

Balanced mix design of asphalt mixtures: Preliminary performance threshold development and mid-term aging evaluation using IDEAL tests

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Abstract

Achieving a balance between cracking and rutting resistance remains a key challenge in asphalt mixture design, particularly under varying materials and aging conditions. This study proposes a performance-based Balanced Mix Design (BMD) framework incorporating the IDEAL Cracking Test (IDEAL-CT) and IDEAL Rutting Test (IDEAL-RT). Eighteen dense-graded Hot Mix Asphalt (HMA) and two Stone Mastic Asphalt (SMA) mixtures were evaluated across multiple asphalt contents around the Optimum Asphalt Content. Results confirmed an inherent trade-off: increasing binder content significantly improved the Cracking Tolerance (CT) Index while decreasing the Rutting Tolerance (RT) Index. Notably, the RT Index exhibited a non-linear (U-shaped) relationship with binder content, reflecting the combined effects of air-void structure and film thickness. Using a 25th-percentile statistical approach to establish rational criteria, preliminary thresholds of CT Index ≥ 52 and RT Index ≥ 44 are recommended for dense-graded mixtures to balance durability and stability. SMA mixtures exhibited superior cracking resistance (CT Index ≥ 296); however, IDEAL-RT likely underestimated their rutting resistance due to its unconfined loading setup. Mid-term aging reduced cracking resistance through binder oxidation, yielding CT retention factors of 0.48 for dense-graded and 0.65 for SMA mixtures, highlighting SMA's lower aging susceptibility. Finally, a field case study on plant-produced mixtures validated these thresholds for performance-based Quality Control/Quality Assurance (QC/QA). Overall, this framework links laboratory performance, statistical thresholds, aging, and field application, effectively enhancing conventional volumetric criteria.

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1. Introduction

Asphalt pavements are constantly exposed to traffic loading and environmental conditions that progressively affect their structural integrity and long-term functional performance [1]. Over time, these combined effects trigger various pavement distresses. Rutting and cracking represent the most critical failure mechanisms. They directly impact pavement durability, ride quality, and maintenance requirements [1,2]. Rutting typically stems from repeated traffic loading under high temperatures. Under these conditions, the asphalt mixture gradually accumulates permanent deformation [3–6]. Cracking, conversely, is driven by fatigue loading, thermal stresses, and long-term binder aging. This aging process reduces mixture flexibility and increases brittleness [7–10]. In practical applications, these two distress mechanisms are deeply interconnected. Improving resistance to one often compromises resistance to the other. This trade-off complicates the achievement of a truly balanced pavement performance [11,12].

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Traditionally, volumetric-based methodologies have governed asphalt mixture design. The Marshall and Superpave design procedures are among the most widely used approaches. They determine the optimum asphalt content based on volumetric parameters, including air voids (AV), voids in mineral aggregate (VMA), and mixture stability indicators. Although widely used in practice, these methods rely primarily on volumetric criteria rather than direct performance measurements and do not explicitly capture how asphalt mixtures mechanically respond to realistic field loading and environmental conditions [13–15]. Consequently, mixtures meeting all volumetric requirements can still suffer premature rutting or cracking under in-service conditions, highlighting a clear limitation in performance prediction.

To address these shortcomings, the asphalt pavement community is moving toward performance-oriented mix design philosophies. BMD has emerged as a key performance-based framework that integrates laboratory performance testing directly into the mixture design process [16,17]. The main objective of BMD is to achieve a balanced performance between rutting and cracking resistance rather than relying solely on volumetric compliance. Within this framework, the IDEAL-CT and IDEAL-RT tests have attracted increasing attention because they provide a practical, rapid, and repeatable means of performance evaluation without complex specimen preparation. Their corresponding CT Index and RT Index quantify cracking tolerance and rutting resistance, making them suitable for both BMD implementation and production-level QC/QA applications [18–20].

Despite the growing adoption of these performance-based approaches, several challenges restrict full BMD implementation in practice. Much of the previous research treats rutting and cracking resistance as separate performance indicators. This approach fails to sufficiently address their interrelationship. Consequently, the combined interpretation of the CT Index and RT Index is not fully established. This is particularly challenging when defining unified and reliable performance thresholds. Additionally, the threshold values reported in current literature often reflect specific material compositions, traffic levels, and climatic conditions. This specificity limits their transferability and also raises concerns about their applicability across different regions or design scenarios [21–28]. Furthermore, QC and QA practices in asphalt production still rely heavily on volumetric properties. Producers focus on three parameters: asphalt content, aggregate gradation, and density rather than direct performance indicators [29].

Another critical aspect requiring deeper investigation is the influence of asphalt aging on mixture performance. Aging progressively oxidizes the binder, increasing mixture stiffness while reducing ductility. As a result, rutting resistance generally improves, whereas cracking resistance deteriorates over time [30,31]. Although this general behavior is well recognized, the influence of mid-term aging on IDEAL-based performance indices, particularly the CT Index, has not been adequately quantified.

Therefore, this study aims to develop a performance-based framework for asphalt mixture evaluation using IDEAL-CT and IDEAL-RT indices. The study investigates the interaction between cracking and rutting resistance, evaluates the influence of asphalt content and aging, and proposes preliminary performance thresholds based on a percentile-based statistical approach for the specific materials and conditions evaluated. In addition, the applicability of the proposed framework is examined using plant-produced asphalt mixtures to assess its suitability for practical QC/QA implementation, ultimately supporting the transition from conventional volumetric mix design toward performance-based asphalt mixture design.

2. Research Objectives

The main objectives of this study are:

- To determine the cracking resistance and the rutting resistance of asphalt mixtures through the performance indicators CT Index and RT Index.
- To investigate the effects of Mid-Term Laboratory Aging on the cracking and rutting performance of asphalt mixtures.
- To develop statistical regression models relating CT Index and RT Index to the governing mixture variables.

- To establish preliminary minimum performance thresholds using the P25 (25th percentile) statistical approach.
- To validate the practical applicability of the BMD framework through a case study involving plant-produced asphalt mixtures.

3. Materials

The materials used in this study included asphalt binder, aggregates from two different sources, mineral fillers, and four aggregate gradation types. A total of twenty mixture configurations, derived from eight base design mixtures (six dense-graded and two SMA), were prepared for each of the IDEAL-CT and IDEAL-RT tests, in addition to eight specimens used to evaluate the effects of mid-term aging on the CT Index.

3.1 Asphalt Cement

The asphalt cement used in this study was sourced from the Doura Refinery, located south of Baghdad. The binder was classified as penetration grade asphalt cement (AC 40–50) in accordance with (SCRB, 2003) specifications [32]. Its physical properties, determined using standard ASTM test methods, are summarized in Table 1.

Table 1. Physical properties of AC (40-50)

Test	Units	Results	SCRB 2003 Limits	ASTM Designation
Penetration (25 °C, 100 g, 5 sec)	1/10 mm	44	40 – 50	D5-06
Ductility (25 °C, 5 cm/min)	Cm	149	≥ 100	D113-07
Softening Point (Ring & Ball)	°C	50	—	D36-06
Flash Point	°C	294	≥ 232	D92-12
Specific gravity at 25 °C	—	1.037	—	D70-09
After Thin-Film Oven Test ASTM D 1754				
Penetration	%	57	≥ 55	D5-06
Ductility	Cm	98	> 25	D113-07

3.2 Aggregate

The coarse and fine aggregates used in the asphalt concrete mixes were from Al-Niba'i (Source 1) quarry and Al-Sudoor (Source 2) quarry. They were crushed quartz, hard, tough grains, free of injurious substances of clay, loam, or other deleterious substances. The physical properties of the coarse and fine aggregates, determined in accordance with relevant ASTM standards, are summarized in Tables 2 and 3, respectively.

