

Automated Displacement Tracking for Asphalt Mixture Crack Analysis

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Abstract

Cracking resistance plays a key role in the durability and service life of asphalt mixtures. Although the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) is widely used to evaluate cracking performance, it mainly relies on global strength-based parameters and provides limited information about how cracks initiate and propagate. This study presents an image-based framework for evaluating crack evolution in asphalt mixtures prepared with conventional (40/50) and modified binders. A dense-graded limestone mixture was designed using the Superpave method with air-void content 4% and an optimum binder content of 5.4%. The modified binder contained 4% of a locally developed polymer-based additive. IDEAL-CT tests were performed at 25 °C, while crack development was recorded using two high-resolution cameras (4K resolution at 60 frames per second (fps)). The recorded videos were analyzed using Tracker software (Ver. 6.3.4) to obtain displacement data, from which four displacement-based indicators (M1-M4) were developed to describe crack initiation, propagation duration, crack growth rate, and propagation stability. The results showed that the modified mixtures exhibited slower crack growth, greater propagation stability, and a lower crack propagation rate than the unmodified mixtures. The most significant improvement was observed during the crack propagation stage rather than at crack initiation, indicating that binder modification mainly influenced the crack growth mechanism. Overall, the proposed framework provides a practical way to monitor crack evolution and complements conventional IDEAL-CT indices by offering additional insight into fracture behavior, which can support the development and evaluation of asphalt mixtures with improved crack resistance.

Keywords: Asphalt mixtures, Displacement-based indicators, IDEAL-CT, Crack behavior.

1. Introduction

Cracking is widely recognized as one of the most critical distress mechanisms affecting the durability and long-term performance of asphalt pavements [1]. The initiation and propagation of cracks are regulated by a complex interaction between properties of asphalt binder, structure of aggregate, environmental conditions, and loading characteristics [2]. Among these factors and due to its viscoelastic nature and its ability to dissipate energy under loading, asphalt binder plays a prevailing role in controlling fracture resistance [3]. Therefore, improving binder properties has been a major aspect in enhancing cracking resistance.

Polymer modification, particularly using styrene-butadiene-styrene (SBS), has been extensively applied to improve the mechanical performance of asphalt binders. X. Zhu et. al. investigated the effects of three types of SBS polymers (diblock, linear triblock and radial), two polymer contents (3% and 6%), and four aging conditions on the physicochemical and performance-related properties of modified asphalt binders [4]. The aim of their research was to provide valuable insights on polymer material selection and help optimize the production, transportation, and construction of SBS-modified asphalt, thereby ensuring the quality and durability of asphalt pavements [5]. investigated the effect of SBS, glass fiber,

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and their combination on the fracture energy of Hot Mix Asphalt (HMA) using the Indirect Tensile Strength Test (ITS), Semi-Circular Bending Test (SCB) and Indirect Tensile Asphalt Cracking Test (IDEAL-CT). The findings indicated that SBS-modified binders exhibit enhanced elasticity, increased resistance to deformation, and improved energy absorption capacity, which contribute to delaying crack initiation and reducing crack propagation rates. In addition to conventional polymer modification, modern developments have presented multi-component modification systems that include additives such as sulfur, mineral oils, and mineral fillers to further enhance binder performance [6], [7], [8].

To evaluate cracking resistance, several laboratory tests have been developed, including bending beam fatigue tests, semi-circular bending (SCB), and indirect tensile tests [9], [10]. Due to its simplicity, repeatability, and applicability in mixture design and quality control, the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) has acquired notable attention among these tests [11]. The IDEAL-CT test assesses cracking performance under monotonic loading conditions and provides indices such as fracture energy and the cracking tolerance index (CT_{Index}), which are widely used to compare the cracking performance of asphalt mixtures.

Despite the advantages of conventional crack assessment methods, they primarily depend on global force-displacement responses, which depict the overall behavior of the specimen but do not fully capture the fracture process [12]. In particular, these methods lack the ability to illustrate crack evolution in terms of propagation rate, stability, and localization of deformation. As a result, important aspects of fracture mechanisms, such as whether crack growth is stable or unstable, may not be sufficiently identified [13].

Recent advances in optical measurement techniques, especially Digital Image Correlation (DIC), have enabled detailed investigation of deformation and cracking behavior in asphalt materials [14]. DIC is a non-contact technique that tracks surface displacements by analyzing sequential images, allowing the measurement of full-field displacement and strain distributions [15]. This approach provides significant insight into crack initiation and propagation processes, enabling a more comprehensive understanding of fracture behavior compared to conventional methods.

In the last decade, several studies have demonstrated the effectiveness of DIC in analyzing crack growth and strain localization in asphalt mixtures. The use of DIC for measuring displacement and strain in asphalt mixtures was demonstrated in study [16] as a possible method for measuring displacement/strain of asphalt mixtures. They used DIC to investigate the appropriate gauge length for a 100-mm-diameter IDT specimen. They demonstrated that the stress concentration under the loading strips can cause errors in the strain calculation if the gauge length is too long for surface-mounted Linear Variable Differential Transformers (LVDTs). Study [17] used DIC to measure local and global deformations within the Fracture Process Zone (FPZ) using a double-notched direct tension test conducted at a constant crosshead rate. By using three different types of notches, the effect of the notch size on process zone evolution was determined. Their results revealed that the evolution of the fracture process zone and the localization of deformation were significantly influenced by increasing the notch size during crack propagation. Study [18] measured the physical development of crack length during the four-point bending fatigue test using the DIC technique on asphalt specimens. The study showed that DIC supported reliable monitoring of crack length evolution during fatigue loading, permitting continuous evaluation of crack growth behavior. Study [19] proposed an integrated methodology combining DIC measurements of the local fracture process zone with cohesive zone modeling to evaluate the fracture properties of asphalt mixtures under various loading rates at intermediate temperatures. Their findings demonstrated that DIC effectively captures crack tip behavior and can be seamlessly coupled with numerical modeling to determine local fracture characteristics.

