Civil Engineering Beyond Limits 2 (2026) 11127
Civil Engineering Beyond Limits
journal home: www.acapublishing.com/journals/1/cebel

Research Article

Multicriteria Evaluation of SBS–WMA Modified Bitumen Using the CRITIC-Based Performance Index

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Keywords

SBS,
CRITIC method,
Warm mix asphalt,
Temperature susceptibility,
Binder Performance Index.

Abstract

In this study, B 70/100 penetration grade bitumen obtained from Batman Refinery was modified using styrene-butadiene-styrene (SBS) polymer (3–5%) and warm mix asphalt (WMA) additives (1–3%) to evaluate the changes in physical properties and temperature sensitivity under cold climate conditions. The modified binders were characterized by penetration, softening point, and flash point tests; and the penetration index (PI) was calculated to represent temperature sensitivity. A 3×3 factorial experimental design was applied in the study; the effects of SBS and WMA additives were analyzed using a two-factor ANOVA method based on variance decomposition. The findings show that the variation in binder properties is largely controlled by the WMA dosage, while SBS provides a secondary but significant contribution. In order to develop a multi-criteria evaluation approach; Softening point, penetration index, flash point, and penetration parameters were combined into a single performance indicator using an objective weighting method, creating the criteria importance through intercriteria correlation (CRITIC)-based Binder Performance Index (BPI_{CRITIC}). Analysis results revealed that flash point had the highest independent information content among the evaluated parameters. According to performance ranking, the combination of 5% SBS and 1% WMA provided the most balanced performance in terms of hardness, temperature sensitivity, and processability criteria. Conversely, higher WMA content, especially at lower polymer ratios, was found to reduce the positive effects of SBS. It should be noted that, since each experimental combination is represented by a single measurement, the findings should be evaluated at a comparative laboratory scale for unaged binders. In conclusion, the proposed BPI_{CRITIC} approach offers a practical and systematic decision support tool that can be used in pre-binder optimization for coating systems to be applied in cold climates.

1. Introduction

Bituminous binders are one of the key components that play a decisive role in the performance and long-term durability of asphalt pavements. Traditional penetration-grade binders, such as B 70/100, exhibit a high degree of sensitivity to temperature variations in their rheological and thermal behavior. Inadequate binder performance, particularly in cold climates, can lead to premature pavement deterioration, such as permanent deformation (running) at high temperatures and thermal cracking at low temperatures. In this context, reducing the temperature sensitivity of bitumen and improving its viscoelastic properties has become a priority research and development area in road engineering applications (1).

Polymer modification, particularly modification using styrene-butadiene-styrene (SBS), is widely accepted as one of the most effective methods for increasing the elasticity, stiffness, and temperature resistance of bituminous binders. Thanks to their elastomeric network structure, SBS-modified binders exhibit higher resistance to deformation at high temperatures, improved fatigue performance, and reduced sensitivity at low temperatures. However, an increase in the polymer ratio also increases the viscosity of the binder. This can lead to increased mixing, laying, and compaction temperatures, potentially negatively impacting workability during the construction process (1–4).

In recent years, warm mix asphalt (WMA) technologies have attracted widespread attention due to their environmental and economic advantages. WMA additives enable asphalt mixes to be produced and compacted at lower temperatures, reducing energy consumption and greenhouse gas emissions, while also increasing the efficiency of the construction process. Furthermore, WMA technologies can improve compaction performance, particularly in cold climates. However, the viscosity-reducing effect of WMA additives, when considered in conjunction with polymer modification, can lead to complex interactions; this can result in significant changes in the stiffness and thermal behavior of the binder (5,6).

Although styrene-butadiene-styrene (SBS) and WMA technologies have been studied extensively individually, the combined effect of these two modifiers on the physical and thermal properties of bitumen remains an important area of research. The interaction of these two components can lead to nonlinear and mutually dependent changes in fundamental binder parameters such as penetration, softening point, flash point, and temperature sensitivity. In this context, the penetration index (PI), which considers both penetration and softening point values together, is an important and widely used indicator in evaluating the temperature sensitivity of the binder (7).