Table 2. Physical properties of coarse aggregates

Property	ASTM Designation	Source 1 (Al-Niba'i)	Source 2 Al-Sudoor	SCRB Limits
Bulk Specific Gravity	C127-07	2.598	2.584	—
Apparent Specific Gravity	C127-07	2.615	2.608	—
Percent Water Absorption	C127-07	0.53	0.58	—
Percent Wear (Los Angeles Abrasion, %)	C535-09	15.65	13.94	30 Max

Table 3. Physical properties of fine aggregates

Property	ASTM Designation	Source 1 (Al-Niba'i)	Source 2 Al-Sudoor
Bulk Specific Gravity	C128-07	2.581	2.602
Apparent Specific Gravity	C128-07	2.634	2.662
Percent Water Absorption	C128-07a	0.953	1.418

3.3 Mineral Filler

Two types of mineral fillers were used in this study: limestone dust and Portland cement. Both fillers were non-plastic and passed the No. 200 sieve (0.075 mm), in accordance with standard specifications. The physical properties of the mineral fillers are summarized in Table 4.

Table 4. Physical Properties of Filler

Filler type	Property	Test Result
Limestone Dust	Specific Gravity	2.71
	% Passing No.200	93
Cement	Specific Gravity	3.15
	% Passing No.200	95

3.4 Glass Fibers (GF)

Glass fibers are inorganic short fibers used to stabilize SMA mixtures by reducing binder drain-down. Type 562A glass fibers, supplied by JUSHI Group (China), were used in this study. GF was incorporated into the SMA mixtures at dosages ranging from 0.2% to 0.5% by weight of the mixture [33,34]. Based on the drain-down test results, a dosage of 0.3% was selected, as it satisfied the maximum drain-down limit specified by AASHTO T305 for effective binder stabilization. The properties of the glass fibers are presented in Table 5.

Table 5. Properties of glass fibers

Property	Density (gm/cm ³)	Melting point (°C)	Poisson's Ratio	Tensile Strength (GPa)	Modulus of Elasticity (GPa)	Length (mm)	Diameter (mm)	Aspect Ratio
Result	2.508	> 400	0.29	3.4	72	7	0.21	33.3

3.5 Selection of Aggregate Gradations

The aggregate gradation for dense-graded mixtures was selected in accordance with SCRB (2003) specifications for a nominal maximum aggregate size (NMAS) of 12.5 mm (Type IIIA surface course). For SMA mixtures, the gradation was adopted based on AASHTO M 325 (2012) requirements. The selected aggregate gradations are listed in Table 6 and presented in Figs. 1-2.

Table 6. Selected aggregate gradation

Sieve Size (mm)	Design Gradation	Production Tolerance	Coarse Gradation	Fine Gradation	Specification Range	SMA	Specification Range
19	100	-	100	100	100	100	100
12.5	95	± 6	90	100	90-100	95	90-100
9.5	83	± 6	77	89	76-90	65	50-80
4.75	59	± 6	53	65	44-74	28	20-35
2.36	43	± 4	39	47	28-58	20	16-24
0.3	13	± 4	9	17	5-21	-	-
0.075	7	± 2	5	9	4-10	10	8-11

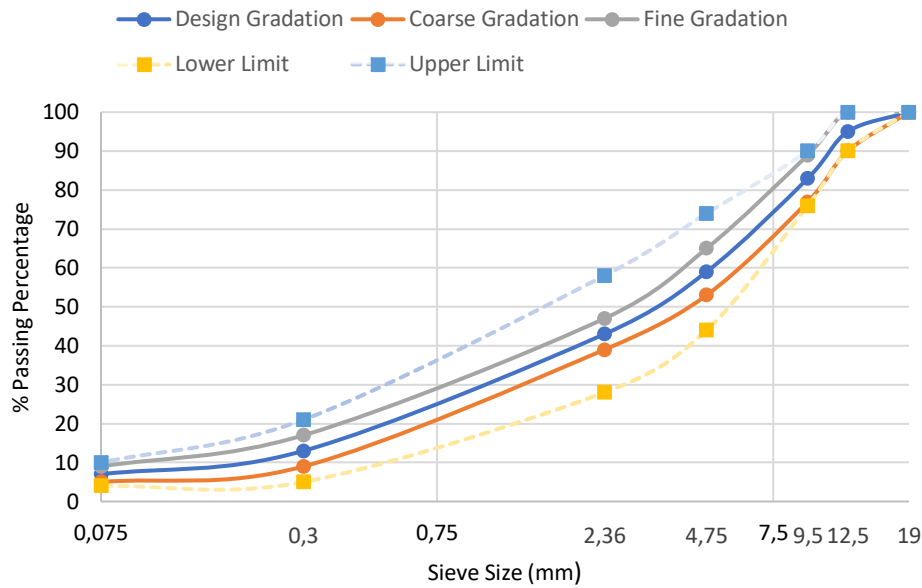


Fig. 1. Specification limits and selected gradation for dense graded mixes

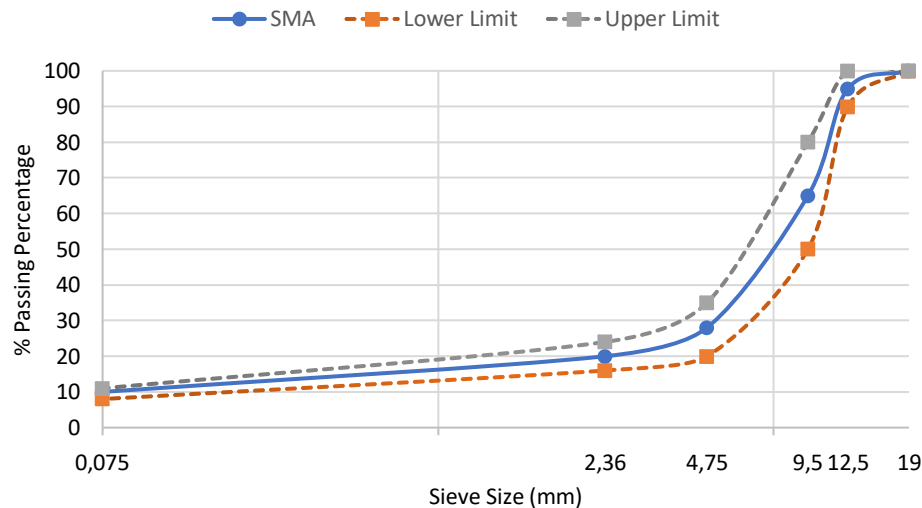


Fig. 2. Specification limits and selected gradation for SMA

4. Methodology

Fig. 3 illustrates the overall methodology adopted to develop and validate the proposed BMD framework. The methodology consists of several integrated stages, beginning with material selection, including asphalt binder, aggregates, mineral filler, and fibers. The mixture design stage includes the preparation of both dense-graded and SMA mixtures at different asphalt contents around the optimum asphalt content (OAC, OAC-0.3% and OAC+0.3%). Subsequently, IDEAL-CT and IDEAL-RT tests were conducted to evaluate cracking and rutting resistance, respectively.

Based on the obtained results, a balanced mix design approach was implemented to identify the optimum asphalt content that satisfies both performance criteria. In addition, regression analysis was performed to investigate the influence of key mixture variables, such as asphalt content, gradation, and filler type, on CT and RT indices, and to establish preliminary threshold values.

Furthermore, the effect of aging was incorporated through short- and mid-term aging conditioning protocols to assess mixture durability. Finally, plant-produced loose mixtures were evaluated to

validate the proposed QC/QA acceptance criteria and demonstrate the practical applicability of the framework.