Although the deformation localization and crack development in asphalt mixtures have been investigated effectively using Digital Image Correlation (DIC) and other image-based techniques, these methods generally depend on specialized imaging systems, full-field subset correlation, speckle surface preparation, and dedicated analysis software. In contrast, the current study adopts a simplified point-based displacement tracking method using Tracker software, in which selected surface points are tracked during the loading process rather than performing full-field DIC analysis. Furthermore, the focus of recent studies on qualitative observations or

conventional fracture parameters derived from load-displacement data has led to the development of a practical displacement-based framework capable of characterizing different stages of crack evolution quantitatively during IDEAL-CT testing, including crack initiation, propagation duration, propagation rate, and propagation stability, especially with the presence of different asphalt binder modification processes.

This study presents a displacement-based crack characterization framework developed through image tracking analysis of IDEAL-CT specimens. It introduces a set of displacement-derived indicators (M1-M4) that quantify crack initiation timing, propagation duration, crack growth rate, and propagation stability by utilizing kinematic data extracted from sequential images. Unlike conventional IDEAL-CT indices that mainly capture the overall cracking response, these proposed indicators offer direct insight into the crack evolution process and the stability of crack growth.

The significance of this study lies in offering a practical and physically meaningful approach to evaluate fracture behavior beyond traditional strength-based parameters. The developed framework is applied to compare asphalt mixtures containing conventional and locally modified binders, demonstrating its capability to detect differences in crack propagation mechanisms that conventional cracking indices alone cannot fully capture. These findings enhance understanding of asphalt fracture behavior and support the advancement of more performance-oriented mixture evaluation methods.

2. Materials and Methods

2.1. Materials

2.1.1. Asphalt binder and modification

In this study, the base binder used was a conventional asphalt binder obtained from the Karbala refinery with a penetration grade of 40/50 and a density of 1.031 g/cm³. Table 1 presents the physical properties of the binder determined according to relevant ASTM standards.

A locally developed multi-component (polymer-based) additive was incorporated into the base binder at dosages of 4%, 8% and 12 % by weight of binder. The additive consisted of a polymeric component, a

crosslinking agent, a mineral reinforcing filler, compatibility-enhancing agents, stabilizing compounds, and processing aids. The formulation was designed to improve the viscoelastic behavior of the binder and enhance its resistance to permanent deformation and crack propagation. The practical goal of selecting this modifier was to provide a balanced combination of stiffness, elasticity, storage stability, and compatibility with the base binder. These characteristics are expected to enhance the asphalt binder's resistance to permanent deformation while maintaining adequate flexibility and energy dissipation during crack propagation, making the additive suitable for asphalt pavement applications. Due to intellectual property considerations and an ongoing patent application, the exact composition and proportions of the additive are not disclosed in this study. The mixing temperature for the SBS modification process was selected based on previous studies reported in the literature. The selected temperature in this study was 170°C, based on the procedure reported by study [20], which was considered suitable for achieving adequate dispersion of the polymer-based additive within the binder. To confirm homogeneous blending, the mixing process was visually monitored with no evidence of phase separation or agglomeration during preparation.

The modified binder was prepared by heating the base binder to 170 ± 5 °C and then incorporating the additive under continuous high-shear mixing. The blending was performed at a rotational speed of 8000-10000 rpm for 60 minutes to ensure thorough dispersion and interaction of the modifier components within the asphalt matrix (Figure 1). After mixing, the modified binder was conditioned prior to rheological characterization and mixture preparation.



Figure 1. Configuration of bitumen modification process.

Table 1. Physical properties of 40/50 asphalt binder.

Property	ASTM Designation	Test Conditions	Units	Result	Specification Limit *GSRB
Penetration	D 5	25°C, 100 gm, 5 sec.	1/10 mm	41	40-50
Ductility	D 113	25°C, 5 cm/min	cm	> 100	> 100
Rotational Viscosity	D 4402	135°C	Pa·s	0.562	-----
		165°C		0.146	-----
Flash Point	D 92	-----	°C	> 270	> 232
Specific Gravity	D 70	25°C	-----	1.031	-----
Solubility in Trichloroethylene	D 2042	-----	% wt	99.5	> 99
% From Origin Penetration after Thin Film Oven Test	D 5	25°C, 100 gm, 5 sec.	%	61	> 55%
Ductility after Thin Film Oven Test	D 113	25°C, 5 cm/min	cm	85	> 25

*GSRB: General specifications for roads and bridges.

To evaluate the effect of modification, the results of rutting resistance parameter ($G^*/\sin \delta$) were determined using the values of G^* and δ that are measured from Dynamic Shear Rheometer (DSR) at different temperatures. This parameter is used to describe the asphalt binder rutting resistance at high temperatures. An increase in the $G^*/\sin \delta$ was observed with the addition of the modifier, whereas $G^*/\sin \delta$ decreased as the testing temperature increased because of the reduction in binder viscosity, as shown in Figure 2.

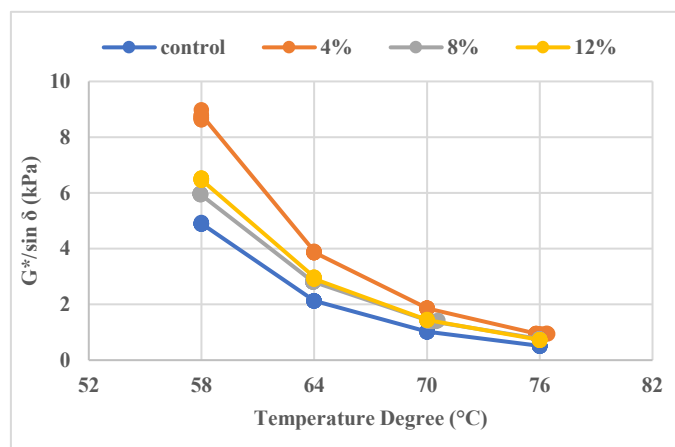


Figure 2. $G^*/\sin \delta$ versus temperature for neat and modified asphalt binders.