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Received 25 Feb 2026; Revised 08 Mar 2026; Accepted 08 Mar 2026
https://doi.org/10.36937/cebel.2026.11127

The climatic conditions of Eastern Anatolia, characterized by low winter temperatures and high seasonal temperature variations, necessitate the use of bituminous binders with high thermal stability and low temperature sensitivity. The bitumens commonly preferred in the region and produced by the Batman Refinery may exhibit performance limitations under these challenging environmental conditions, particularly when the asphaltene phase stability is not optimal. In this context, investigating the modification of this binder with SBS and WMA additives is considered a crucial requirement for improving the performance of regional road pavements (8–10).

The aim of this study is to investigate the effects of SBS polymer and hot-mix asphalt (WMA) additives on the physical properties and temperature sensitivity of B 70/100 penetration grade bitumen obtained from the Batman Refinery. In this context, modified binders were prepared using a high-shear mixer with different SBS ratios (3–5%) and WMA dosages (1–3%). Penetration, softening point, and flash point tests were performed on the prepared binders; and the PI was calculated based on the experimental data obtained. PI is one of the fundamental parameters representing the temperature sensitivity and rheological behavior of the binder. Higher PI values indicate lower temperature sensitivity and more elastic behavior, while lower PI values indicate a more viscous and temperature-sensitive behavior (11).

Experimental data were analyzed using factorial analysis of variance (ANOVA) to evaluate the main and interaction effects of SBS and WMA additives. Furthermore, a CRITIC-based Binder Performance Index BPI_{CRITIC} was developed to enable multi-criteria evaluation of binder performance. In this context, softening point, penetration index, flash point, and penetration parameters were normalized according to an objective weighting approach and combined into a single performance indicator. The CRITIC analysis revealed that the flash point, representing thermal stability, had the highest independent information content among the evaluated parameters. In addition, a response surface analysis based on a second-order polynomial model was applied to visualize the combined effects of SBS and WMA additives and to determine the optimum modification region. This analysis revealed a nonlinear interaction between SBS content and WMA dosage on the binder performance index, enabling the determination of the most suitable modifier combination. The findings provide a practical and systematic framework for the optimum design of SBS–WMA modified binders in cold climate regions. This provides significant contributions in terms of increasing coating durability, reducing temperature sensitivity, and improving construction efficiency.

2. Testing Process

2.1. Base binder

The primary binder used in this study is conventional B 70/100 penetration grade bitumen supplied by Batman Refinery. This binder is widely used in the Eastern Anatolia region and exhibits moderate temperature sensitivity under cold climatic conditions.

The fundamental properties of the base bitumen were determined in accordance with European standards and are presented below:

- Penetration (25°C): 74.7 dmm (EN 1426)
- Soft Point (Ring-and-Ball): 50.8°C (EN 1427)
- Flash Point: 282°C (EN ISO 2592)

These values indicate that the binder satisfies the requirements of the 70/100 penetration grade bitumen.

2.2. SBS polymer modifier

In this study, a linear-structured styrene–butadiene–styrene (SBS) polymer was used as the elastomeric modifier. SBS modification forms an elastomeric network within the bitumen matrix, thereby enhancing the elasticity, stiffness, and temperature resistance of the binder.

The SBS additive was incorporated into the bitumen at three different dosages by weight:

- %3
- %4
- %5

2.3. Warm Mix Asphalt (WMA) additive

To improve the workability of the bitumen and to reduce mixing and compaction temperatures, a commercial WMA additive was used. The additive was incorporated into the bitumen at the following dosages:

- %1
- %2
- %3

Modified binders were prepared using a high-shear force mixer to ensure homogeneous distribution of SBS within the bitumen matrix. The procedure followed was as follows:

2.4. Binder preparation procedure

The modified binders were prepared using a high-shear mixer to ensure the homogeneous dispersion of SBS within the bitumen matrix. The procedure applied is as follows:

- The base bitumen was heated to 170–180°C until it reached a fluid state.
- The required amount of SBS polymer was gradually added into the hot bitumen.
- The mixture was blended using a high-shear mixer at 4000–5000 rpm for 60 minutes.
- After SBS modification, the WMA additive was introduced at the specified dosage and the blending process was continued for an additional 10–15 minutes.
- The prepared modified binders were stored in airtight containers prior to testing.

