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Balancing Cracking and Rutting Resistance in RAP Asphalt Mixtures: Practical Testing Approaches for Resource-limited Conditions

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Abstract:

Introduction: In many emerging economies, highways constitute the main transportation infrastructure. However, a significant portion of the paved network remains in fair-to-poor condition and requires rehabilitation.Pavement milling is widely used for this purpose, generating Reclaimed Asphalt Pavement (RAP). Although RAP recycling offers economic and environmental benefits, especially in resource-limited contexts, Hot Mix Asphalt (HMA) designs based solely on volumetric parameters do not ensure adequate resistance to fatigue cracking and permanent deformation, and advanced dynamic testing methods are often unavailable. This study evaluates the potential of the High-Temperature Indirect Tensile (HT-IDT) and indirect tensile asphalt cracking (IDEAL-CT) tests on Marshall specimens to optimize binder content in asphalt mixtures with and without RAP, focusing on two heavily trafficked rural highways in Brazil.

Methods: The HT-IDT and IDEAL-CT tests were applied to Marshall-compacted specimens at varying binder contents (4%, 5%, and 6%), with and without RAP as a partial replacement for coarse aggregates, enabling the application of the Balanced Mix Design (BMD) concept.

Results: The Marshall method tends to produce mixtures with higher binder contents, improving cracking resistance but reducing rutting performance. Binder content optimization improved rutting resistance by up to 51% for RAP mixtures and 22% for reference mixtures without compromising cracking resistance. CT_{Index} at the design binder content (165 and 182 for mixtures without and with RAP, respectively) significantly exceeded the minimum threshold of 100 recommended for heavy-traffic conditions.

Discussion: These findings suggest that conventional volumetric mix design methods may fail to provide durable solutions for highways subjected to high temperatures and heavy loads. The use of RAP as a partial replacement for coarse aggregates proved technically feasible, with mechanical behavior comparable to or better than that of the reference mixture.

Conclusion: The integrated use of HT-IDT and IDEAL-CT tests on Marshall specimens provides a practical and accessible framework for implementing the BMD concept in resource-limited laboratory environments, demonstrating that volumetric criteria alone are insufficient to ensure adequate pavement performance under heavy traffic and high-temperature conditions.

Keywords: RAP, Asphalt, Rutting, Cracking, IDEAL-CT, HT-IDT.

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1. INTRODUCTION

The HMA surface layer must provide structural support against vehicular loads and environmental exposures. It is also designed to provide characteristics such as friction, smoothness, noise reduction, and effective drainage of the road surface. These characteristics are essential for user safety and driving comfort [1].

Due to progressive surface degradation, periodic maintenance is required to preserve the pavement's serviceability. In this context, milling is a technique commonly employed in pavement rehabilitation, generating RAP, which consists of aggregates and aged asphalt binder. When properly processed, this material can be incorporated into new asphalt mixtures, depending on the mix design specification [2].

RAP has been widely adopted as a sustainable solution, especially given the increasing emphasis on pavement recycling incentives, offering an alternative that enables cost savings while reducing the consumption of natural resources [3]. In the United States, RAP is the most widely recycled material, with a recycling rate of 99% [2]. In 2020, estimates indicated a reduction in the need for 4.4 million tons of asphalt binder and more than 82 million tons of natural aggregates, corresponding to savings of over 2.9 billion dollars [4].

In addition to its environmental and economic benefits, incorporating RAP into HMA has been shown to enhance the mechanical behavior of the mixtures. Usanga *et al.* [5] reported that RAP incorporation reduces rutting susceptibility and generally improves resistance to permanent deformation under lower stress conditions, likely due to the higher stiffness of aged binders present in the RAP, while Suzuki *et al*. [6] observed that higher RAP contents improve fatigue resistance without adversely affecting rutting performance.

However, several technical challenges persist, primarily related to material variability, moisture sensitivity, and potential incompatibilities between new and aged binders [3, 6]. Consequently, evaluating the mechanical behavior of HMA containing RAP requires appropriate testing, particularly for fatigue and rutting performance. In emerging economies such as Brazil, RAP recycling rates remain significantly below global trends, despite the large volume of pavement milling performed annually for highway rehabilitation [6].

The low rates of RAP utilization are partly due to infrastructure gaps, including a lack of sophisticated laboratory facilities and technological limitations, especially in regions far from major industrial centers. The need for sophisticated equipment creates a technical barrier, leading to underutilization of RAP, and potentially resulting in premature pavement distress and increased environmental impact. Furthermore, additional factors contribute to the underutilization of RAP in Brazil, including the absence of regulatory frameworks that mandate or incentivize its use in public contracts. A technical capacity gap also persists among regional contractors and highway agencies, often leading them to favor conservative pavement designs based exclusively on virgin materials [6].

Thus, the HT-IDT (Indirect Tensile Test at High Temperature) and IDEAL-CT (Indirect Tensile Cracking Test at Intermediate Temperature) have been identified as cost-effective and practical alternatives for assessing asphalt mixture performance. These tests are particularly valuable for implementing the Balanced Mix Design (BMD) concept using accessible performance parameters, especially where access to advanced laboratory infrastructure is limited [7].

The HT-IDT is regarded as a viable alternative to the Asphalt Pavement Analyzer (APA) test and has been adopted by the Virginia Department of Transportation (VDOT) [8]. The IDEAL-CT, developed by Zhou [9], stands out as a more practical alternative to the Overlay Test (Tex-248-F) and I-FIT, as it eliminates the need for complex sample preparation and uses standard equipment commonly found in paving laboratories [9, 10].

The use of these tests is particularly relevant in contexts where reduced costs and rapid execution are decisive factors in selecting and implementing technical solutions for low-budget construction projects or those located far from major technological hubs. The possibility of conducting these tests using Marshall specimens makes it feasible to develop a BMD without purchasing expensive gyratory compactors [7, 10].

Thus, the adoption of HT-IDT and IDEAL-CT tests may contribute to greater RAP incorporation in asphalt mixtures, promoting cost efficiency, technical performance, and sustainability in road construction. Within this context, this study evaluates the feasibility of optimizing binder content within a BMD framework, using simple and accessible tests on Marshall specimens of asphalt mixtures with and without RAP. The mixture designs were developed for the rehabilitation of two high-traffic federal highways in Brazil, which serve as a representative case for other emerging economies facing similar infrastructure limitations.

2. MATERIALS AND METHODS

This study was conducted in the city of Uberlandia, Brazil, for the purpose of rehabilitating the BR-365 and BR-050 highways. The sections are characterized by traffic interruptions and a high volume of heavy vehicles traveling at low speeds in a hot tropical climate. The reference mixture was produced using basaltic aggregates and hydrated lime, both commercially sourced in Uberlandia, Minas Gerais, Brazil. The HMA was designed as a Dense Coarse-Graded (DCG) mixture according to Brazilian standards, utilizing a 12.5 mm Nominal Maximum Aggregate Size (NMAS) [1]. The binder selected for this project was a PG 76-22 polymer-modified asphalt, supplied by a commercial distributor located in Ribeirão Preto, Sao Paulo, Brazil.

The reclaimed material was obtained from a stockpile along highway BR-365 in the state of Minas Gerais, Brazil,

maintained by a roadway concessionaire. The milling process was conducted at ambient temperature, resulting in the fragmentation of the aggregate and alterations in the gradation of the existing HMA. The RAP was characterized through standardized tests, including the maximum theoretical specific gravity (Gmm) (ASTM D2041/D2041M-19) [11], yielding an average value of 2.736. Additionally, sieve analysis was performed before and after binder ignition in accordance with AASHTO T 164 [12], which indicated a binder content of 4.61%.

The milled material was fractionated into two groups: (i) particles retained on the 4.8 mm sieve and (ii) particles passing the 4.8 mm sieve. The retained fraction was used as the aggregate ("black rock"), representing 15% of the total aggregate weight. This procedure facilitated the development of a gradation curve that closely approximated the control mixture. Figure **1** shows the final gradation curves of the asphalt mixtures, specification limits from the local authority [13], and Superpave control points.