As reported by the Asphalt Institute (2003), elevated $G^*/\sin \delta$ values typically indicate increased asphalt binder stiffness, which correlates with enhanced resistance to permanent deformation. On the other hand, the two key parameters obtained from the Multiple Stress Creep Recovery (MSCR) test, namely the non-recoverable creep compliance (J_{nr}) and percent recovery (% R), were calculated from the DSR measurements. Figures 3 and 4 show the variation of creep compliance and the variation

of percent recovery with temperature of neat and modified asphalt binder at two stress levels of 0.1 and 3.2 kPa respectively. These figures show that the addition of modifier into asphalt binder reduced the J_{nr} value compared with the neat binder at both low and high stress levels and increased %R values, indicating improved resistance to rutting and greater asphalt binder elasticity.

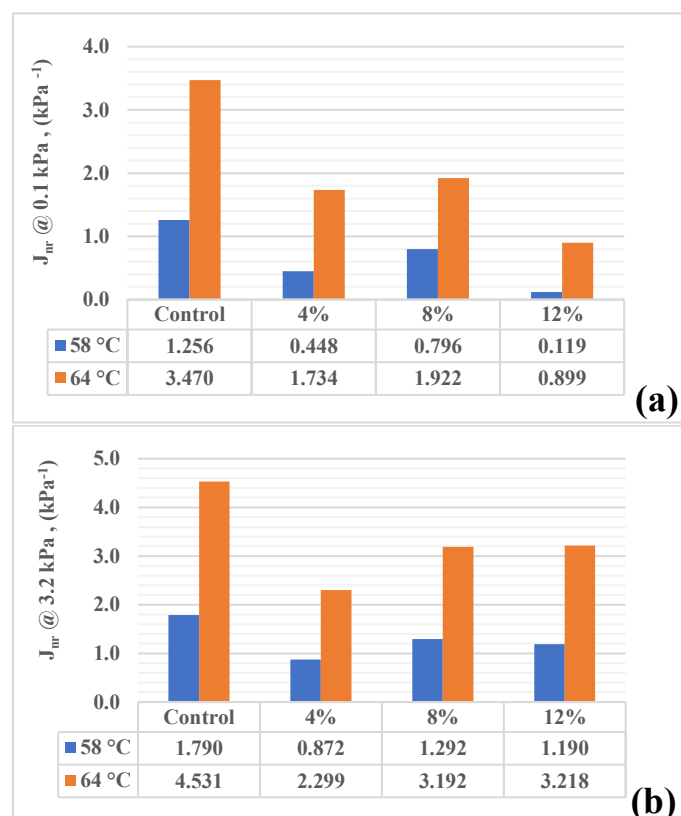


Figure 3. (a) Low stress non-recoverable creep compliance; (b) High stress non-recoverable creep compliance for neat and modified asphalt binders.

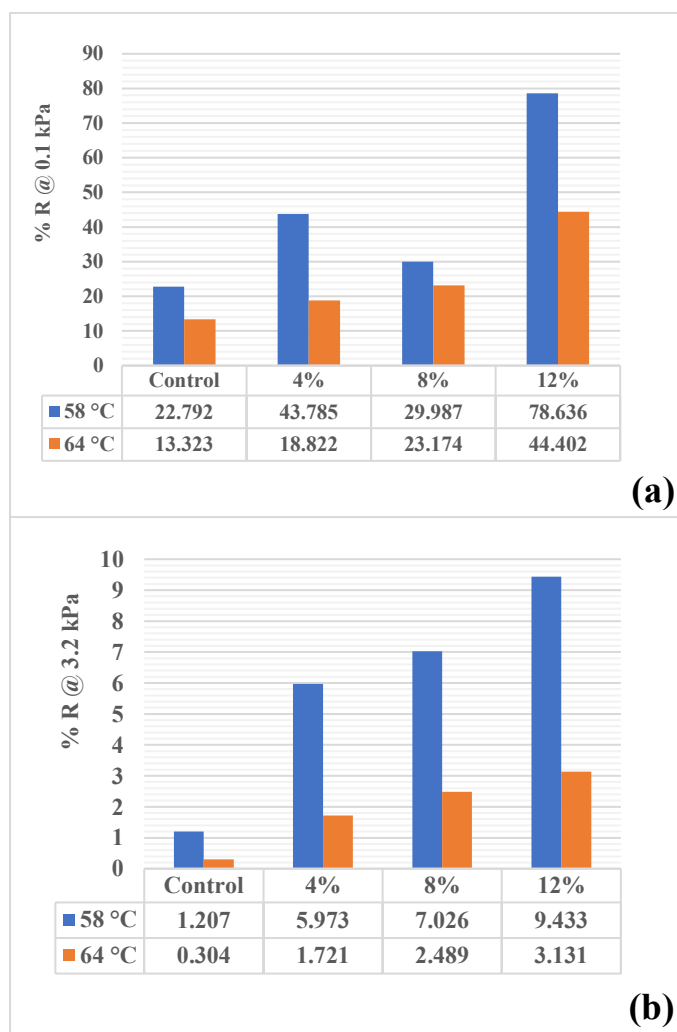


Figure 4. (a) Low stress percent recovery (b) High stress percent recovery for neat and modified asphalt binders.

