviors at 20 °C. Among the three mixtures, the GA mixture exhibited the greatest fatigue life, followed by the HMA and SMA mixtures. Under a reference strain of 1,000 με and a 50% stiffness reduction criterion, the GA mixture demonstrated exceptional durability, sustaining about 230,000 cycles to failure. In contrast, the HMA mixture reached failure after only 3,588 cycles, which is more than 60 times fewer than that of the GA mixture. The SMA mixture exhibited the poorest performance, failing after just 1,925 cycles, roughly a half of the fatigue life of the HMA mixture. The superior fatigue performance of the GA mixture can be attributed to its dense aggregate gradation and higher binder content, as evidenced by the results. The dense aggregate structure ensures strong interlocking and effective load distribution, thereby minimizing stress concentrations at the micro-crack level. Meanwhile, the high binder content improves cohesion, flexibility, and the ability to dissipate energy under cyclic tensile loading. Consequently, the GA mixture demonstrates outstanding resistance to both crack initiation and propagation, indicating its suitability for heavy-duty or long-life pavement applications, including bridge decks, airport runways, and urban roads.

From the standpoint of field application, the laboratory results offer important guidance for selecting appropriate mixtures under varying climatic and loading conditions. The HMA mixture exhibits moderate fatigue resistance and is expected to perform adequately under moderate climatic conditions and medium traffic. However, structural reinforcement or reduced tensile strain levels may be necessary to attain a service life comparable to that of the GA mixture. The SMA mixture, although often selected for its superior rutting resistance, exhibits limited fatigue endurance and should therefore be applied in layers or locations subjected to lower tensile stresses or fewer traffic repetitions to prevent early cracking. It is important to note that the high binder content and dense gradation responsible for the GA mixture's remarkable fatigue resistance should be carefully optimized to ensure balanced performance under both high and low temperature conditions. In high-temperature climates, an excessive binder content may lead to mixture softening, thereby increasing susceptibility to rutting and permanent deformation. In cold climates, dense gradation or low binder content may cause thermal cracking. Hence, optimizing the binder type, content, and aggregate gradation with respect to local climatic conditions and loading demands is critical for achieving a durable and stable pavement structure. Moreover, the impermeable nature of the GA mixture provides excellent resistance to moisture penetration, which is particularly beneficial for bridge deck pavements, as it minimizes water-induced reinforcement corrosion and structural damage. However, this impermeability also limits internal drainage, making the balance between temperature and binder properties even more critical to prevent thermal stress accumulation.

Overall, the laboratory findings not only confirm the superior fatigue performance of the GA mixture, but also highlight the importance of optimizing mixture design for practical field implementation. Therefore, future research should focus on evaluating the long-term field performance of these mixtures across diverse climatic conditions and traffic loadings, emphasizing binder modification approaches that improve thermal sensitivity and maintain stable performance. This line of research would not only improve the practical relevance of the current findings, but also support the formulation of performance-based specifications for asphalt mixtures adapted to specific regional climates and service conditions.

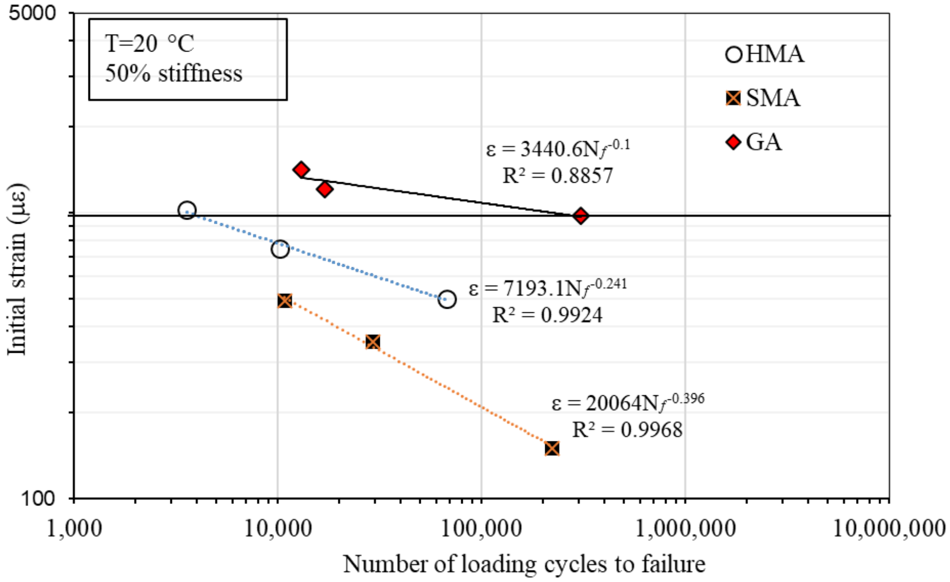

Figure 11. The fatigue life versus the initial strain

CONCLUSIONS

In this study, the fatigue and cracking behavior of HMA, SMA, and GA mixtures was evaluated through indirect tensile (IDT) and four-point beam fatigue tests. Results indicated that the GA mixture exhibited the highest indirect tensile strength, surpassing that of HMA and SMA by 15% and 47%, respectively, mainly attributed to its dense aggregate structure and increased stiffness. The SMA mixture exhibited the lowest IDT toughness, indicating limited resistance to crack initiation. Furthermore, the GA mixture exhibited significantly smaller crack lengths and widths compared with those of the other mixtures, indicating greater resistance to fracture propagation under tensile loading. In terms of fatigue performance, the GA mixture demonstrated exceptional durability, achieving approximately 230,000 cycles. This is more than 60 times the fatigue life of the HMA mixture and nearly 120 times that of the SMA mixture, emphasizing its suitability for heavy-traffic applications.

Future studies should prioritize evaluating the field performance of these mixtures under real-world service conditions to confirm the laboratory results. Key aspects to examine include their long-term durability, resistance to rutting and cracking, and maintenance needs, ensuring that the findings are practically applicable. An evaluation of life-cycle costs would offer valuable insights into the cost-effectiveness of these mixtures, thereby facilitating more informed decisions on pavement design and material selection. In addition, it is highly recommended to integrate binder optimization strategies along with considerations for fatigue and rutting resistance across various temperature regimes into performance-based specifications.

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