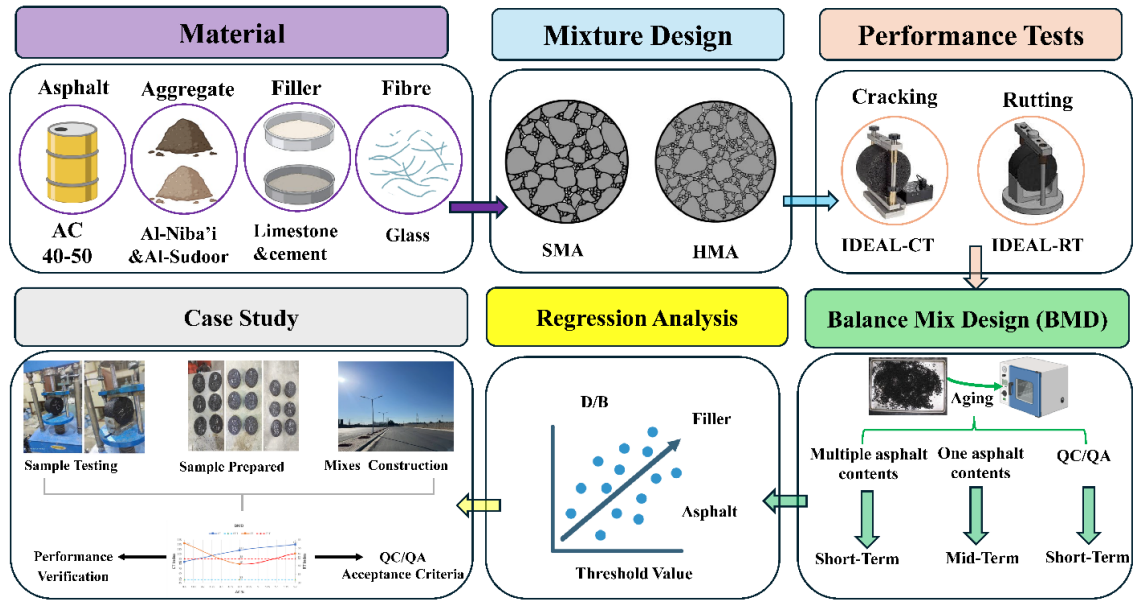


Fig. 3. Overall methodological framework for BMD evaluation and QC/QA validation

A total of eight asphalt mixtures were prepared, including six dense-graded mixtures and two SMA mixtures for (OAC) analysis. For dense-graded mixtures, asphalt contents of 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% were used to capture a wide range of volumetric and performance responses. In contrast, SMA mixtures were evaluated at higher binder contents of 5.5%, 6.0%, 6.5%, 7.0%, and 7.5%, consistent with SMA design requirements to ensure adequate stone-on-stone contact and enhanced durability. The OAC was initially determined using Marshall compaction (ASTM D6927), with specimens of 101 mm diameter and 63.5 mm height. Table 7 presents the Marshall properties for each of the eight design mixtures. All performance test specimens were prepared using a Superpave Gyratory Compactor (SGC) in accordance with ASTM D6925, with dimensions of 150 mm diameter and 62 ± 1 mm height. These eight base design mixtures were subsequently evaluated at three binder contents (OAC-0.3%, OAC, OAC+0.3%), yielding the twenty performance-testing configurations.

Table 7. Marshall properties of design mixtures

Filler	Gradation	OAC (%)	Va (%)	VMA (%)	VFA (%)	Gmb (g/cm ³)	Gmm (g/cm ³)	Stability (kN)	Flow (mm)
Limestone	Coarse	4.5	4.2	14.8	71.6	2.250	2.349	10.1	3.2
Limestone	Design	4.8	4.0	15.2	73.7	2.307	2.403	11	3.5
Limestone	Fine	5.1	4.1	15.6	73.7	2.299	2.397	13.3	3.8
Limestone	SMA	6.2	3.3	17	80.6	2.238	2.314	5.7	4.2
Cement	Coarse	4.85	4.3	15.1	71.5	2.238	2.339	8.7	3.1
Cement	Design	5.1	4.0	15.5	74.2	2.295	2.391	9.5	3.4
Cement	Fine	5.5	4.2	15.9	73.6	2.287	2.387	11.5	3.7
Cement	SMA	6.5	3.6	17.4	79.3	2.254	2.338	4.9	4.5

4.1 Laboratory Performance Testing

4.1.1 Cracking Resistance (IDEAL-CT)

IDEAL-CT was conducted in accordance with ASTM D8225 [35] at a temperature of 25 °C and a loading rate of 50 mm/min. The test is typically completed in less than 2 minutes after removing

the specimen from the conditioning chamber (e.g., water bath). The cracking parameter for the IDEAL-CT is the CT Index, which is calculated as per Eq (1).

$$CT\ Index = \frac{t}{62} \times \frac{l75}{D} \times \frac{Gf}{|m75|} \times 10^6 \quad (1)$$

where: Gf = failure energy (Joules/m²), $|m75|$ = absolute value of the post-peak slope $m75$ (N/m), $l75$ = displacement at 75 percent the peak load after the peak (mm), D = specimen diameter (mm), and t = specimen thickness (mm).

Higher CT Index values indicate greater resistance to cracking. The IDEAL-CT test has been shown to correlate well with field cracking performance [18,19]. Three test specimens, 150 mm diameter and 62 mm height, at $7 \pm 0.5\%$ air voids are cast using the Superpave gyratory compactor. The IDEAL-CT test is a rapid and simple method, providing repeatable results that are sensitive to key mixture variables, including aggregate structure, binder properties, recycled content, and aging conditions. It can be used for both BMD-based cracking performance evaluation and production-level QC/QA to assess the adequacy of cracking resistance.

4.1.2 Rutting Test (IDEAL-RT)

The high-temperature rutting resistance of the asphalt mixtures was evaluated using the IDEAL Shear Rutting Test (IDEAL-RT), performed in accordance with ASTM D8360-22 [36]. The test is performed at a temperature of 60 °C with a loading rate of 50 mm/min. Similar to the IDEAL-CT procedure, the test is completed in less than 2 minutes after removing the specimen from the conditioning chamber (e.g., water bath). Rutting resistance is evaluated using the RT Index, which reflects the ability of the asphalt mixture to resist permanent deformation under shear loading. The RT Index is calculated as per Eq (2).

$$RT\ Index = 6.618 \times 10^{-5} \times \frac{\tau f}{1\ Pa} \quad (2)$$

where: $\tau f = 0.356 \times \frac{P_{max}}{t \times w}$ = shear strength (Pa), P_{max} = maximum load (N), t = specimen thickness (m), and w = width of upper loading strip (=0.0191 m).

The IDEAL-RT test has been shown to correlate well with field rutting performance [37]. In this study, three specimens with a diameter of 150 mm and a height of 62 mm were compacted using a Superpave Gyratory Compactor to achieve a target air void level of $7 \pm 0.5\%$. The test provides a rapid and reliable assessment of mixture resistance to permanent deformation and is sensitive to key factors such as aggregate structure, binder characteristics, recycled content, and aging. Owing to its rapidity, repeatability, and minimal specimen preparation (requiring no saw-cutting or notching), the IDEAL-RT test serves as a practical tool for BMD-based mixture performance screening and shows high potential as a surrogate monitoring test for production-level QC/QA.

4.2 Laboratory Aging Protocols

4.2.1 Aging Protocol for IDEAL-RT Specimens

For the preparation of IDEAL-RT specimens, short-term aging was applied to simulate plant production conditions. Loose mixtures were conditioned at the compaction temperature of 135 °C for 2 hours at a layer thickness of approximately 38–50 mm. The mixture was stirred periodically (once every hour) to ensure uniform aging. This conditioning procedure was used to evaluate the rutting resistance of asphalt mixtures under both laboratory performance testing and production-level QC/QA conditions [38–41].

4.2.2 Aging Protocol for IDEAL-CT Specimens

For IDEAL-CT testing, a hybrid aging protocol combining short- and mid-term aging conditioning was adopted, following the approach proposed in previous studies [31,42]. The detailed procedure is presented Table 8.