While the aims of the additive formulation were to enhance elasticity and improve the binder's fracture resistance through a combination of polymer modification and chemical stabilization, the results revealed distinct

Although the 12% modified binder exhibited the highest elastic recovery (%R), the DSR and MSCR analyses indicated that excessive modification resulted in reduced stiffness and increased stress sensitivity, which may negatively influence the binder performance under high loading conditions. In contrast, the 4% modified binder revealed lower J_{nr} values under the higher stress level (3.2 kPa) together with the highest $G/\sin\delta$ values, indicating a balanced viscoelastic response under severe loading conditions. Although the MSCR test primarily evaluates rutting-related binder performance, it was used in this study as a preliminary rheological screening tool to identify the most suitable modifier content before conducting the image-based crack analysis. Consequently, the selection of a 4% modification was due to the best overall balance between stiffness and elastic response, while the influence of this selected binder on crack initiation and propagation was subsequently evaluated directly using the proposed displacement-based methodology.

2.1.2. Aggregates

Limestone aggregates sourced from Al-Nibaie quarry (Taji, Baghdad) were used in this study. The aggregates were selected due to their common use in local pavement construction. The physical properties of the aggregates were determined according to ASTM standards and are summarized in Table 2.

Limestone dust was employed as the filler material in this study. The filler is a non-plastic by-product obtained from the lime factory in Baghdad Governorate, and its physical properties are presented in Table 3.

Table 2. Coarse and fine aggregate physical properties.

Property	ASTM Designation	Units	Result		Specification limit GSRB
			Coarse Aggregate	Fine Aggregate	
Bulk Specific Gravity	C 127 & C 128	-----	2.615	2.640	-----
Apparent Specific Gravity	C 127 & C 128	-----	2.635	2.690	-----
Percent Water Absorption	C 127 & C 128	%	0.443	0.698	-----
Percent Wear (Los Angeles Abrasion)	C 131	%	21.7	-----	30% max
Soundness loss by sodium Sulfate solution	C 88	%	3.75	-----	12% max
Fractured pieces,	D 5821	%	94	-----	90% min
Sand Equivalent,	D 2419	%	-----	52	45% min

Table 3. Mineral filler physical properties

Property	Test result
Specific Gravity	2.91
Passing Sieve No.200 (0.075 mm)	95%

The aggregate gradation was selected in accordance with GSRB (2003) for dense-graded asphalt mixtures. The gradation curve used in this study is presented in Figure 5.

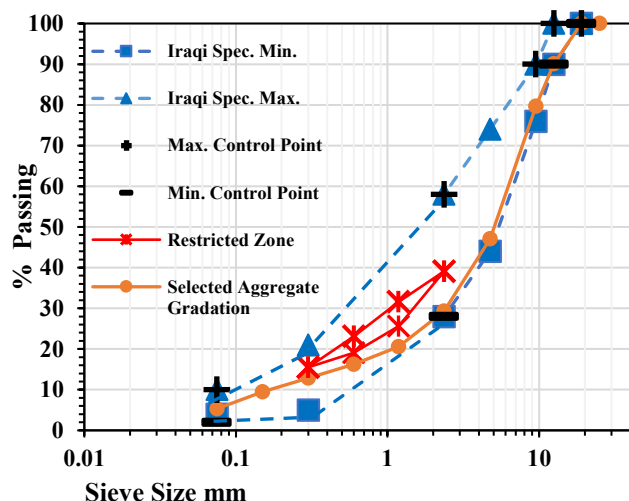


Figure 5. Aggregate gradation according to GSRB for the asphalt mixtures.

2.2. Mixture design

The asphalt mixtures were designed using the Superpave method with a target air void content of 4%. The design binder content was determined to be 5.4% by weight of the total mixture. The number of gyrations ($N_{\text{design}} = 100$) was selected in accordance with Superpave design requirements [21].

Two types of mixtures were prepared:

- Mixture 1: Unmodified asphalt binder mixture.
- Mixture 2: Modified asphalt binder mixture with (4% additive).

Three replicate specimens were prepared for each mixture to ensure repeatability of the results.

2.3. IDEAL-CT test procedure

Cracking performance was evaluated using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) in

accordance with ASTM D8225-19. Cylindrical specimens with a diameter of 150 ± 2 mm and a thickness of 62 ± 1 mm were tested at a temperature of 25 ± 1 °C. The test was conducted under monotonic loading at a constant displacement rate of 50 ± 2 mm/min until failure. The load and displacement data were recorded continuously throughout the test.

Three replicate specimens were prepared and tested for each mixture condition (unmodified and modified). Accordingly, a total of six IDEAL-CT specimens were included in the reported experimental program. The average values of the three replicate specimens were used in the subsequent analysis to evaluate the proposed displacement-based indicators.

2.4. Image acquisition and analysis

The deformation behavior of the specimens was captured during test using a dual-camera imaging system. Two cameras were positioned on opposite sides of the specimen at a fixed distance of approximately 15 cm, as shown in Figure 6.



Figure 6. Camera setup and imaging configuration.

The cameras recorded high-resolution videos at a spatial resolution of 3840×2160 pixels (4K Ultra HD) and a frame rate of 60 fps. The two independent cameras were positioned at a distance of 15 cm from each face of the specimen to simultaneously record the opposite faces of the specimen. Video recording was initiated on both cameras before the commencement of the IDEAL-CT test. During post-processing, the recordings were temporally synchronized by aligning the first visible movement associated with the onset of loading. This synchronization procedure established a common time

reference for both videos, after which displacement tracking was performed independently on each specimen face using Tracker software. The acquired videos were subsequently analyzed using Tracker software (Version 6.3.4) through a point-based displacement tracking approach, rather than conventional full-field Digital Image Correlation (DIC). In this approach, selected surface points were manually defined on the specimen prior to analysis and then automatically tracked throughout the loading process to obtain their displacement histories. Unlike full-field DIC, which relies on subset correlation to generate continuous displacement fields, the proposed method follows discrete feature points to quantify crack initiation and propagation using the proposed displacement-based metrics.