During HMA production, virgin aggregates were heated to 175 °C and the asphalt binder to 162 °C. For the RAP mixtures, the reclaimed material was preconditioned by drying at 60 °C for 24 h, cooling to room temperature, and adjusting the heat transfer to ensure proper mixing. The mixtures were manually homogenized with superheated aggregates (185 °C) and compacted using the Marshall method at 145 °C with 75 blows. The Asphalt Institute volumetric criteria [14] were used for the mix design, and the results are shown in Table **1**.

Table 1. Volumetric and mechanical properties at the design binder content.

Parameter	Result	Parameter	Result
Binder content (%)	5.55	VMA - Voids in Mineral Aggregates (%)	16.5
G_{mm} - Maximum Theoretical Specific $_{Gravity}$	2.595	Dust-to-binder ratio	1.5
G_{mb} - Bulk Specific Gravity	2.467	TSR - Tensile Strength Ratio (MPa)	1.0
V_a – Air Void (%)	4.3	ITS - Indirect Tensile Strength (MPa)	1.28
VFA – Voids Filled with Asphalt (%)	72.5		

Although the mix design followed a "black rock" aggregate replacement approach to simulate plant operations, the mechanical analysis accounted for the RAP Binder Ratio (RBR). Given the RAP binder content (4.61%) and virgin binder addition (5.55%), the RBR for the evaluated mixture was 10.5%. It is important to note that the "black rock" treatment conservatively assumes the aged RAP binder to be in an inert state, with no contribution to the effective binder content of the mixture. However, partial binder activity cannot be entirely excluded, and this limitation is further discussed in the context of the cracking and rutting results.

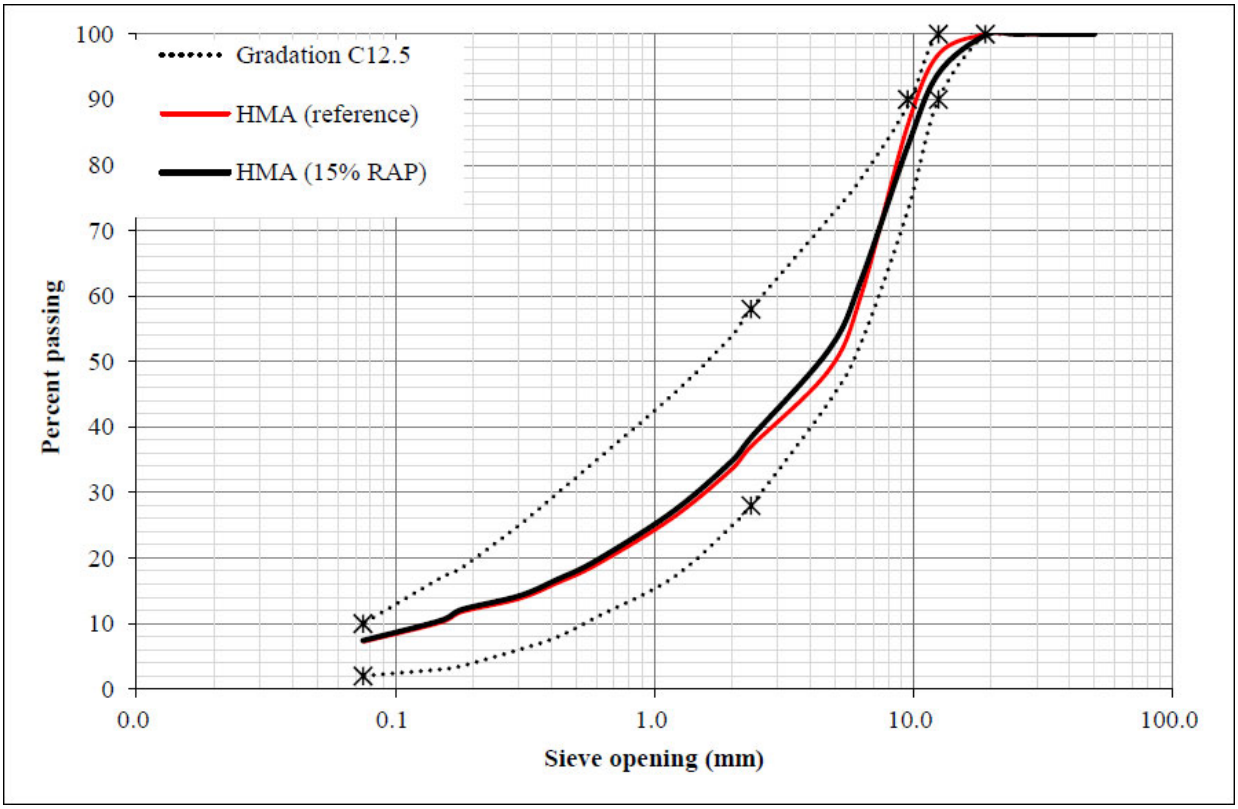


Fig. (1). Gradation curves of reference asphalt mixture and mixture with RAP substitution.

Binder contents of 4%, 5%, and 6% were used to assess the rutting and cracking resistance. For each binder content, a minimum of three specimens per condition was adopted based on the repeatability requirements established in ASTM D8225-19 for the IDEAL-CT test and on the standard practice for Marshall mix design testing. The control mixture specimens were compacted to a target of 7% (±0.5%) air voids (V_a). In contrast, mixtures incorporating RAP required adjustments to the target V_a to account for the specific characteristics of the reclaimed material, particularly at lower binder contents. The cracking and rutting potentials were assessed using the IDEAL-CT and HT-IDT tests, respectively.

2.1. HT-IDT Tests

The HT-IDT test was used to evaluate the rutting susceptibility. A constant loading rate of 50 mm/min was applied, and the specimens were conditioned in a water bath at 50 °C for 2 h, following the procedure established by Christensen and Bonaquist [15]. This test is distinguished by its simplicity, rapid execution, high repeatability, and correlation with field performance [8, 15]. The HT-IDT test offers a reliable and efficient alternative to conventional permanent deformation tests with no loss of accuracy [8].

A water bath was selected for specimen conditioning because of its operational simplicity and rapid temperature stabilization capabilities [8]. The specimens were conditioned without plastic film protection to better simulate actual service conditions. The 2 h conditioning time was chosen based on laboratory observations and standardization adopted in other tests, including the IDEAL-CT, which follows the same conditioning protocol. Once the HT-IDT test was complete, the indirect tensile strength for rutting evaluation was determined using Eq. (**1**). A higher strength value indicates better resistance to rutting.

$$\sigma_{HT-IDT} = \frac{20 \times P_{max}}{\pi \times t \times D} \quad (1)$$

Where:

$\sigma_{HT\text{-}IDT}$ is the indirect tensile strength for rutting evaluation [kPa];

P_{max} is the maximum load [N];

t is the specimen thickness [cm];

D is the specimen diameter [cm].

Boz *et al*. [16] established a minimum strength threshold of 100 kPa for coarse dense mixtures with unmodified asphalt. Additionally, Yin and West [17] reported a reference value of 137.9 kPa for mixtures designed for heavy traffic conditions (10M ESALs), with specimens molded at 7% air voids, 62 mm in height, and conditioned at 50 °C. Table **2** presents the classification of asphalt mixtures based on σHT-IDT values as a function of traffic level [15].

2.2. IDEAL-CT Tests

The IDEAL-CT test was used to evaluate the cracking susceptibility of the asphalt mixtures. The test was conducted on cylindrical specimens at 25 °C with a loading rate of 50 mm/min, utilizing an indirect tensile loading device on the Marshall press. The test is simple, practical, cost-effective, and correlates with the cracking performance of HMA [9]. In addition, it does not require complex specimen preparation, such as cutting notches or advanced instrumentation.

Table 2. Classification of HMA regarding permanent deformation behavior in HT-IDT tests as a function of traffic level [15].

Design Traffic Level [a] (ESALs - 10^6)	Rut Resistance Category	[a]HT-IDT Range (kPa)
-	Very poor	< 50
< 0.3	Poor	50 to < 110
0.3 to < 3	Minimal	110 to < 170
3 to < 10	Fair	170 to < 270
10 to < 30	Good	270 to < 430
30 to < 100	Very good	430 to < 660
100 to < 300	Excellent	≥ 660

Note:[a] At 70 km/h; to adjust the estimated traffic level to 70 km/h, multiply by (70/*v*), where *v* is the average traffic speed in kilometers per hour.