Table 8. Laboratory aging protocols for preparing performance tests specimens

Stage	Aging protocol	Condition
BMD performance evaluation at multiple asphalt contents	Short-term aging	2-hr at 135 °C with a loose mix thickness of preferably 38–50 mm; stir the loose mix every hour
BMD performance verification with one asphalt content	Mid-term aging	(1) 2 h at 135 °C (same as short-term aging); (2) 20 h at 100 °C with a thickness equal to one NMAS (no stirring); (3) 2 h at 135 °C
QC/QA	Short-term aging	2-hr at 135 °C with a loose mix thickness of preferably 38–50 mm; stir the loose mix every hour

The primary objective of this hybrid aging protocol is to simulate the influence of short- and mid-term aging on cracking resistance without the need for time-consuming long-term conditioning [31]. Recent field-calibrated research reported that 20 h of loose-mix oven aging at 100 °C can simulate approximately six years of field aging under hot-climate conditions for the materials investigated [42]. The same short-term aging protocol used for IDEAL-RT testing was also applied to IDEAL-CT specimens to ensure consistency in performance evaluation. This approach enables the use of laboratory performance data to establish practical QC/QA acceptance criteria for asphalt mixtures with respect to both cracking and rutting resistance.

5. Results and Discussion

5.1 CT Index and RT Index Results

The combined analysis of CT and RT Indices offers a detailed understanding of asphalt mixture performance, particularly in terms of the balance between cracking resistance and rutting resistance. The results obtained in this study clearly demonstrate that mixture performance is governed by the interaction between asphalt content, aggregate gradation, filler type, and aging conditions.

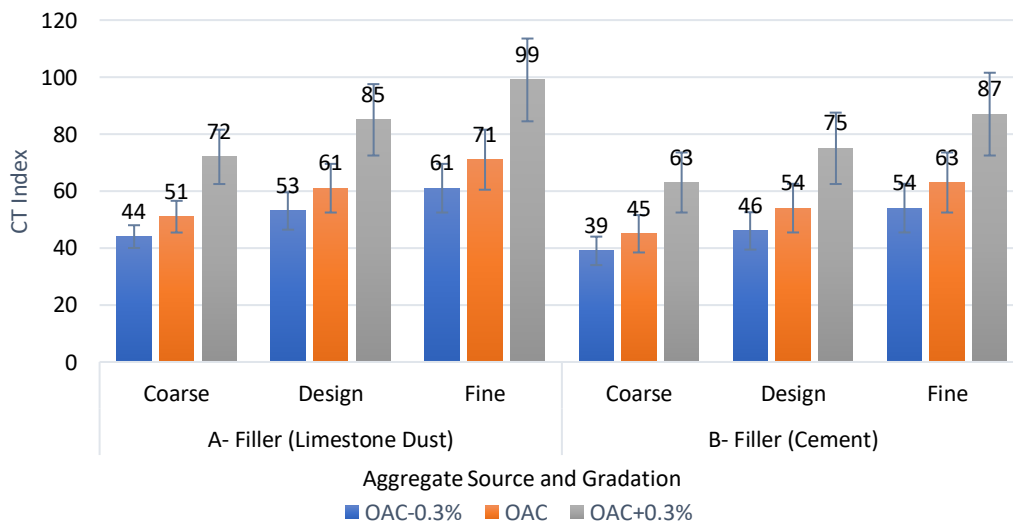


Fig. 4. CT Index values with aggregate source, aggregate gradation and asphalt content

Increasing asphalt content resulted in a consistent increase in CT Index values for all mixtures as illustrated in Fig. 4. This increase indicates improved resistance to cracking due to enhanced binder flexibility and increased energy absorption capacity. However, this improvement in cracking resistance was accompanied by a reduction in RT Index values near the optimum asphalt content, indicating the well-known trade-off between mixture flexibility and resistance to permanent deformation. The coefficient of variation (COV) for CT Index values ranged from 9.1% to 16.7%, with an overall average of approximately 14.1%. This wide range reflects realistic experimental variability in asphalt mixture testing, with all values remaining well below the acceptable limit of

20% [19]. The variation observed across different mixture types and filler combinations confirms the reliability and repeatability of the test results while capturing genuine differences in material behavior.

A notable observation in this study is the non-linear relationship between asphalt content and rutting resistance, where the RT Index exhibited a U-shaped trend as shown in Fig. 5. This behavior can be attributed to the combined effects of binder film thickness, air-void structure, and aggregate interaction. At moderate increases in asphalt content (e.g., +0.3%), these mechanisms improve stress distribution within the mixture before the softening effect of excessive binder becomes dominant [31,43]. These effects can temporarily enhance rutting resistance before the softening effect of excessive binder becomes dominant, leading to reduced mixture stability. The COV for RT Index values ranged from 4.7% to 10.1%, with an overall average of approximately 8.4%. All COV values remained near or below the acceptable limit of 10% [44], confirming the high repeatability of the IDEAL-RT test and supporting the reliability of the rutting performance comparisons across different mixture types and filler combinations.

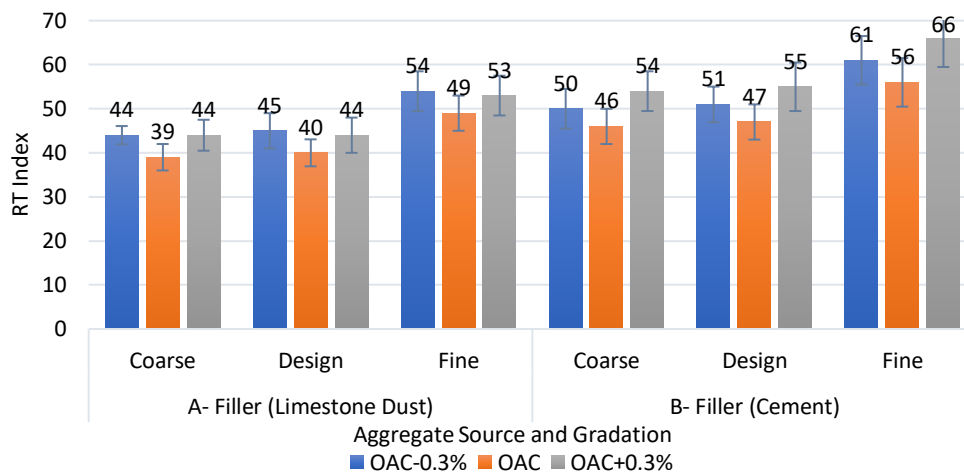


Fig. 5. RT Index values with aggregate source, aggregate gradation and asphalt content

Aggregate gradation played a major role in controlling both cracking and rutting performance. Fine-graded mixtures exhibited higher CT Index values than coarse mixtures due to improved binder retention and greater resistance to crack propagation. Similarly, RT Index values increased from coarse to fine gradations, indicating improved rutting resistance as a result of better aggregate interlock and reduced internal voids. These findings suggest that fine gradation contributes to a better balance between cracking resistance and rutting resistance, particularly when combined with an appropriate binder content. Filler type also significantly influenced mixture behavior. Mixtures containing limestone dust generally exhibited slightly higher CT Index values, indicating improved cracking resistance, likely due to better binder compatibility. In contrast, mixtures prepared with cement filler demonstrated superior RT Index values across all gradations, reflecting enhanced stiffness and greater resistance to permanent deformation. This behavior may be associated with the greater stiffness contribution of the cement–binder mastic. Therefore, while limestone filler favors cracking resistance, cement filler is more effective in enhancing rutting performance.

The interaction between asphalt content and filler type further influenced mixture performance. For limestone mixtures, increasing asphalt content beyond the optimum resulted in only a slight recovery in RT Index, which remained lower than the values observed at the lower asphalt content (-0.3%). This shows that the softening effect of the binder was not fully compensated by the stiffness contribution of the limestone-dust mastic. In contrast, in cement mixtures, increasing asphalt content resulted in a considerable increase in RT Index at the upper limit (+0.3%), exceeding the initial values at (-0.3%). This demonstrates the ability of cement filler to counterbalance the softening effect associated with higher binder contents and maintain adequate rutting resistance.