2.5. Displacement measurement and point selection

To quantify crack opening behavior, horizontal displacement (X-direction) was used as the primary parameter. Four measurement points were selected symmetrically on both sides of the crack (Red Dots) to calculate crack opening displacement (Spread). In addition, to monitor displacement evolution along the crack path, eight points (Yellow Dots) were selected along one side of the crack as depicted in Figure 7.

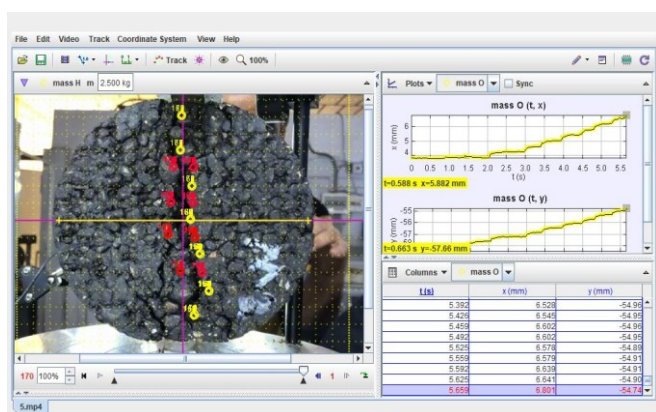


Figure 7. Tracking points and crack path identification in Tracker software.

The recorded videos were analyzed after completion of the IDEAL-CT test. To ensure that the tracking points were positioned adjacent to the actual crack path, the video was first advanced to the initial frame in which crack initiation became visible, and the tracking points were manually positioned approximately 5 mm from both

sides of the crack. The video was then reset to the first frame, and the selected points were automatically tracked throughout the entire loading sequence using Tracker software. This procedure enabled displacement measurements to be obtained from the beginning of the test while ensuring that the selected points remained adjacent to the actual crack path. At approximately 5 mm on either side of the crack path, the tracking points were positioned to ensure that the measured displacement represents the deformation of the material directly adjacent to the crack and to avoid potential tracking instability that could occur during crack initiation if the points were located directly on the crack. In contrast, if the tracking points were placed farther from the crack path, this may reduce their ability to represent the local deformation related to crack propagation accurately. The overall deformation behavior was captured using the selected configuration while reducing the impact of localized measurement noise or isolated tracking errors. The main reason for using multiple tracking points rather than a single point was to improve the robustness displacement measurements by representing the collective movement of the material adjacent to the crack during loading.

2.6. Displacement-based crack characterization framework

A developed displacement-based analytical framework was used to quantify crack evolution during the IDEAL-CT test using image-tracking measurement. The methodology is based on the relative displacement between tracked points located on both sides of the crack path. The resulting displacement spread was used to characterize crack initiation, crack propagation, and crack stability throughout the failure process.

Figure 8 illustrates a representative crack opening evolution curve (Spread vs. time), which exhibits three distinct stages: an initial stage with negligible displacement corresponding to elastic behavior, followed by a rapid increase associated with crack initiation and propagation, and finally a plateau indicating post-failure stabilization. These stages form the basis for defining the key thresholds (t_{20} , t_{80} , and t_{90}), which are used in the formulation of the proposed indicators. The 20% displacement level (t_{20}) was used to indicate the onset of stable crack initiation, minimizing the effects of initial

seating and measurement fluctuations. The 80% displacement level (t_{80}) characterizes the main stage of crack propagation, during which crack propagation remains relatively stable. Finally, the 90% displacement level (t_{90}) marks the transition to final crack instability immediately before specimen failure.

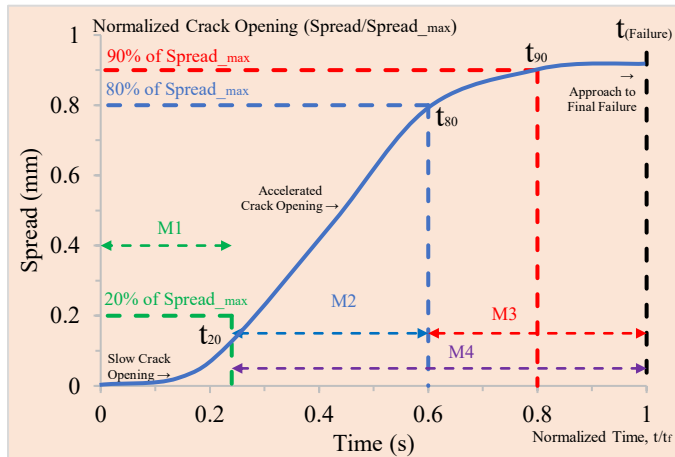


Figure 8. Conceptual schematic of the displacement-based crack evaluation and the proposed indicators.

The maximum displacement spread ($Spread_{max}$) calculated during the IDEAL-CT test was employed as a reference parameter. 20%, 80%, and 90% of $Spread_{max}$ was identified as accredited time characteristics in this study and denoted as t_{20} , t_{80} , and t_{90} , respectively. The adopted threshold values (t_{20} , t_{80} , and t_{90}) were developed as part of the proposed displacement-based crack characterization framework. To distinguish different stages of crack evolution, these thresholds were selected to represent crack initiation, stable crack propagation, and the final propagation stage prior to failure. Unlike conventional fracture parameters, the introduced thresholds were used to provide a consistent basis for quantifying crack development from displacement measurements.