ASTM D8225-19 [18] specifies the preparation of 150 mm × 62 mm cylindrical specimens compacted with a Superpave Gyratory Compactor (SGC) for testing. However, owing to the limited availability of SGC in Brazil, this study employed compacted Marshall specimens. These dimensions align with findings by Zhou (2019) [9], Castillo-Camarena and Hall [10], and Shaikh and Gupta [19], who reported that specimen diameters of 100–150 mm and heights of 38–75 mm yield comparable results. It should be acknowledged that Marshall impact compaction produces specimens with greater air void heterogeneity and preferential aggregate orientation compared to gyratory compaction, which may influence crack propagation geometry and the absolute magnitude of CT_{Index} (Cracking Tolerance Index) values. Furthermore, the CT_{Index} thresholds established by agencies such as TDOT (Tennessee Department of Transportation) were calibrated using SGC specimens. Therefore, results obtained with Marshall specimens should be interpreted as relative performance indicators rather than as absolute pass-or-fail values against those specific thresholds. This limitation is acknowledged in the Limitations section.

The CT_{Index} is used to evaluate the cracking resistance of asphalt mixtures. It is calculated based on three key components: (1) fracture energy (G_f), (2) post-peak slope ($|m_{75}|$), and (3) deformation tolerance (l_{75}). *Gf* was obtained from the area under the load-displacement curve, representing the energy required to propagate a crack. The post-peak slope was determined at the point corresponding to 75% of the maximum load after the peak, whereas the deformation tolerance was defined as the

displacement at that same point. The CT_{Index} can be calculated using Eq. (**2**).

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \times 10^6 \quad (2)$$

Where:

CT_{Index} is the cracking tolerance index;

G_f is the fracture energy [J/m²];

$|m_{75}|$ is the absolute value of the post-peak slope m_{75} [N/m];

l_{75} is the displacement at 75% of the peak load after the peak [mm];

D is the specimen diameter [mm];

t is the specimen thickness [mm].

Higher G_f and l_{75} values increase the CT_{Index}, while a higher $|m_{75}|$ has a detrimental effect. A higher CT_{Index} is desired for asphalt mixtures to resist intermediate temperature cracking [20]. Many State Departments of Transportation (DOTs) are developing performance-based specifications for asphalt mixtures, where the CT_{Index} has been adopted as a simple, repeatable, and reliable cracking test for asphalt mixtures. Moreover, the CT_{Index} results are sensitive to HMA variables, including RAP content, asphalt type and content, and aging conditions [20]. Multiple State DOTs have defined CT_{Index} reference values for asphalt HMA performance (Table **3**).

The development of locally calibrated thresholds represents a critical gap in the Brazilian pavement engineering literature and constitutes a primary objective of the ongoing research project, of which the present study is the first stage. In the next phase, experimental pavement sections will be constructed incorporating the optimized mix designs evaluated herein. Long-term field performance monitoring will provide the dataset necessary to correlate laboratory values obtained with Marshall specimens under tropical conditions with observed cracking performance, enabling the calibration of locally applicable performance thresholds.

3. RESULTS AND DISCUSSIONS

The results of the HT-IDT and IDEAL-CT tests are summarized in this section and presented as a function of the binder content variation. For outlier identification, a procedure was developed based on the integration of Grubbs, Dixon, and Hampel tests. The method consists of (1) ordering the data, (2) calculating descriptive statistics, and (3) sequentially applying the tests, prioritizing the most extreme value. The Grubbs test evaluates deviations from the mean in units of standard deviation (threshold: $G > 1.154$ for $n = 3$, $\alpha = 0.05$), whereas Dixon's Q test assesses the ratio between distances (threshold: $Q > 0.941$). Hampel's criterion, based on the median and the Median Absolute Deviation (MAD), classifies values beyond $\pm 2.5 \times MAD$ as outliers. The function explicitly returns the outlier value and the method that identified it. This approach is particularly useful in laboratory analyses, ensuring reproducibility in excluding anomalous data without disregarding the contextual evaluation of the experiment. Finally, a one-way Analysis of Variance (ANOVA) was performed to investigate the statistical significance of the effects of different binder contents on the results.

3.1. Evaluation of Permanent Deformation Potential Using the HT-IDT Test

The HT-IDT test was used to evaluate the rutting potential of asphalt mixtures using peak load response. Table **4** summarizes the HT-IDT test results for the reference asphalt mixtures (0% RAP) across varying binder contents, with identified outliers noted. Figure **2** presents the average HT-IDT values for specimens compacted to a target air void content (V_A) of 7% ± 0.5%.

Table 3. CT_{Index} Criteria for HMA design approval.

Reference	CT_{Index}	Indication for Use	Observation
Virginia DOT [17]	≥ 70	-	-
Texas DOT [17]	> 90	OT[a] cycles > 125	Dense graded mixes
	> 55	OT cycles > 50	
Oklahoma DOT [17]	≥ 80	-	For all mixtures regardless of virgin binder grade
Zhou *et al.* (2021) [21]	≥ 90	-	Dense graded mixes
	≥ 50	State Routes (< 10,000 ADT[b])	
Tennessee DOT [17]	≥ 75	State Routes (> 10,000 ADT[b])	-
	≥ 100	Interstates (≥ 20,000)	
	≥ 55	< 1 million (ESALs[c])	
Alabama DOT [17]	≥ 83	1 to 10 million (ESALs[c])	-
	≥ 110	10 to 30 million (ESALs[c])	

Note: [a] Overlay Tester
[b] Average Daily Traffic
[c] Equivalent Single Axle Load

Table 4. HT-IDT rutting resistance of control mixtures (0% RAP) as a function of binder content.

Binder Content	Specimen ID	HT-IDT	Mean	Standard Deviation	Outlier	Corrected Mean HT-IDT
(%)		(kPa)	(kPa)	(kPa)		(kPa)
	16	353.25			Yes	
4%	17	310.43	321.84	27.54	No	306.14
	18	301.84			No	
	25	280.38			No	
5%	26	269.91	242.91	56.08	No	275.14
	27	178.44			Yes	
	36	176.27			No	
6%	37	175.70	184.00	13.88	No	175.99
	39	200.01			Yes	