Mid-term aging had a pronounced influence on CT Index values, leading to a considerable reduction in cracking resistance across all mixtures, as illustrated in Fig. 6. This reduction is mainly attributed to binder oxidation, which increases stiffness while reducing the material's ability to dissipate strain energy. The results further indicate that mixtures exhibiting high CT Index values under unaged conditions may not maintain the same level of performance after aging, highlighting the limitation of evaluating cracking resistance based solely on unaged specimens.

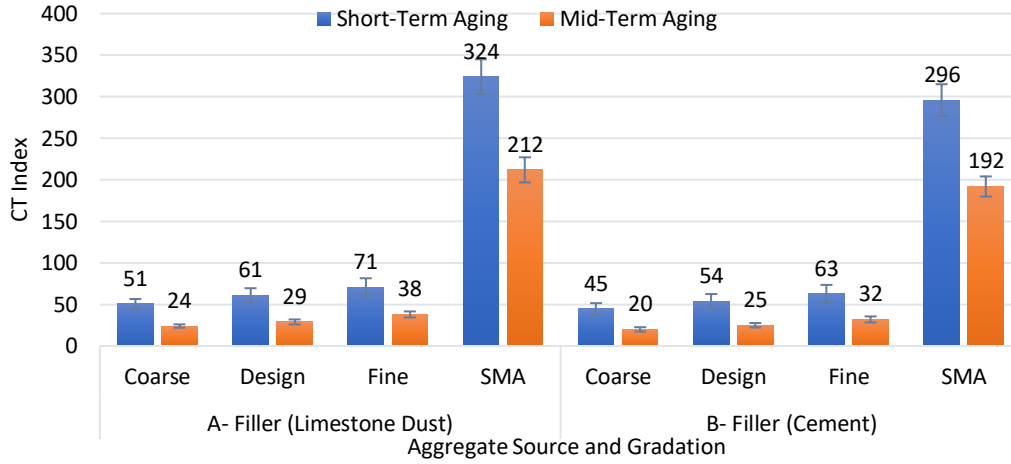


Fig. 6. CT Index values for both short- and mid-term aging

The combined evaluation of CT and RT indices clearly indicates that asphalt mixture performance cannot be optimized using a single parameter. Although cracking resistance generally improves with increased asphalt content and finer gradations, these factors may adversely affect rutting performance unless compensated by appropriate filler selection. The results demonstrate that mixtures incorporating fine gradation and cement filler provide a more balanced performance, particularly at higher asphalt contents, where both adequate cracking resistance and improved rutting resistance can be achieved. Overall, the findings confirm that the interaction between asphalt content, aggregate gradation, and filler type governs the balance between cracking and rutting performance. Therefore, evaluating CT and RT Indices together provides a more reliable basis for mixture optimization than relying on either performance indicator alone, supporting the implementation of BMD.

5.2 Regression Equations

Regression analysis was conducted using Minitab software to evaluate the influence of mixture variables on CT and RT Indices and to establish quantitative relationships between these performance indicators. The regression equation for CT Index is presented in Eq (3).

$$CT\ Index = -136.2 + 46.39\ AC - 13.92\ D/B - 25.50\ Filler \quad (3)$$

Where D/B: Dust/Binder content (passing 200 / asphalt content), Filler = 0 for limestone dust and Filler = 1 for cement.

Multicollinearity was assessed using variance inflation factors (VIF) and the Pearson correlation between AC and D/B. The VIF values were 1.68 for AC, 1.40 for D/B, and 1.50 for Filler, all below 3.0. The Pearson correlation between AC and D/B was 0.370 ($p = 0.131$), indicating no strong linear association between these predictors. Therefore, multicollinearity was not a substantial concern in the CT Index regression model.

The CT Index model exhibited a strong fit to the experimental data ($R^2 = 92.96\%$). Asphalt content was identified as the dominant variable governing cracking resistance, with increasing binder content significantly improving the CT Index. In contrast, higher dust-to-binder ratios and the use of cement filler reduced the CT Index, indicating that increased mixture stiffness and reduced strain tolerance adversely affected cracking performance. The statistical significance of the model parameters is summarized in Table 9.

Table 9. Regression statistics and significance of variables for the IDEAL-CT model

Variable	Coefficient	P-value	Effect on CT Index
Constant	-136.2	...	Intercept
Asphalt Content (AC)	46.39	0	Increases CT Index
Dust-to-Binder Ratio (D/B)	-13.92	0.014	Reduces CT Index
Filler Type (Cement = 1)	-25.50	0	Reduces CT Index
Model Statistics	SD = 4.8099	R ² = 92.96%	Adj. R ² = 91.45%

The regression equation developed for the RT Index is presented in Eq (4). Since the experimental results demonstrated a U-shaped relationship between asphalt content and the RT Index, a second-order polynomial regression model was adopted by incorporating the quadratic asphalt content term (AC²).

$$RT\ Index = 259.42 - 86.52\ AC + 9.08\ AC^2 + 6.79\ Filler - 21.12\ C/F \quad (4)$$

Where AC: asphalt content (%), C/F: Coarse/Fine content (retained on 9.5 mm sieve / passing 2.36 mm sieve), Filler= 0 for limestone dust and Filler=1 for cement.

For the RT Index regression model, the VIF values were 426.68 for AC, 424.37 for AC², 1.50 for Filler, and 2.05 for C/F. The high VIF values for AC and AC² are expected because the quadratic term is mathematically derived from AC, whereas the VIF values for Filler and C/F indicate no substantial multicollinearity among the non-polynomial predictors. The proposed second-order polynomial model showed satisfactory agreement with the experimental results, yielding an R² of 79.26%. Filler type and the coarse-to-fine ratio (C/F) were identified as statistically significant variables affecting the RT Index. The inclusion of the quadratic asphalt content term enabled the regression model to represent the experimentally observed U-shaped relationship between asphalt content and rutting resistance. The statistical significance of the model parameters is summarized in Table 10. Although the linear and quadratic asphalt binder content terms had p-values slightly above 0.05 (0.080 and 0.067, respectively), they were retained because they jointly represent the experimentally observed U-shaped relationship between asphalt binder content and the RT Index and contribute to the overall model fit (R² = 79.26%). Thus, their retention was based on the combined statistical and physical interpretation of the nonlinear relationship rather than on individual p-values alone.

Table 10. Regression statistics and significance of variables for the IDEAL-RT model

Variable	Coefficient	P-value	Effect on RT Index
Constant	259.42	...	Intercept
Asphalt Content (AC)	-86.52	0.080	Linear term of AC
Asphalt Content (AC ²)	9.08	0.067	Quadratic term of AC
Filler Type (Cement = 1)	6.79	0.007	Increases RT Index
Coarse-to-Fine Ratio (C/F)	-21.12	0.029	Reduces RT Index
Model Statistics	SD = 3.70	R ² = 79.26%	Adj. R ² = 72.88%

The predicted R² values based on PRESS were 88.61% for the CT Index model and 62.70% for the RT Index model. The relatively high predicted R² for the CT Index model supports its predictive stability, whereas the lower predicted R² for the RT Index model indicates greater predictive uncertainty associated with the limited sample size. Overall, the regression analysis demonstrates that asphalt content is the dominant variable governing cracking resistance, whereas filler type and aggregate structure are the primary factors influencing rutting resistance.

5.3 Selection of The Threshold Value

5.3.1 Dense-Graded Mixes

Table 11 presents four alternative approaches considered for establishing threshold values for the CT and RT indices in dense-graded mixtures. Alternatives 1 and 2 resulted in relatively low threshold values, which provide less stringent performance screening. Alternative 4, based on the

average value, represents a substantially more restrictive criterion and would result in approximately 50% of the evaluated mixtures falling below the threshold. Therefore, the 25th percentile (P25) was selected as a reasonable intermediate approach for establishing preliminary, dataset-informed performance criteria.