Accordingly, the obtained indicators are defined as follows. M1 represents the normalized crack initiation time and is calculated as:

$$M1 = \frac{t_{20}}{t_{failure}} \quad (1)$$

where t_{20} is the time corresponding to 20% of $Spread_{max}$, and $t_{failure}$ is the total time to specimen failure. Lower M1 values indicate earlier crack initiation,

whereas higher values reflect a delayed onset of crack development.

M2 represents the normalized duration of the crack propagation stage and is calculated as:

$$M2 = \frac{t_{80} - t_{20}}{t_{failure}} \quad (2)$$

where t_{80} is the time corresponding to 80% of $Spread_{max}$. Higher M2 values indicate a more gradual crack growth process and longer propagation duration before failure.

M3 represents the average crack propagation rate between t_{20} and t_{90} , and is calculated as:

$$M3 = \frac{Spread_{max}}{t_{90} - t_{20}} \quad (3)$$

where t_{90} is the time corresponding to 90% of $Spread_{max}$. Lower M3 values indicate slower crack propagation and greater resistance to rapid crack growth.

M4 represents the propagation stability index and is defined as the coefficient of determination of the linear regression between displacement and normalized time over the interval from t_{20} to t_{80} .

$$M4 = R^2 \quad (4)$$

Higher M4 values indicate a more consistent and stable displacement evolution during crack propagation.

These indicators presented in Table 4 provide a physically meaningful and comprehensive description of crack behavior, capturing initiation timing, propagation rate, and propagation stability.

Table 4. Displacement-based crack indicators.

Parameter	Definition	Physical Meaning
M1	$t_{20}/t_{failure}$	Crack initiation
M2	$(t_{80} - t_{20})/t_{failure}$	Propagation Duration
M3	$Spread_{max}/(t_{90} - t_{20})$	Propagation Rate
M4	R^2	Propagation Stability

2.7. Data Processing

Tracker Software (ver. 6.3.4) was used to obtain the displacement data, while the performance indicators were calculated using Microsoft Excel. Crack opening

displacement was defined as the difference between the horizontal displacements of the points tracked on the left and right sides of the crack. Median values were used to reduce the influence of measurement noise.

3. Results and Discussion

3.1. Overview of crack behavior

The results presented in Figures 9(a) and 9(b), obtained from three replicate specimens for each mixture type, reveal crack opening (spread vs. time) evolution acquired from the image-based analysis. The progression of cracking behavior is illustrated clearly by the curves, starting with an initial elastic deformation, followed by a rapid increase consistent with crack initiation and propagation, and finally reaching a plateau after failure.

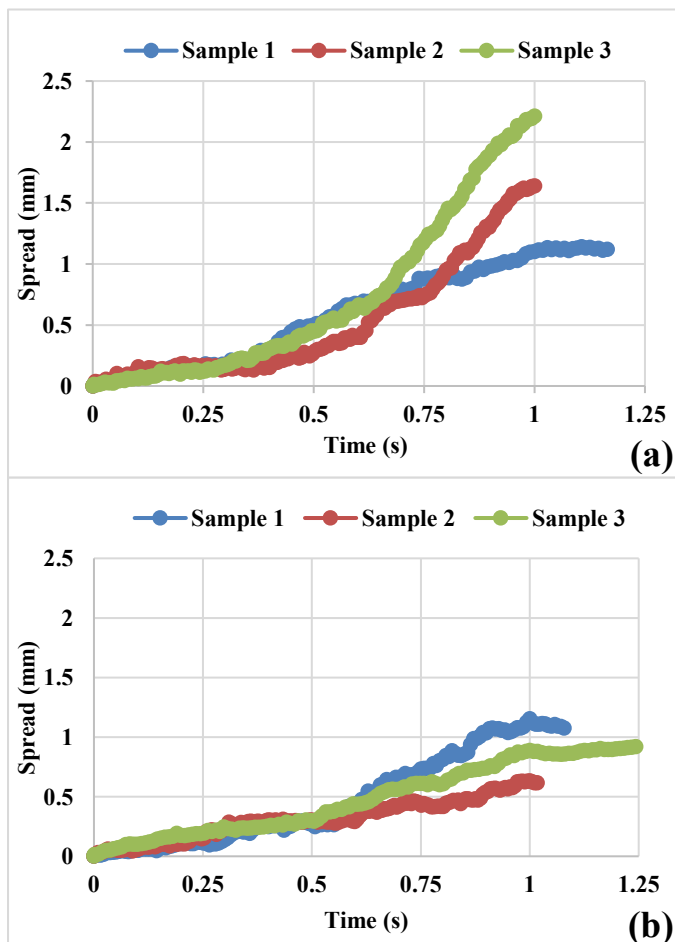


Figure 9. Evolution of crack opening (Spread vs. Time) obtained from image-based displacement analysis: a) Unmodified mixture; b) Modified mixture.

An expected difference was observed among the three replicate specimens because of the heterogeneity of

composite materials. The measured crack opening and propagation characteristics could be affected by local variation in aggregate arrangement, air-void distribution, and crack path development, even though all specimens are prepared and tested under identical conditions. However, all replicate specimens exhibited consistent trends overall in crack evolution, revealing that the proposed indicators capture the overall crack evolution consistently in spite of the inherent specimen-to-specimen variability of asphalt mixtures.

3.2. Crack initiation behavior (M1)

Crack initiation was characterized using the M1 indicator, which is based on the normalized time corresponding to t_{20} , or 20% of the maximum crack opening. The results indicated that the modified mixtures generally exhibited lower M1 values than the unmodified mixtures, indicating that the crack reached 20% of its maximum opening at an earlier normalized time. This represents an earlier transition from the initial crack-opening stage to subsequent crack propagation. However, the earlier crack initiation observed in modified mixtures did not indicate accelerated fracture development, as evidenced by their longer propagation duration (M2), lower crack propagation rate (M3), and higher propagation stability (M4). These findings suggest that binder modification primarily influenced the crack propagation stage by promoting slower and more stable crack growth after initiation.