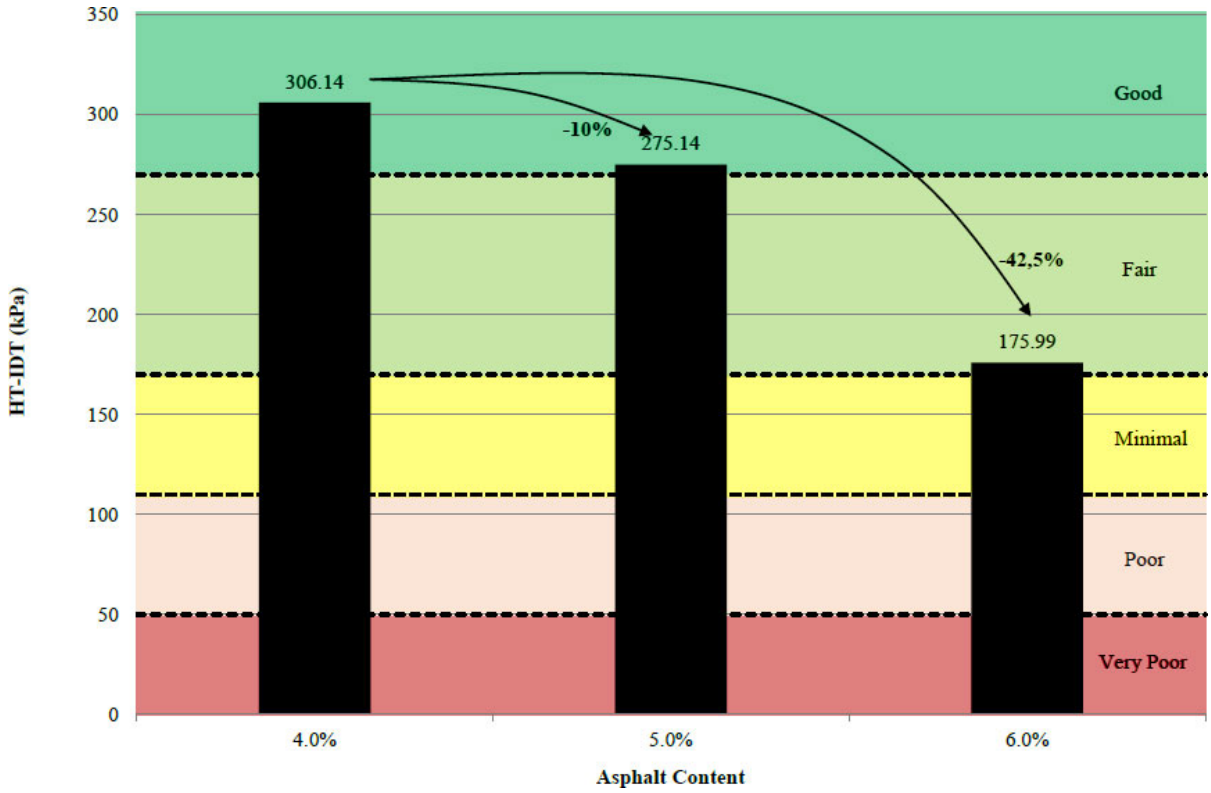


Fig. (2). HT-IDT mean results of control mixtures (0% RAP) across binder contents, evaluated against the rutting criteria proposed by Christensen and Bonaquist [15].

The analysis of Table 4 reveals the expected inverse relationship between the binder content and permanent deformation resistance, which is attributable to the higher asphalt concentration. A reduction in HT-IDT values was observed, decreasing from 306.14 kPa at 4% asphalt to 175.99 kPa at 6%. Figure 2 shows that increasing the binder content from 4% to 5% and 6% noticeably affects the mixture's resistance to permanent deformation, with a reduction of up to 42.5% in the HT-IDT values for the 5% and 6% binder content levels. Statistical analysis confirmed these observations: ANOVA indicated a significant effect of binder content on HT-IDT results ($p < 0.05$), and Tukey's post-hoc test revealed that the 6% mixture differed significantly from both the 4% and 5% mixtures, whereas no significant difference was observed between the 4% and 5% mixtures. The eta-squared effect size (η^2) was 0.995, indicating that binder content accounted for 99.5% of the total variance in HT-IDT results, representing a very large effect.

Based on (Fig. 2), the mixtures with up to 5% binder content exhibited performance characteristics of the "Good" category, according to the criterion proposed by

Christensen and Bonaquist [15], corresponding to traffic levels of up to 30×10^6 ESALs. In contrast, increasing the binder content to 6% resulted in a classification of "Fair," which corresponds to traffic levels ranging from 3×10^6 to 10×10^6 ESALs. Therefore, mixtures containing up to 5% binder are recommended for pavements subjected to high traffic conditions (ESALs ≥ 10^7), according to the criteria established by Garcia and Hansen [1], whereas a mixture with 6% binder content is suitable for moderate-traffic pavements (0.3×10^6 ≤ ESALs < 10×10^6). Furthermore, all the tested mixtures met the minimum HT-IDT strength thresholds proposed by Boz *et al*. (≥ 100 kPa) [16], Yin and West (≥ 137.9 kPa) [17], and Vamsikrishna and Singh (≥ 135 kPa) [22].

For mixtures with RAP as a replacement for the coarse fraction, the V_a was adjusted to 8% ±0.5% for the specimens with 4% binder content. This outcome may be attributed to the presence of reclaimed asphalt clusters, which exhibit shapes, textures, and absorption characteristics distinct from those of virgin aggregates, resulting in a different compactability response under Marshall impact loading. It should be noted that the difference in target V_a between the RAP mixture at 4% binder content (8.0% ± 0.5%) and the corresponding control mixture (7.0% ± 0.5%) introduces a confounding variable in the direct comparison of mechanical performance at this specific binder content level. Higher V_a generally reduces both HT-IDT strength and CT_{Index} values. Consequently, the performance of the RAP mixture at 4% binder content may be slightly underestimated relative to the control. For this reason, direct comparative conclusions between the control and RAP mixtures are restricted to the 5% and 6% binder content conditions, where equivalent target void levels were achieved. The HT-IDT results for the RAP mixtures are presented in Table **5**, while (Fig. **3**) displays the mean HT-IDT values and the corresponding permanent deformation resistance categories according to Christensen and Bonaquist [15].

The analysis in Table **5** reveals that the mixtures with RAP exhibited a similar trend to that observed in the control mixtures (Table **4**), except for the mixture with 4% binder content. In this case, the HT-IDT value was lower than that recorded for the 5% binder content. This behavior may be attributed to the higher V_a (8.0% ± 0.5%) in the specimens with 4% binder. Statistical validation corroborated these findings: ANOVA results highlighted a significant influence of binder content on HT-IDT performance ($p < 0.05$), with Tukey's test confirming that the HT-IDT value for the 6% mixture was significantly lower than that for the 4% and 5% mixtures. The latter two compositions showed statistically comparable results. The eta-squared effect size (η^2) was 0.859, indicating that binder content explained 85.9% of the total variance in HT-IDT results for RAP mixtures, representing a very large effect.

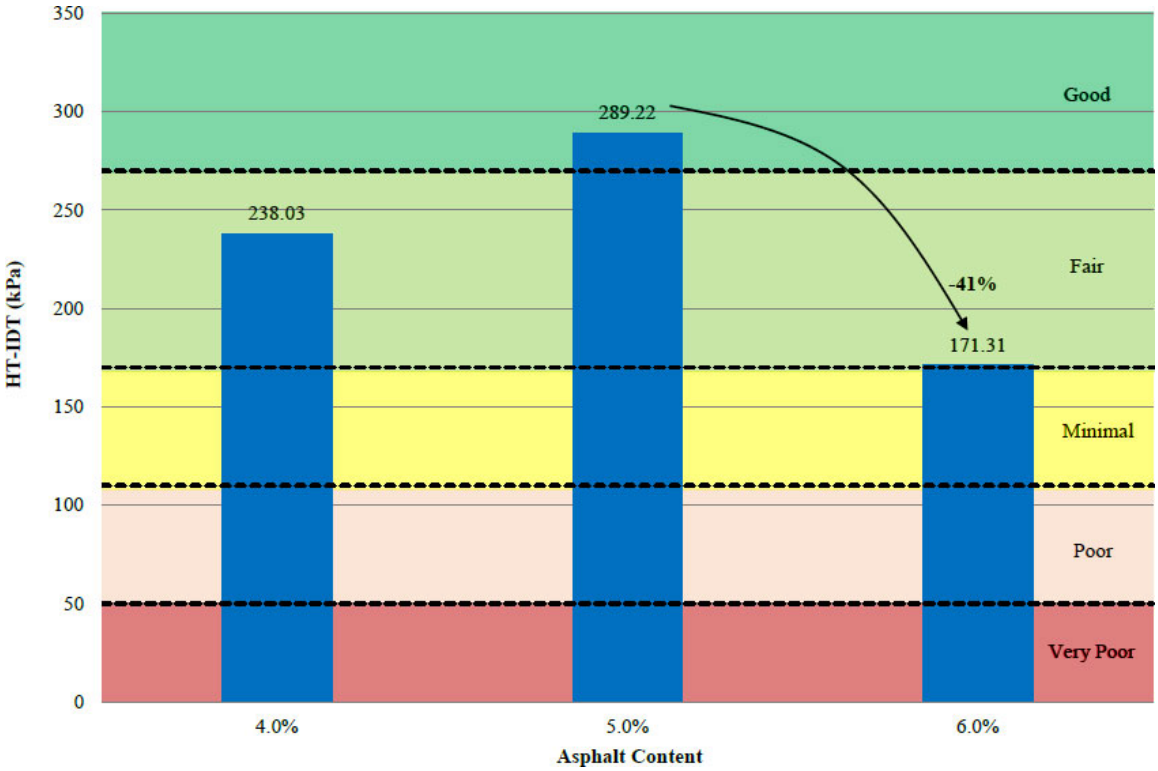


Fig. (3). HT-IDT mean results of mixtures with RAP across binder contents, evaluated against Christensen and Bonaquist [15] rutting criteria.

Table 5. HT-IDT rutting resistance of mixtures with RAP as a function of binder content.