Table 11. Proposed threshold approaches for dense-graded mixtures based on IDEAL-CT and IDEAL-RT results

Threshold	Criterion	CT Index	RT Index
Alternative 1	Minimum value	39	39
Alternative 2	Average value – 1 × standard deviation	46	41
Alternative 3	25 th percentile (P25)	52	44
Alternative 4	Average value	62	50

The selection of P25 was further examined through a sensitivity analysis using P20, P25, and P30 based on the same 18 dense-graded mixture observations. As shown in Table 12, the resulting CT Index values were 48.0, 51.5, and 53.1, respectively, while the corresponding RT Index values were 44.0, 44.25, and 45.1. P25 provides an intermediate criterion between the lower P20 and higher P30 values and was therefore retained as a reasonable percentile-based criterion. This percentile-based approach is also consistent with previous research [45], which used empirical data distributions as a basis for developing performance-related thresholds.

Table 12. Sensitivity analysis of percentile-based performance thresholds

Percentile	CT Index	RT Index
P20	48.0	44.0
P25	51.5	44.25
P30	53.1	45.1

To further quantify the sampling uncertainty associated with the P25 estimates, a nonparametric bootstrap analysis was performed using 10,000 resamples with replacement from the 18 observations. For each resample, the P25 was recalculated, and the bootstrap standard error and percentile-based 95% confidence interval were obtained from the resulting bootstrap distribution. The bootstrap standard errors were 4.17 for CT Index and 1.66 for RT Index, with corresponding 95% confidence intervals of 44.25–61.00 and 41.00–49.25, respectively (Table 13).

Table 13. Bootstrap uncertainty of P25 estimates based on 10,000 resamples

Performance Index	P25	Bootstrap SE	95% Bootstrap CI
CT Index	51.50	4.17	44.25–61.00
RT Index	44.25	1.66	41.00–49.25

Accordingly, the proposed criteria of CT Index ≥ 52 and RT Index ≥ 44 are considered preliminary, dataset-informed performance criteria for the investigated dense-graded mixture population. They are not intended to represent universal field-performance limits, and their broader applicability should be further evaluated using larger and independent datasets incorporating field performance and distress observations.

5.3.2 SMA Mixtures

SMA mixtures are widely recognized for their excellent rutting resistance in field applications; however, the RT Index values obtained in this study were consistently lower than those of dense-graded mixtures, as shown in Table 14.

Table 14. IDEAL-CT and IDEAL-RT test results of SMA mixes

Filler Type	CT Index	RT Index
Limestone Dust	324	28
Cement	296	30

This observation is consistent with previous studies [46,47], in which SMA mixtures exhibited relatively low RT Index values despite demonstrating excellent rutting resistance in the Hamburg Wheel Tracking Test (HWTT). This discrepancy can be explained by the loading configuration of the IDEAL-RT test. Unlike dense-graded mixtures, the rutting resistance of SMA is primarily provided by its stone-on-stone aggregate skeleton, whereas the IDEAL-RT test applies unconfined shear loading that does not provide the lateral confinement required to fully mobilize this structural mechanism. Consequently, the test tends to underestimate the rutting resistance of SMA mixtures while adequately evaluating conventional dense-graded mixtures.

Therefore, applying a unified RT Index threshold developed for dense-graded mixtures ($P_{25} = 44$) to SMA mixtures may lead to misleading acceptance decisions and the unnecessary rejection of mixtures that are known to perform well in the field. Accordingly, a separate performance criterion should be established for SMA mixtures, preferably through calibration against field performance or simulative rutting tests such as the HWTT.

Conversely, SMA mixtures exhibited exceptionally high cracking resistance, with CT Index values ranging from 296 to 324. This superior performance is attributed to the combined effect of the stone-on-stone aggregate skeleton, rich asphalt mortar, and stabilizing fibers, which collectively enhance fracture energy absorption and retard crack propagation. Based on the minimum measured value, a preliminary CT Index threshold of 296 is proposed for SMA mixtures within the scope of this study. This value is intended as a starting point for further investigation and should be validated with a wider range of SMA mixtures.

5.4 Mid-Term Aging IDEAL-CT Criteria

To evaluate the influence of laboratory mid-term aging on cracking performance, the reduction in CT Index was quantified relative to short-term aging conditions. A total of six dense-graded mixtures and two SMA mixtures were included in the analysis. As shown in Table 15, all mixtures exhibited a reduction in CT Index after mid-term aging, although the magnitude of reduction varied depending on mixture type. Dense-graded mixtures showed an average CT Index retention factor of approximately 0.48, whereas SMA mixtures exhibited a higher CT Index retention factor of approximately 0.65, indicating lower aging susceptibility due to their stone-on-stone aggregate skeleton and rich asphalt mortar.

Based on these findings, preliminary mid-term aging criteria for dense-graded and SMA mixtures were estimated by combining the CT Index retention factors with the previously proposed short-term aging performance thresholds.

Table 15. IDEAL-CT results after mid-term aging

Mixture Type	Short-Term Aging CT Index	Average CT Index retention Factors	Standard Deviation	Proposed CT Index retention Factors	Mid-Term Aging CT Index
Dense-Graded	52	0.48	0.03	0.45	23
SMA	296	0.65	0.00	0.65	192

The results demonstrate that mixtures satisfying the proposed short-term aging performance criteria may experience a substantial reduction in cracking resistance after aging. Therefore, incorporating laboratory mid-term aging into the BMD framework provides a more realistic assessment of long-term cracking performance than relying solely on short-term aging test results. Based on the observed performance retention, preliminary minimum mid-term aging CT Index criteria of 23 for dense-graded mixtures and 192 for SMA mixtures are proposed under the adopted laboratory aging protocol.

5.5 Field Case Study and Preliminary Demonstration of Applicability

To validate the proposed Balanced Mix Design (BMD) framework under practical conditions, field cores and loose asphalt mixtures were collected from two roadway sections located west of Baghdad. The pavements consisted of 6-cm asphalt concrete wearing courses constructed over a newly constructed binder course. Field cores (150 mm diameter and 60 mm height) were extracted

after opening the roads to traffic and tested using the IDEAL-CT and IDEAL-RT procedures. In addition, loose mixtures were collected during paving operations for laboratory performance evaluation. The two sections were intentionally selected to represent contrasting field behaviors: one with relatively lower rutting resistance (S2) and one with satisfactory performance (AS-1/1). Fig. 7 illustrates the field construction activities, including asphalt placement, compaction, and coring operations for Site S2.

Although both field mixtures satisfied the proposed cracking criterion (CT Index ≥ 52), mixture S2 produced an RT Index of only 39, which is below the proposed minimum threshold of 44 (Table 16).



(A) Placement



(B) Compaction



(C) Extraction of field cores

Fig. 7. Field implementation of the case study, including asphalt placement, compaction, and coring operations for Site S2

Table 16. Field locations and corresponding CT and RT Index results

Field Code	Location	CT Index	RT Index
S2	33°19'07.0"N, 44°14'17.2"E	123	39
AS-1/1	33°19'04.9" N, 43°52'47.0"E	84	45

To further investigate the performance deficiency of mixture S2, the BMD approach was applied using the actual plant-produced gradation. The combined aggregate gradation obtained from extracted field samples showed close agreement with the approved Job Mix Formula (JMF), indicating that plant production remained within the specified gradation limits, as illustrated in Fig. 8 and Table 17.