The differences in crack initiation between the two mixture types were relatively small compared with those observed in crack propagation behavior, indicating that binder modification has a more pronounced effect on crack evolution than on crack onset. This observation is consistent with rheological findings at intermediate service temperatures (0-30 °C), where the modified binders exhibited properties similar to those of the base binder below approximately 25 °C, as indicated by converging phase angle (δ) values and limited polymer mobility [22]. Consequently, the influence of modification on crack initiation appears to be relatively limited, whereas its effect becomes more significant during crack propagation, where energy dissipation mechanisms play a greater role in controlling fracture behavior.

3.3. Crack propagation duration (M2)

The indicator (M2) represents the propagation duration between the intervals t_{20} and t_{80} . Comparison between the unmodified and modified mixtures showed higher M2 values for the modified mixtures. This indicates that crack growth in the modified mixtures occurred over a longer period.

A longer propagation duration reflects the ability of the material to sustain deformation and dissipate energy before failure. This behavior is consistent with [23], [24], which confirmed that the strength values against crack propagation increase with SBS modification due to the presence of polymer modification that enhances the ductility and allows the material to undergo gradual damage accumulation rather than abrupt fracture.

3.4. Crack propagation rate (M3)

A significant difference was observed in the crack propagation rate (M3) between the two mixture types. The modified ones had lower (M3) values consistently, indicating slower crack growth. While the unmodified mixtures exhibited higher (M3) values for some specimens, indicating rapid crack propagation.

This behavior may be attributed to the enhanced viscoelastic properties of the modified asphalt binder, which may promote improved energy dissipation and reduce stress concentration at the crack tip, resulting in more controlled and gradual crack growth. This is in agreement with the findings that the presence of SBS increases the critical stress energy dissipation rate (J_c) at average service temperatures ($\approx 25^\circ\text{C}$) by improving deformation capacity and energy absorption [24]. In contrast, limited energy absorption capacity was noticed with unmodified mixtures, indicated by faster crack propagation after crack initiation and a more responsive brittle fracture behavior.

3.5. Crack propagation stability (M4)

The (M4) indicator was used to evaluate the crack propagation stability, which is defined as the coefficient of determination (R^2) calculated over the t_{20} - t_{80} displacement interval. Higher (M4) values were observed for modified mixtures, reflecting a more linear and stable crack propagation process.

On the other hand, the unmodified mixtures exhibited lower and more variable (M4) values, exhibiting non-linear and unstable crack growth. The intermittent crack growth observed in the unmodified mixtures may be associated with material heterogeneity and localized stress concentrations.

In contrast to Figure 9, which illustrates specimen-to-specimen variability, Figure 10 introduces the mean displacement evolution curves obtained from three replicate specimens for both the unmodified and modified mixtures. These displacement-time curves provide a direct comparison of the overall deformation behavior as they represent the average response of each mixture condition. While the modified mixture shows an approximately linear trend, the unmodified mixture displays a significant deviation from linearity, confirming the observed differences in crack propagation stability.

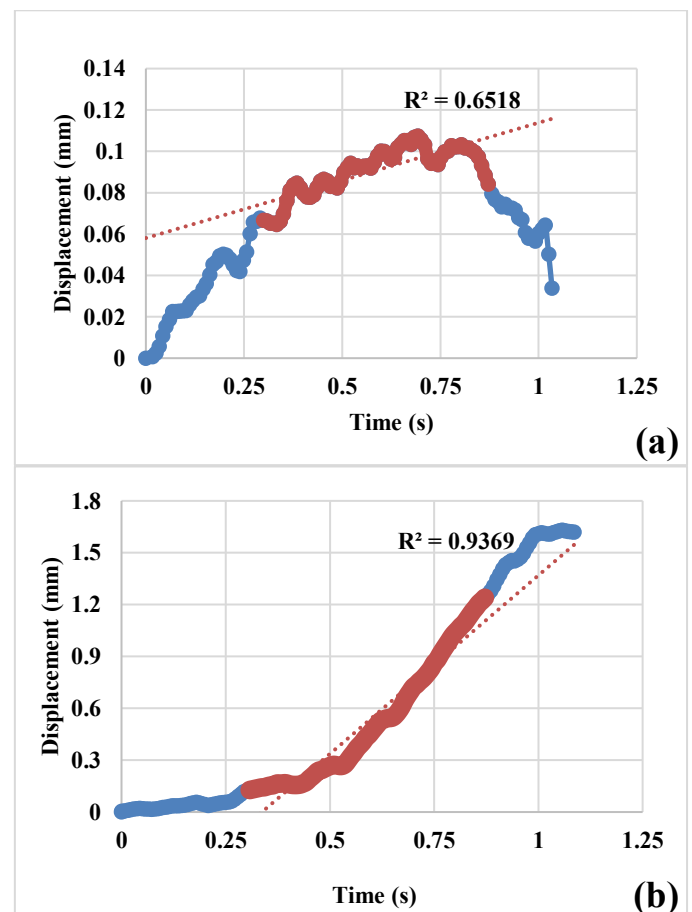


Figure 10. Representative displacement evolution (median_disp. vs. normalized time) used to evaluate crack propagation stability (M4) for Sample (1) (a) Unmodified mixture (b) Modified mixture.

3.6. Integrated analysis of crack behavior

The performance indicators for all mixtures were calculated and summarized in Table 5. The values of crack initiation (M1), propagation duration (M2), crack growth rate (M3), and propagation stability (M4) obtained from both faces of each specimen, along with their average values.