Binder Content	Specimen ID	HT-IDT	Mean	Standard Deviation	Outlier	Corrected Mean HT-IDT
(%)		(kPa)	(kPa)	(kPa)		(kPa)
	7	244.34			No	
	8	243.83			No	
4%	31	227.32	242.10	11.43	No	238.03
	32	258.41			Yes	
	33	236.62			No	
	13	272.91			No	
5%	14	309.67	289.22	18.73	No	289.22
	23	285.09			No	
	12	183.72			No	
6%	21	209.60	171.31	32.25	No	171.31
	34	156.30			No	
	35	135.61			No	

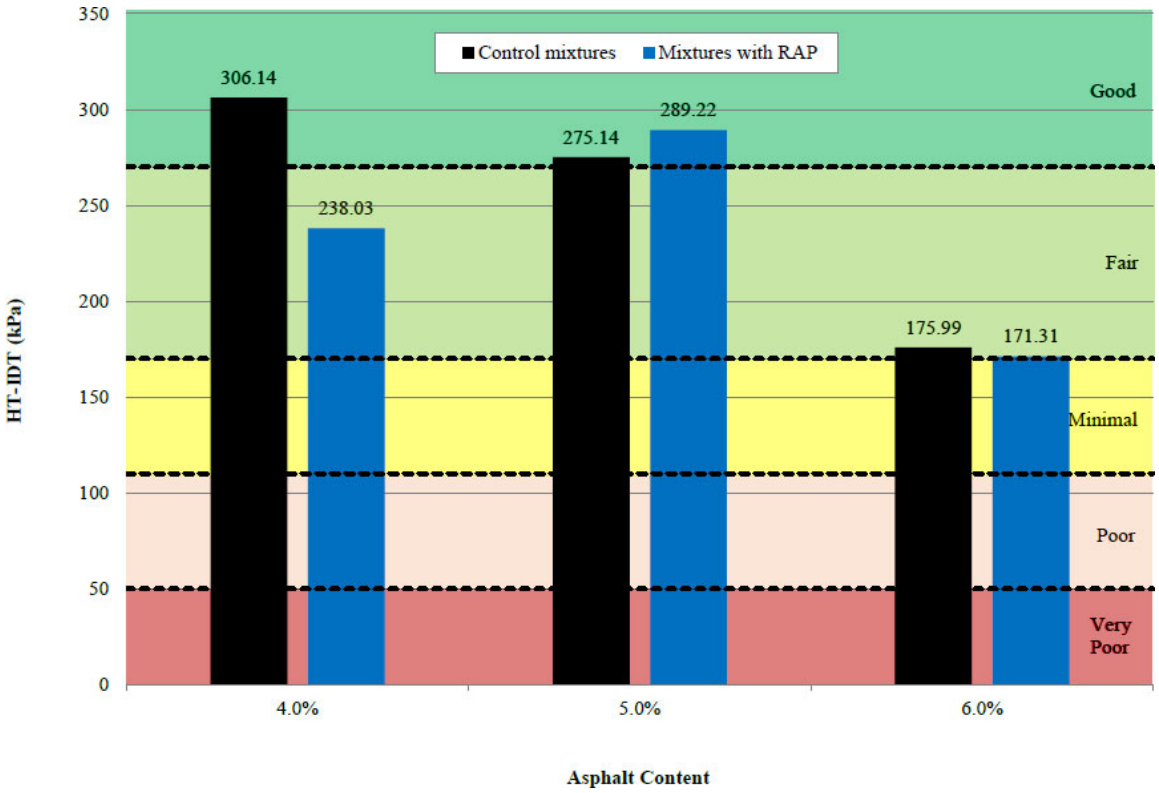


Fig. (4). Mean HT-IDT results for mixtures with and without RAP as a function of binder content.

For binder contents of 5% and 6%, the decreasing trend in permanent deformation resistance was similar to that observed in the mixtures with basaltic aggregates (Table **4** and Fig. **2**). A 41% reduction in the HT-IDT values was recorded for the mixture with 6% binder compared to the 5% binder condition. This behavior is further highlighted in Fig. (**3**), where it is evident that mixtures with lower binder contents (4% and 5%) exhibited higher resistance to permanent deformation.

Conversely, the mixture with the highest binder content (6%) is limited in its applicability, being recommended solely for medium-traffic conditions. Nonetheless, as noted by Yin and West [17], mixtures with HT-IDT values of 137.9 kPa or higher may be deemed appropriate for heavy-traffic pavements. Figure **4** illustrates the HT-IDT results for both scenarios: with and without RAP incorporation.

The analysis of (Fig. **4**) indicates that replacing 15% of the coarse basaltic aggregate with RAP did not significantly affect the rutting performance of the mixtures at 5% and 6% binder content, where equivalent target

void levels were maintained. For the 4% binder content, a reduction of approximately 22% in the HT-IDT value was observed for the mixture containing RAP compared with the control mixture. As discussedpreviously, this difference is partly attributable to the higher V_a in the RAP specimens. It therefore should not be interpreted as evidence of inferior mechanical performance of the RAP mixture in isolation. From a mechanistic standpoint, the comparable rutting performance between RAP and control mixtures at 5% and 6% binder content can be attributed to the higher effective stiffness of the RAP coarse fraction (even when treated as "black rock"), which partially compensates for any softening effect introduced by the presence of the aged binder at elevated temperatures.

3.2. Evaluation of Cracking Potential Using the IDEAL-CT test

The evaluation of the cracking potential of the asphalt mixtures was carried out using the IDEAL-CT test, in accordance with ASTM D8225-19 [18] and the modifications proposed by Shaikh and Gupta [19], who employed Marshall specimens for the tests. Table **6** presents the CT_{Index} results for the mixtures produced with the reference aggregate, while (Fig. **5**) shows the mean CT_{Index} values along with the acceptability threshold proposed by the Tennessee Department of Transportation (TDOT) [17].

Table 6. CT_{Index} results for reference mixtures as a function of binder content.

Binder Content (%)	Specimen ID	CT_{Index}	Mean	Standard Deviation	Outlier	Corrected Mean CT_{Index}
	1	33.59			No	
4%	2	33.69	43.11	16.40	No	33.64
	3	62.05			Yes	
	7	99.19			No	
5%	8	113.84	95.49	20.46	No	95.49
	9	73.43			No	
	13	274.72			No	
6%	14	241.52	232.27	47.77	No	232.27
	15	180.55			No	

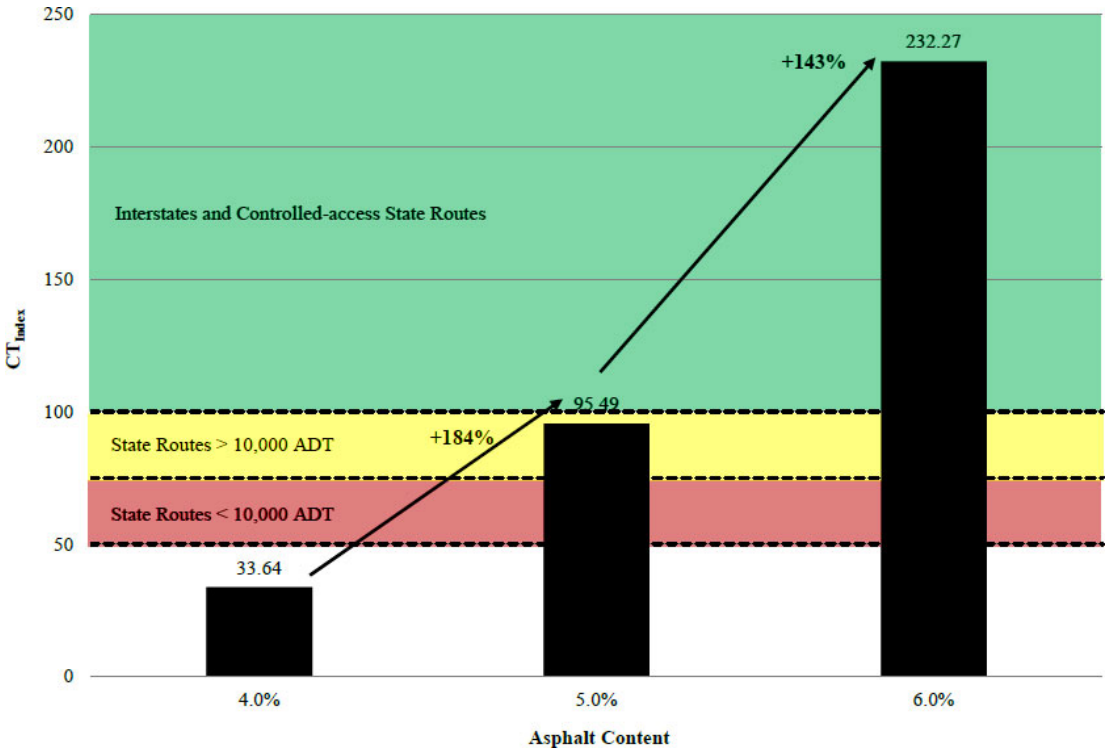


Fig. (5). Mean CT_{Index} results for the reference mixtures as a function of binder content and TDOT recommendation [17].