Table 17. Strength and volumetric properties of the evaluated field mixture

Volumetric Parameters	Asphalt content (%)	OAC (%)	Marshall stability (kN)	Marshall flow (mm)	Marshall density (gm/cm ³)	Theoretical maximum specific gravity	Air void (%)
Results	4.99	4.9	8.67	3.5	2.268	2.380	4.7

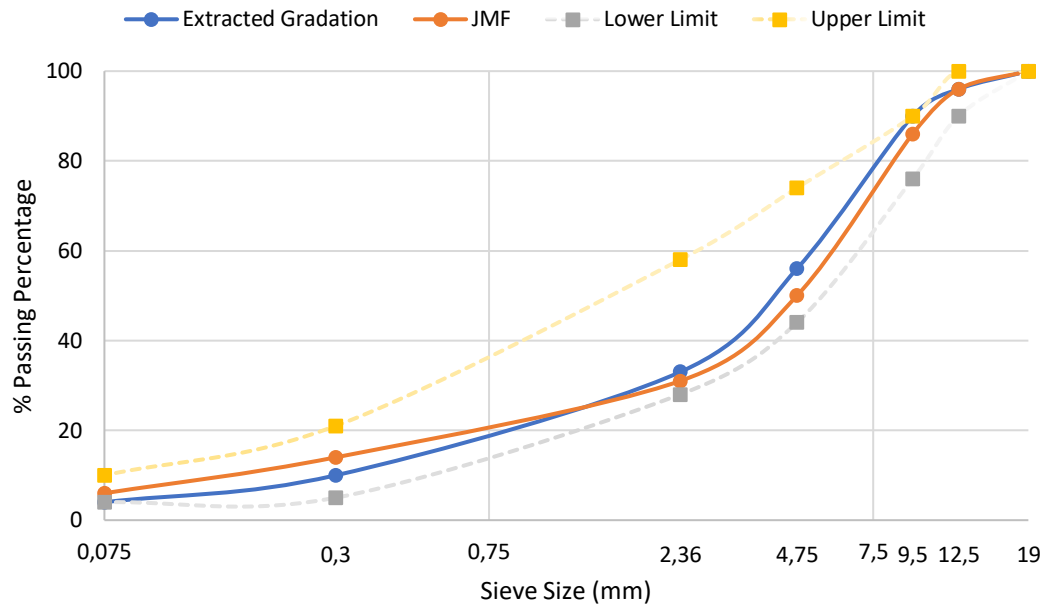


Fig. 8. Aggregates gradation for field code S2

Despite the satisfactory volumetric and Marshall properties shown in Table 17, the RT Index remained below the proposed acceptance threshold. This finding confirms that compliance with conventional volumetric specifications alone does not necessarily ensure balanced field performance and supports the use of IDEAL-CT and IDEAL-RT as complementary performance indicators during mixture design and quality control.

5.5.1. Selected Performance-Based Binder Content

The asphalt content was varied at three levels (OAC, OAC – 0.3%, and OAC + 0.3%) to evaluate its influence on cracking and rutting performance. Loose mixtures with a nominal maximum aggregate size (NMAS) of 12.5 mm were short-term aged at 135 °C for 2 h prior to specimen compaction for IDEAL-CT and IDEAL-RT testing. For each binder content, six specimens were prepared at a target air void level of $7 \pm 0.5\%$, including three specimens for IDEAL-CT testing and three specimens for IDEAL-RT testing. The resulting CT and RT Index values are presented in Figs. 9 and 10, respectively.

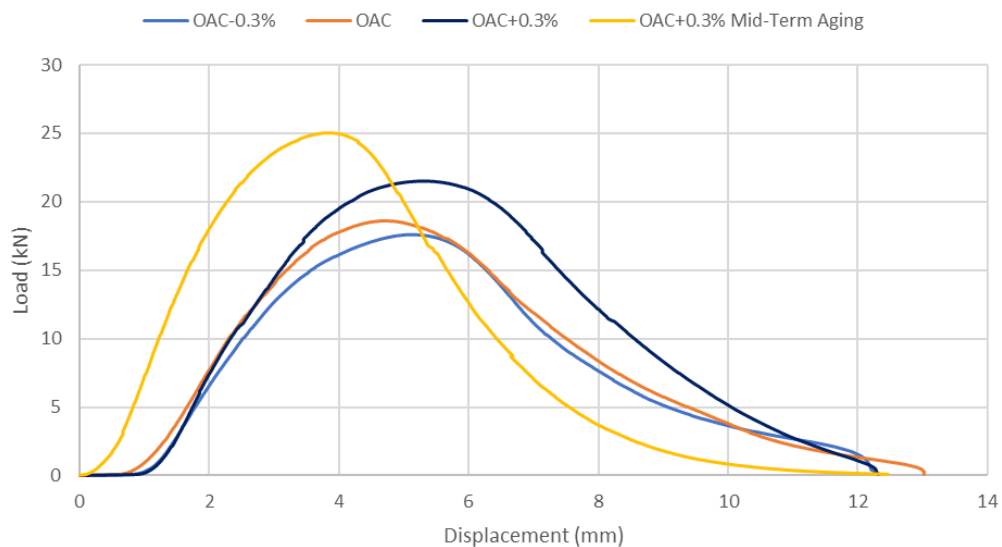


Fig. 9. Load-displacement curves from IDEAL-CT testing at different asphalt binder contents and after mid-term aging

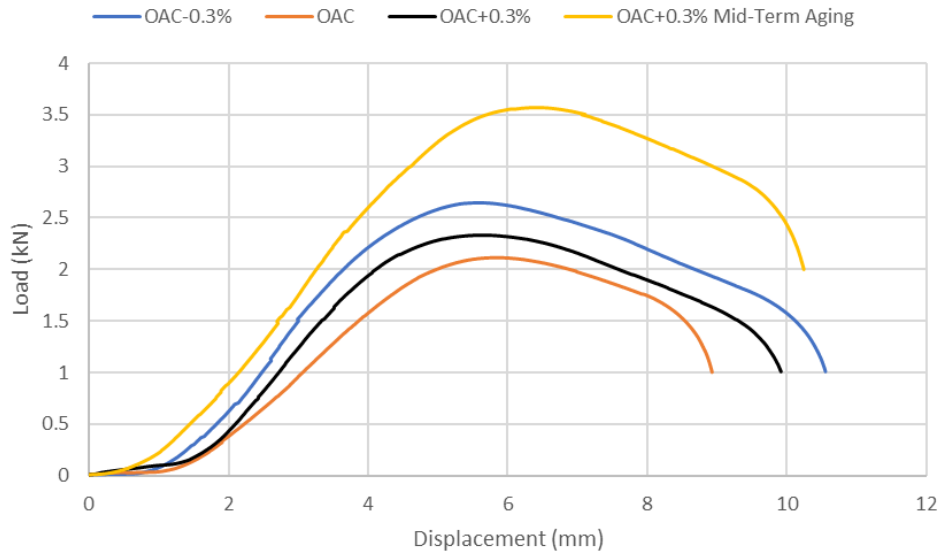


Fig. 10. Load–displacement curves from IDEAL-RT testing at different asphalt binder contents and after mid-term aging

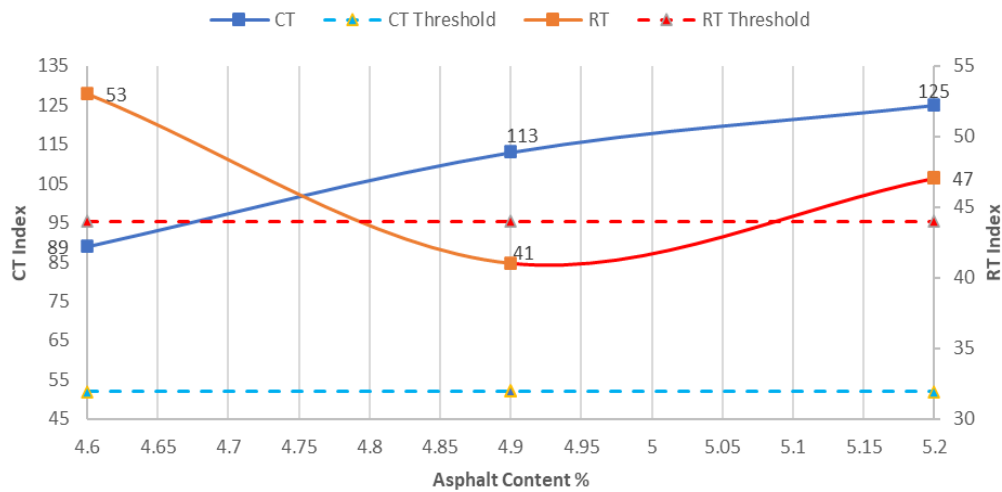


Fig. 11. Balanced performance zone based on CT and RT Index criteria

Based on the proposed IDEAL performance criteria ($CT\ Index \geq 52$ and $RT\ Index \geq 44$), a balanced performance zone was established, as illustrated in Fig. 11. The balanced zone corresponded to asphalt contents ranging approximately from 4.6–4.8% and 5.1–5.2%, within which the mixture satisfied both cracking and rutting requirements. Considering that asphalt mixtures may become either dryer or finer, selecting the binder content near the upper limit of the balanced zone provides a more conservative design approach [31]. Accordingly, an asphalt content of 5.2% was selected for the subsequent performance verification stage.