The largest inconsistencies between the displacement metrics obtained from face 1 and face 2 were observed for the unmodified mixture specimens, whereas only minor differences were observed between the two faces for some modified mixtures specimens. These differences may be associated with slight out-of-plane deformation, asymmetric crack propagation, and minor specimen tilting during IDEAL-CT loading. The apparent displacement recorded from each viewing side may therefore be influenced by these factors. However, the general trends remained consistent between the two faces, while the influence of localized measurements was reduced by averaging the measurements obtained from the two cameras views, providing a more representative estimation of the crack evolution.

As the proposed displacement-based parameters reflect different stages of the fracture process, they should not be considered independently. (M1) refers to stable crack initiation, (M2) illustrates the duration of stable crack propagation, (M3) measures the average crack growth rate, and (M4) quantifies the crack evaluation

stability. The combination of these parameters helps to describe fracture development from crack initiation to final failure, supporting a more comprehensive assessment of cracking behavior compared with conventional methods.

The results show that the behavior of crack propagation presents greater variation between mixture types than crack initiation alone. While the differences in the initiation stage (M1) were limited, the differences in propagation duration (M2), propagation rate (M3), and propagation stability (M4) were significantly larger. This suggests that, although crack initiation occurred slightly earlier in the modified mixtures, the subsequent crack growth mechanism was substantially altered by binder modification. Therefore, evaluating crack propagation characteristics provides a more informative measure of fracture performance than relying solely on crack initiation or conventional strength-based indices.

A consistent fracture mechanism is demonstrated through the relationship among (M2), (M3), and (M4). Lower crack propagation rates and more stable displacement evolution were shown in mixtures with longer propagation durations. This means that the growth of the crack is slow rather than sudden, and more energy can be absorbed before failure. In contrast, rapid crack propagation is predictably related to lower propagation stability, which reflects crack advancement localization and a more brittle fracture response.

Table 5. Displacement-based performance indicators and maximum crack opening for unmodified and modified mixtures.

Unmodified Mixture									
Property	Sample 1			Sample 2			Sample 3		
	Face 1	Face 2	Avg.	Face 1	Face 2	Avg.	Face 1	Face 2	Avg.
Spread_max (mm)	1.655	0.670	1.162	2.488	0.939	1.713	0.961	3.484	2.222
M1 (t20_norm)	0.361	0.333	0.347	0.703	0.598	0.650	0.690	0.496	0.593
M2	0.512	0.572	0.542	0.242	0.357	0.299	0.290	0.444	0.367
M3 (mm/s)	2.583	0.936	1.760	8.212	2.103	5.158	2.647	6.272	4.459
M4 (R ²)	0.469	0.841	0.655	0.421	0.702	0.562	0.876	0.908	0.892
Modified Mixture									
Property	Sample 1			Sample 2			Sample 3		
	Face 1	Face 2	Avg.	Face 1	Face 2	Avg.	Face 1	Face 2	Avg.
Spread_max (mm)	0.913	1.390	1.152	1.024	0.427	0.725	0.991	0.578	0.785
M1 (t20_norm)	0.464	0.321	0.393	0.309	0.188	0.249	0.189	0.127	0.158
M2	0.421	0.585	0.503	0.645	0.453	0.549	0.747	0.858	0.802
M3 (mm/s)	1.735	1.900	1.817	1.269	0.753	1.011	1.061	0.539	0.800
M4 (R ²)	0.934	0.942	0.938	0.801	0.793	0.797	0.797	0.797	0.797

The proposed indicators can reveal details that cannot be obtained from the conventional load-displacement response alone while using the same displacement data from the IDEAL-CT test. As the parameters of the traditional IDEAL-CT test measure the overall cracking resistance at failure, the new framework recognizes different stages of crack evolution, including crack initiation, stable propagation, propagation rate, and propagation stability. Thus, this technique complements rather than replaces the standard IDEAL-CT indices, providing a more detailed understanding of fracture behavior.

3.7. Discussion of material behavior

The improved performance of the modified mixtures could be explained by the synergistic effect of the additive, which enhances binder elasticity and promotes energy dissipation during loading. While elastic recovery is mainly attributed to the presence of SBS polymer, other components, such as the crosslinking agent and mineral fillers, may contribute to structural integrity and crack-growth resistance.

In this study, the displacement-based analysis offers a deeper insight into fracture behavior compared to conventional strength-based methods. By following the evolution of crack opening, the distinction between stable and unstable crack growth becomes possible, which is

essential for evaluating pavement performance under realistic loading conditions.

4. Conclusions

A displacement-based crack characterization framework was successfully employed to quantify crack initiation, propagation duration, propagation rate, and propagation stability using an image-based point-tracking methodology during the IDEAL-CT test.

The suggested method offered additional insight into the crack assessment process beyond the conventional load-displacement response, indicating the capability of this approach to recognize different stages of fracture development in asphalt mixtures.

Depending on the evaluation of asphalt binder rheological characteristics, the 4% hybrid modifier was selected for mixture-level investigation because of the balanced viscoelastic performance that it showed. The selected modification improved crack propagation behavior compared with the unmodified mixture.

The proposed displacement-based indicators could be used as complementary parameters for evaluating the fracture performance in asphalt mixtures because of their ability to distinguish differences in crack evolution among the investigated mixtures.

Although the optimum modifier content was identified as 4% within the investigated range, modifier contents below 4% were not evaluated. Therefore, lower dosages may also provide favorable performance and should be investigated in future studies.

The developed methodology represents a practical and cost-effective alternative for crack characterization and provides a foundation for future studies integrating image-based displacement analysis with conventional asphalt performance evaluation.

Competing Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

Supplementary materials and data used in this research are accessible upon request. For access, please contact the corresponding author via

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Statement on the Ethical Use of AI Tools

ChatGPT (OpenAI) was used solely to improve language and readability during manuscript preparation. All scientific content was developed, reviewed, and verified by the authors, who take full responsibility for the manuscript.

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