The analysis of Table 6 and Fig. 5 reveals that the CT_{Index} values consistently increased with higher binder content, and ANOVA followed by Tukey's test confirmed significant differences ($p < 0.05$) among the corrected mean CT_{Index} values $_{for}$ binder contents of 4%, 5%, and 6%. The eta-squared effect size (η^2) was 0.908, indicating that binder content explained 90.8% of the total variance in CT_{Index} results for the reference mixtures, representing a very large effect.

The increase in binder content from 4% to 5% resulted in a 184% increase in CT_{Index}, whereas the increase from 5% to 6% yielded a 143% increase. According to the criterion proposed by Zhou *et al*. [21], the mixtures with higher binder contents (5% and 6%) met the minimum CT_{Index} threshold of 90 and could be recommended for medium- to heavy-traffic conditions, as outlined by TDOT [17].

Regarding the mixtures produced with RAP, it is important to note that, based on preliminary laboratory compaction trials, the target Va was adjusted to 8% ±0.5% for mixtures containing 4% binder content. Table 7 presents the CT_{Index} results for the mixtures produced with RAP, and (Fig. 6) displays the mean CT_{Index} values as a function of binder content.

Table 7. CT_{Index} results for mixtures produced with RAP as a function of binder content.

Binder Content (%)	Specimen ID	CT_{Index}	Mean	Standard Deviation	Outlier	Corrected Mean CT_{Index}
	F9	56.26			No	
4%	F16	71.98	91.80	10.45	No	60.15
	F17	52.20			No	
	F18	186.75			Yes	
	F22	115.55			No	
5%	F29	145.23	143.12	26.59	No	143.12
	F30	168.60			No	
	F20	234.42			No	
6%	F27	179.11	214.29	30.57	No	214.29
	F26	229.34			No	

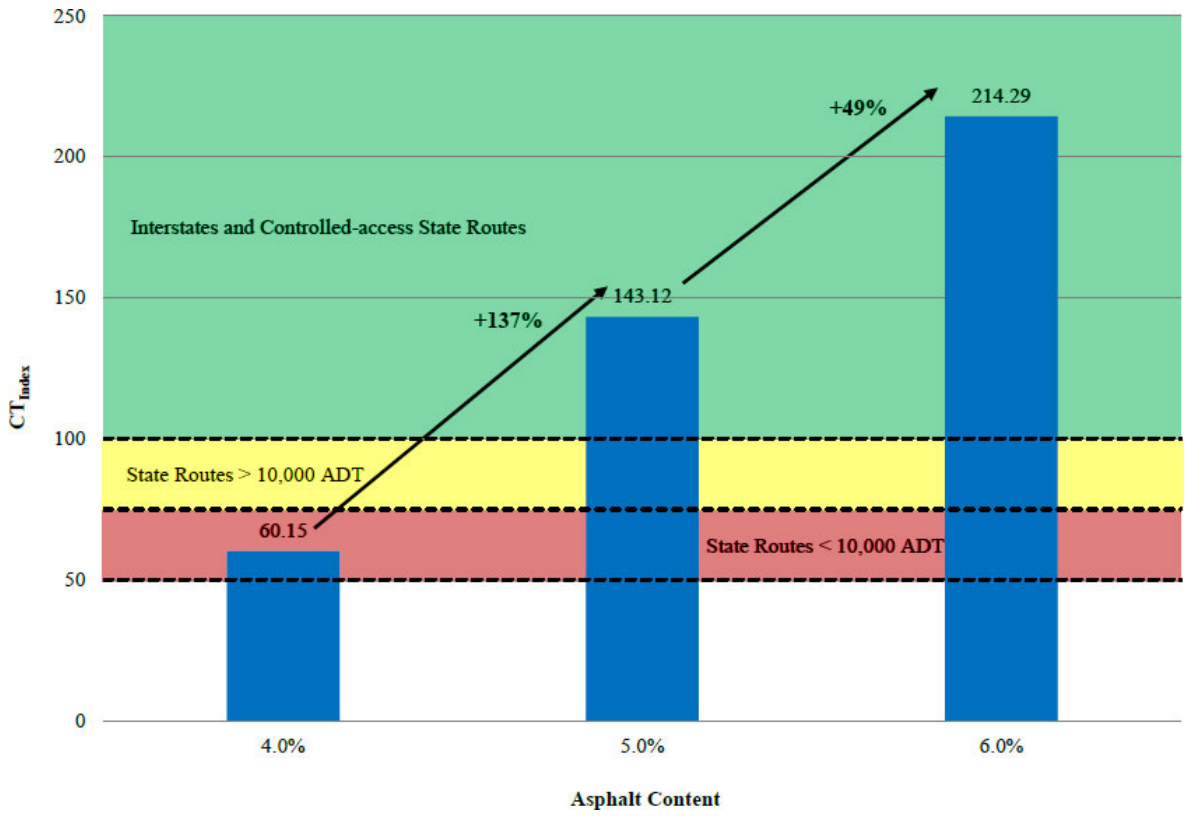


Fig. (6). Mean CT_{Index} results for mixtures produced with RAP as a function of binder content and TDOT recommendation [17].

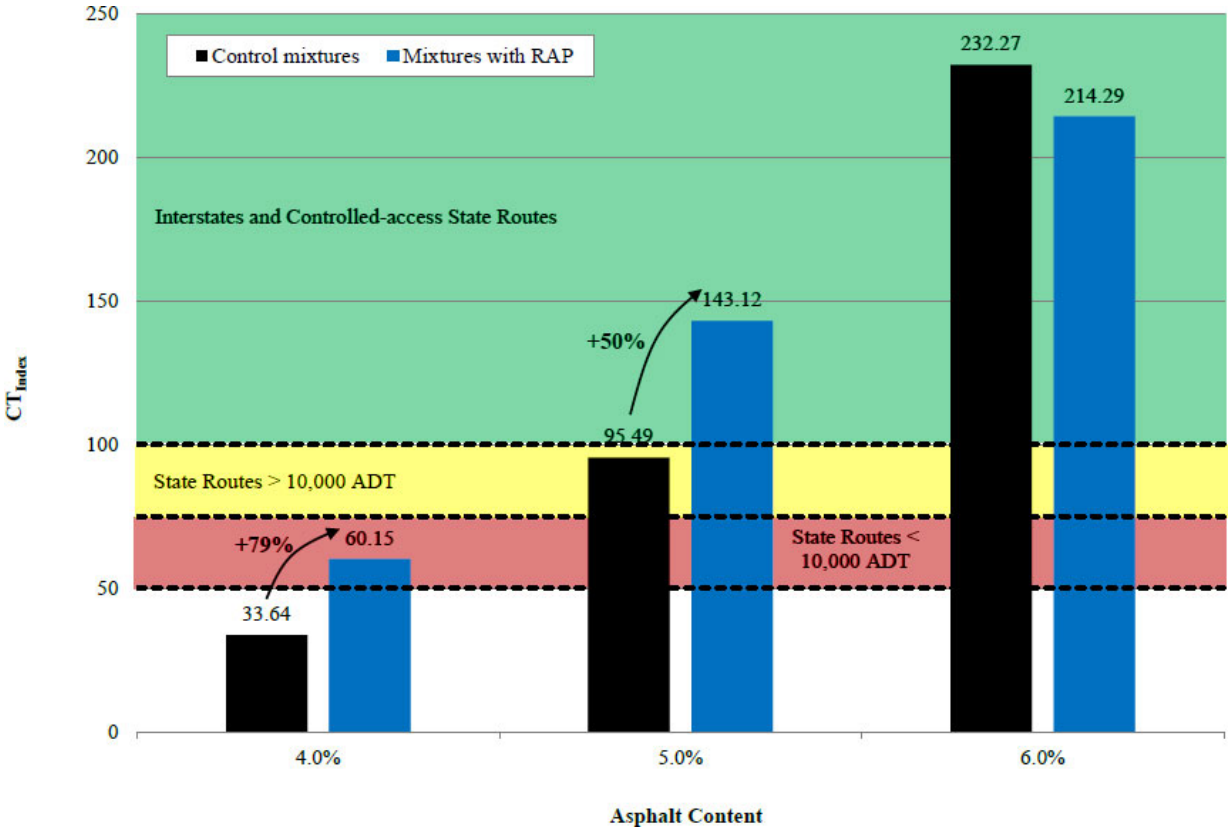


Fig. (7). Mean CT_{Index} results for mixtures with and without RAP as a function of the binder content.