5.5.2. Performance Verification

After determining the selected performance-based binder content (5.2%) based on mixture performance, the designed mixture was further evaluated to verify its cracking and rutting resistance under mid-term aging conditions. The IDEAL-CT specimens subjected to mid-term aging were tested at 25 °C in accordance with ASTM D8225. The average CT Index of the aged specimens was 60, compared with 125 under short-term aging conditions. Accordingly, the ratio between mid- and short-term aging CT Index values was 0.48 (60/125), which exceeds the proposed minimum acceptance criterion of 0.45.

The RT Index after mid-term aging was 76, while the corresponding value under short-term aging was 47, indicating a significant improvement in rutting resistance due to aging-induced stiffening of the binder. These results confirm that the selected binder content (5.2%) satisfies the proposed

cracking and rutting performance requirements after aging. Based on these findings, the next stage involved developing a QC/QA testing framework and corresponding acceptance criteria for plant production.

5.5.3 Development of QC/QA Testing Plan and Acceptance Criteria

A QC/QA framework was developed based on the performance characteristics corresponding to the balanced asphalt content obtained through the BMD process. The acceptance criteria were established using IDEAL-CT and IDEAL-RT indices to ensure adequate cracking and rutting resistance during production. Two approaches may be adopted to define the acceptance criteria. The first is the general threshold approach, where acceptance is based on the minimum specification limits established during mixture design. In the present study, these limits were defined as:

- CT Index ≥ 52
- RT Index ≥ 44

Accordingly, any production mixture satisfying these criteria may be considered acceptable for field application. The second approach is the mix-specific performance approach, in which the acceptance values are derived from the actual performance corresponding to the balanced asphalt content obtained from the BMD analysis. In the present case study, the CT and RT Index values at the balanced binder content were 125 and 47, respectively. Comparison between the threshold criteria and the mix-specific performance values indicates that the designed mixture provides substantially higher cracking resistance than the minimum required limit, while maintaining acceptable rutting resistance.

Considering the variability associated with plant production and field compaction, the general threshold values (CT Index ≥ 52 and RT Index ≥ 44) are recommended as practical QC/QA acceptance criteria. Meanwhile, the mix-specific values may serve as reference indicators representing the optimum expected performance of the designed mixture.

5.5.4 QC/QA Verification Using Plant-Produced Loose Mix

To validate the proposed QC/QA framework, a loose asphalt mixture sample was collected directly from the asphalt plant after establishing the balanced asphalt content through the BMD procedure. The sampled mixture was conditioned and tested in the laboratory using the IDEAL-CT and IDEAL-RT methods at a target air void level of $7 \pm 0.5\%$. As shown in Table 18, the plant-produced mixture exhibited a CT Index of 135 compared with 125 from the BMD performance evaluation, representing an 8.0% difference. The RT Index was 46 for the plant-produced mixture compared with 47 from the BMD evaluation, representing a 2.1% difference. These results indicate close agreement between the BMD performance evaluation and plant-produced mixture results. The proposed threshold criteria were therefore applicable to plant-level QC/QA verification.

Table 18. QC/QA acceptance criteria and corresponding plant verification results

QC/QA Parameters	Acceptance Criteria	BMD Performance Value	Plant QC/QA result
CT Index	52	125	135
RT Index	44	47	46

Overall, the case study demonstrates that mixtures designed solely using conventional volumetric methods may not always achieve balanced performance. The results suggest that incorporating IDEAL-CT and IDEAL-RT into mixture design can provide additional performance information beyond conventional volumetric criteria. The selected performance-based binder content determined through performance evaluation was 5.2%, compared with 4.9% obtained using the conventional volumetric mix design method.

6. Summary and Conclusions

This study established a performance-based BMD framework using IDEAL-CT and IDEAL-RT tests to evaluate asphalt mixture cracking and rutting resistance. Based on the experimental results, the following conclusions are drawn:

- Combined CT Index and RT Index evaluation successfully captured the balance between cracking resistance and rutting resistance, supporting the implementation of the BMD concept.
- Increasing asphalt content improved CT Index, whereas RT Index followed a U-shaped relationship with asphalt content, demonstrating that the effect of binder content on rutting resistance was nonlinear.
- For the materials investigated, preliminary performance thresholds of CT Index ≥ 52 and RT Index ≥ 44 were established for dense-graded mixtures using the 25th percentile (P25) approach. Sensitivity analysis using P20, P25, and P30 confirmed that P25 provided an intermediate criterion. Bootstrap analysis based on 10,000 resamples further quantified the sampling uncertainty of the P25 estimates.
- The regression analysis showed that the CT model provided a strong fit to the experimental data ($R^2 = 92.96\%$), while the RT model captured the observed nonlinear relationship with an R^2 of 79.26%. Asphalt content was the dominant variable governing cracking resistance, whereas filler type and aggregate structure were the primary factors influencing rutting resistance.
- SMA mixtures exhibited much higher cracking resistance than dense-graded mixtures. A preliminary CT Index threshold of 296 is suggested, whereas no RT Index threshold is recommended because the unconfined IDEAL-RT configuration does not adequately represent the stone-on-stone behavior of SMA mixtures.
- Mid-term aging reduced CT Index for all mixtures, with average CT Index retention factors of 0.48 for dense-graded mixtures and 0.65 for SMA mixtures, indicating greater aging resistance of SMA. The results demonstrate the importance of considering aging effects when evaluating cracking resistance within a performance-based mixture design framework.
- Field application provided a preliminary demonstration of the applicability of the proposed thresholds and the BMD-based QC/QA framework in identifying mixtures with inadequate rutting performance despite satisfying conventional volumetric specifications. The plant-produced mixture showed close agreement with the BMD performance evaluation, with differences of 8.0% for CT Index and 2.1% for RT Index.

Overall, the proposed framework integrates performance testing, statistical threshold development, aging evaluation, and field application into a practical methodology for implementing Balanced Mix Design. The proposed criteria should be considered preliminary and specific to the materials and conditions investigated, and further validation using larger and independent datasets is required before broader application.

7. Limitations and Future Research

This study has several limitations that should be considered when interpreting the proposed framework. First, only one asphalt binder source (Doura Refinery) and two aggregate sources from Iraq were used. Although this material selection provided consistency in material properties and controlled evaluation of the investigated mixture variables, it limits the generalizability of the proposed performance thresholds to other binder sources, aggregate types, and regions. Second, the relatively limited number of mixtures used for threshold development means that the proposed CT and RT criteria should be considered preliminary and require further validation using larger and independent datasets.

In addition, IDEAL-RT may underestimate the rutting resistance of SMA mixtures because of its unconfined loading configuration. Since no HWTT results were available in the present study, future research should investigate this behavior through calibration against HWTT results.

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