Table 7 and Fig. 6 indicate that the behavior trend of the mixtures containing RAP was similar to that observed for the control mixtures, in which the binder content had a significant influence ($p < 0.05$) on the reduction of cracking potential. The eta-squared effect size (η^2) was 0.911, indicating that binder content explained 91.1% of the total variance in CT_{Index} results for RAP mixtures, representing a very large effect.

This effect resulted in a 246% increase in the CT_{Index} value between the lowest and highest binder contents. Furthermore, the mixtures with 5% and 6% binder content met the acceptability threshold proposed by Zhou *et al.* [21] and can be considered suitable for heavy-traffic pavements according to the TDOT guidelines [17]. Figure 7 compares the CT_{Index} results for mixtures with and without RAP.

As shown in Fig. (7), mixtures containing RAP exhibited higher cracking resistance at 4% binder content, followed by 5% binder content. At 6% binder content, the difference between the HMA and RAP mixtures was minimal, with HMA exhibiting a higher CT_{Index}. This behavior can be attributed to the relatively high binder content of 6%, where additional asphalt has a reduced effect on the CT_{Index}, thereby narrowing the gap between the two conditions. The superior cracking performance of RAP mixtures at lower binder contents is consistent with a partial mobilization of the aged binder from the RAP fraction during mixing. Even under "black rock" treatment, thermal energy during HMA production may promote limited diffusion of the aged binder into the surrounding virgin binder film, increasing the effective binder content and consequently the fracture energy (G_f) and post-peak deformation capacity (l_{75}) of the mixture. As the virgin binder content increases toward 6%, this mechanism becomes progressively less influential relative to the dominant effect of the virgin binder itself, explaining the convergence of CT_{Index} values between the RAP and control mixtures at higher binder contents.

3.3. Optimization of Binder Content *via* Integrated HT-IDT and IDEAL-CT Analysis

The effects of binder content variation, considering the same gradation and different aggregate sources, may be assessed through a joint analysis of the primary phenomena that lead to defects in flexible asphalt pavements, such as fatigue cracking and rutting. For this evaluation, (Figs. 8 and 9) present the HT-IDT (rutting resistance) and CT_{Index} (cracking resistance) results for the reference and RAP mixtures, respectively. The results are shown as a function of the tested binder contents, and the design binder content (5.55%) is indicated, for which the corresponding expected values of HT-IDT and CT_{Index} can be determined. These figures also present the minimum

CT_{Index} value that characterizes the recommendation for using asphalt mixtures under heavy traffic conditions, according to TDOT [17]. From this CT_{Index} level (≥ 100), it is possible to determine the minimum binder content that represents the highest level of resistance to permanent deformation (HT-IDT).

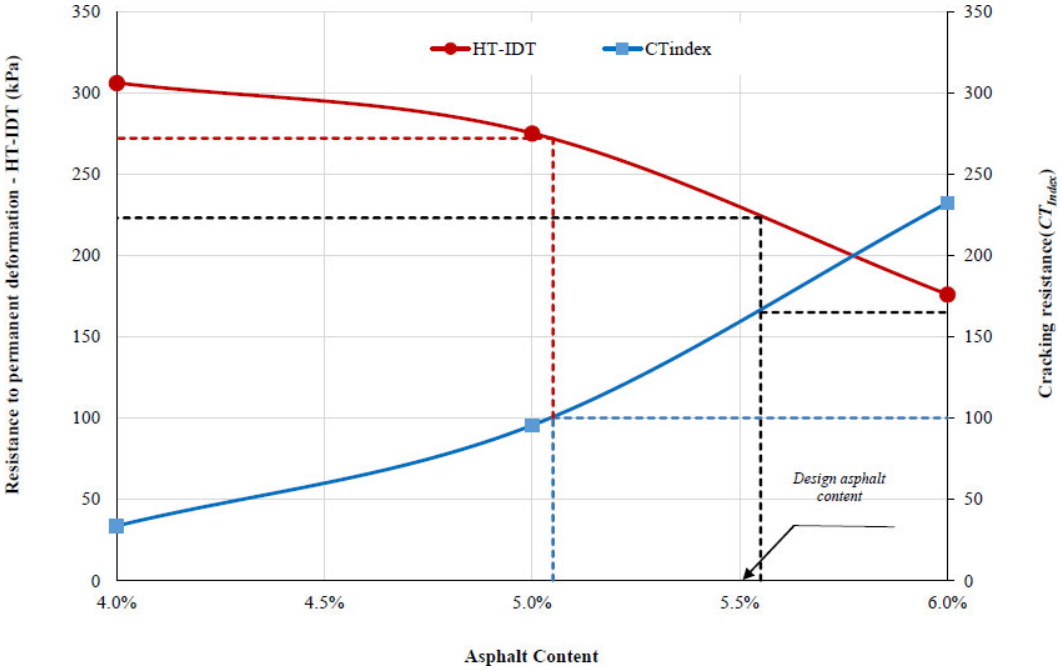


Fig. (8). Mean HT-IDT and CT_{Index} results for the reference mixtures as a function of binder content, with an indication of the design binder content.

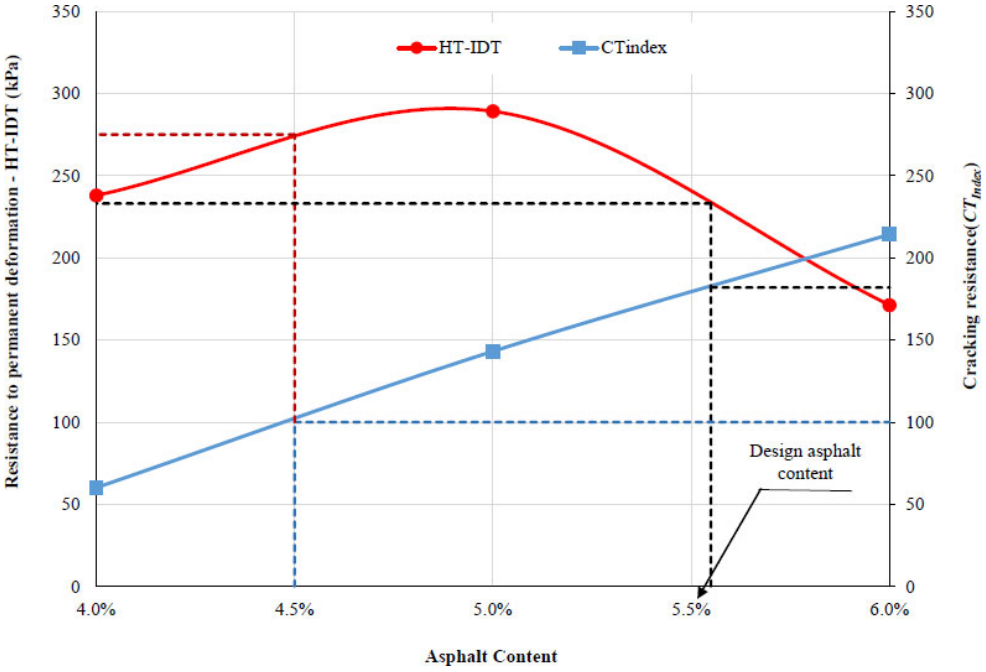


Fig. (9). Mean HT-IDT and CT_{Index} results for the mixtures with RAP as a function of binder content, with an indication of the design binder content.

The analysis of (Figs. **8** and **9**) reveals the typical behavior of asphalt mixtures concerning permanent deformation and fatigue cracking as a function of the binder content. As the amount of binder increased, a relevant improvement in the cracking resistance was observed. Conversely, a considerable reduction in the resistance to permanent deformation occurred.

The results indicate that the optimum binder content, determined using the Marshall method, yielded a mixture with high cracking resistance. This demonstrates the technical feasibility of using these mixtures under heavy traffic conditions, as defined by the TDOT guidelines [17], given that the CT_{Index} values (165 and 182 for the mixtures without and with RAP, respectively) significantly exceeded the minimum threshold of 100.

The HT-IDT results indicated similar behavior for the HMA mixtures with and without RAP at the design binder content (Fig. **8** and Fig. **9**). The reference and RAP mixtures reached 223 and 233 kPa, respectively. In both cases, the rutting resistance was classified as "fair," limiting their application to medium-traffic conditions [15].

Considering a minimumCT_{Index}value of 100 as the threshold for characterizing the feasibility of using an asphalt mixture under heavy traffic conditions, the minimum binder contents were identified as 4.50% and 5.05% for the mixtures with and without RAP, respectively. These minimum contents represent the point at which maximum permanent deformation resistance is achievable without compromising the cracking resistance. The binder demand was lower in the RAP scenario, possibly because of the mobilization of the aged binder.

For the reference mixture, the minimum possible binder content (5.05%) yielded an expected HT-IDT value of 272 kPa, which was higher than that obtained at the Marshall design content (223 kPa). This represents an increase of nearly 22% in rutting resistance without compromising the cracking resistance. Under this condition, the mixture can be classified as "Good," making it technically feasible for application in heavy traffic situations, according to the TDOT specifications [17].

A similar trend was observed for the RAP mixtures. The minimum binder content (4.5%) yielded an expected HT-IDT value of 275 kPa, representing a 51% increase in rutting resistance compared to the design binder content, without a detrimental effect on cracking resistance. Consequently, the RAP mixture was also classified as exhibiting "Good" rutting resistance performance, and its use can be recommended for heavy-traffic applications [17].

Therefore, the level of compaction achieved by the Marshall compaction method leads to a higher binder content, which enhances fatigue performance but may compromise rutting resistance, especially under critical conditions such as high volumes of heavy traffic, hot climates, and reduced speeds. Thus, it is evident that the resistance of both mixtures to permanent deformation can be enhanced without compromising their resistance to cracking. This trade-off is inherent to the viscoelastic behavior of asphalt mixtures: higher binder contents increase ductility and fracture energy, improving cracking resistance, but reduce shear resistance at high temperatures, increasing rutting susceptibility. The simultaneous evaluation of both distress modes through the HT-IDT and IDEAL-CT tests enables rational binder content optimization within the BMD framework.

The possibility of improving the rutting resistance in mixtures designed using the Marshall method has already been identified in previous studies [23, 24]. However, this approach requires field evaluation to confirm laboratory predictions under actual service conditions. Field durability of the optimized binder contents remains unconfirmed, and the findings presented herein should be interpreted within a laboratory feasibility framework. In this context, the next stages of this research include the construction and monitoring of three experimental sections on high-traffic Brazilian highways, which will provide direct validation of the optimized mix designs under tropical climate conditions and heavy traffic loading.

4. LIMITATIONS

Some limitations of this study should be acknowledged. The experimental program was conducted using a single binder type and one aggregate gradation, chosen to reflect the actual material specifications of the BR-365 and BR-050 highway rehabilitation projects, which may limit generalizability to other mix types or climatic conditions. RAP was evaluated at a fixed 15% substitution rate of the coarse aggregate fraction, and conclusions may not extend to higher incorporation levels.

The use of Marshall specimens, although intentional given the study's resource-limited scope, deviates from the SGC-compacted geometry specified in ASTM D8225-19 [18]. Therefore, absolute CT_{Index} values should be interpreted as relative performance indicators, as the thresholds established by U.S. agencies were calibrated on SGC specimens.

Similarly, the $CT_{Index} \geq 100$ threshold adopted from TDOT guidelines was developed under specific material, climate, and traffic conditions in the United States. In the absence of Brazil-specific calibration data, this threshold is used herein as a reference benchmark for relative binder content optimization. Field correlation studies are needed to establish locally validated CT_{Index} limits for tropical conditions.

It should be noted that the "black rock" treatment of RAP assumes an inert aged binder. However, partial binder mobilization during mixing cannot be entirely ruled out and may affect the effective binder content and mechanical response of RAP mixtures. Furthermore, the findings are based on laboratory testing, and field validation remains necessary to verify whether the observed performance trends are maintained under actual service conditions. The construction and monitoring of three experimental sections on high-traffic Brazilian highways are planned as the next stage of this research.

CONCLUSION

The results of this case study indicate the potential benefit of adopting the BMD approach, which simultaneously considers the main mechanisms of asphalt pavement degradation: fatigue cracking and permanent deformation. The modified IDEAL-CT and HT-IDT tests demonstrate potential as complementary tools to traditional mix design methodologies predominantly based on volumetric criteria, particularly in resource-limited laboratory contexts.

The optimum binder content established using the Marshall method yielded satisfactory cracking resistance, although it showed lower effectiveness in terms of rutting resistance. Optimizing the binder content through the integrated HT-IDT and IDEAL-CT analysis improved rutting resistance without compromising cracking performance for both mixtures with and without RAP. These results indicate that conventional volumetric design methods may not always achieve the most balanced mechanical performance under high-temperature and heavy-traffic loading conditions. Consequently, incorporating performance-based criteria into the mix design process can contribute to more durable asphalt mixtures, particularly in tropical climates.

The HMA containing RAP exhibited behavior comparable to or superior to that of the reference mixture. Finally, the BMD application through the IDEAL-CT and HT-IDT tests on Marshall specimens offers a pragmatic framework for expanding RAP utilization in emerging economies, effectively integrating technical performance, environmental sustainability, and cost efficiency.

Ultimately, the design binder content should not be defined solely by volumetric criteria, but should also reflect the specific conditions of use, including pavement structure, climate, topography, and traffic characteristics.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: R.P.L.: Conceptualization, writing of the original draft, review and editing, and submission; E.J.B.J.: Data collection, laboratory testing, and formal analysis; L.M.R.A.: Experimental methodology design. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

RAP	=	Reclaimed Asphalt Pavement
HT-IDT	=	Indirect Tensile Test at High Temperature
IDEAL-CT	=	Indirect Tensile Cracking Test at Intermediate Temperature
DOT	=	State Departments of Transportation
VMA	=	Voids in Mineral Aggregates
TSR	=	Tensile Strength Ratio
ITS	=	Indirect Tensile Strength
VFA	=	Voids Filled with Asphalt
V_a	=	Air Void
HMA	=	Hot Mix Asphalt
ADT	=	Average Daily Traffic
ESAL	=	Equivalent Single Axle Load
VDOT	=	Virginia Department of Transportation
RBR	=	RAP Binder Ratio
SGC	=	Superpave Gyratory Compactor
BMD	=	Balanced Mix Design
APA	=	Asphalt Pavement Analyzer
DCG	=	Dense Coarse-Graded
NMAS	=	Nominal Maximum Aggregate Size
G_{mm}	=	Maximum Theoretical Specific Gravity
G_{mb}	=	Bulk Specific Gravity
$\sigma_{HT\text{-}IDT}$	=	Indirect Tensile Strength for Rutting Evaluation
TDOT	=	Tennessee Department of Transportation
CT*Index*	=	Cracking Tolerance Index
G*f*	=	Fracture Energy
$\lvert m_{75} \rvert$	=	Post-peak Slope
l_{75}	=	Deformation Tolerance
OT	=	Overlay Tester
MAD	=	Median Absolute Deviation
PG	=	Performance Grade

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated during the study are available from the corresponding author on reasonable request.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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