Within this scope, nine different SBS–WMA combinations and one control (unmodified) bitumen were prepared.

2.5. Experimental design

A full factorial experimental design (3 × 3) was employed to investigate the combined effects of SBS and WMA additives on binder properties.

➢ Independent variables:

- Factor A (SBS content): 3%, 4%, 5%
- Factor B (WMA dosage): 1%, 2%, 3%

As a result of this design, nine different binder combinations were obtained (Table 1). A control sample (0% SBS, 0% WMA) was used for reference purposes but was not included in the statistical analyses.

Table 1. Experimental matrix

Mix ID	SBS Content (%)	WMA Dosage (%)
M1	3	1
M2	3	2
M3	3	3
M4	4	1
M5	4	2
M6	4	3
M7	5	1
M8	5	2
M9	5	3

Control Binder: 0% SBS – 0% WMA (used only for comparison, not included in statistical modeling).

2.6. Test methods

The physical and thermal properties of the binders were determined using the following standard tests:

- Penetration Test (EN 1426)

Conducted at 25°C to evaluate the consistency and hardness of the binder.
- Softening Point Test (EN 1427)

The Ring-and-Ball method was used to assess the high-temperature performance and deformation resistance of the binder.
- Flash Point Test (EN ISO 2592)

The Cleveland open cup method was employed to evaluate the production and application safety of the binder.

2.7. Penetration Index (PI)

The PI was calculated from penetration and softening point values using the Pfeiffer and Van Doormaal relationship. The PI value was used as an important parameter representing the temperature sensitivity and viscoelastic behavior of the binder (11).

$$PI = \frac{1952 - 500. \quad \log(Pen_{25}) - 20. T_{R\&B}}{50. \log(Pen_{25}) - T_{R\&B} + 120} \tag{1}$$

Pen_{25} = Penetration value of the bitumen at 25 °C

$T_{R\&B}$ = Softening Point (Ring & Ball)

2.8. Statistical and optimization analysis

To evaluate the effects of SBS and WMA additives on the binder properties, the following analyses were performed:

2.8.1. Factorial ANOVA analysis

Since each experimental combination involved a single measure, a two-factor ANOVA without repeated measures was applied, and the results were interpreted according to the contribution ratios of the sum of squares. Through this analysis, the contributions of SBS, WMA, and their interaction effects to the binding properties were determined (12).

2.8.2. CRITIC-Based Binder Performance Index (BPI_{CRITIC})

To evaluate the binding performance in a multi-criteria framework, a composite performance index was developed using the criteria importance through inter-criteria correlation (CRITIC) method (13). Within the CRITIC approach, the information content of each criterion was calculated by considering both its standard deviation and the correlation structure between the criteria, and these values were normalized to obtain the criterion weights. The resulting weights were then used as coefficients in the calculation of the binding performance index.

➢ **Data Normalization**

Each criterion was scaled to the range of 0–1 as follows:

$$x_{ij}^{norm} = \frac{x_{ij} - \min(x_j)}{\max(X_j - \min(X_j)} \quad (2)$$

➢ **Standard Deviation (σj)**

The variability of each criterion:

$$\sigma_j = std(X_j^{norm} \quad (3)$$

➢ **Correlation Matrix (rjk)**

Interrelationships among the criteria:

$$r_{jk} = corr(X_i, X_k \quad (4)$$

➢ **Information Content (Cj)**

$$C_j = \sigma_j \sum_{k=1}^{m} (1 - r_{jk} \quad (5)$$

➢ Final Weights (wj)

$$w_j = \frac{C_j}{\sum C_j} \quad (6)$$

i=1,2,3,...,n : number of observations/experiments (SBS–WMA combinations)

j=1,2,3,...,m_j = 1, 2, 3, \ldots, m_j=1,2,3,...,m : number of criteria (SP, PI, FP, Pen)

k=1,2,3,...,m_k = 1, 2, 3, \ldots, m_k=1,2,3,...,m : index of the other criteria

X_{ij} =original value of criterion j for observation i

Within this framework, the following parameters were used:

- **Softening Point (SP):** High-temperature stiffness and rutting resistance
- **Penetration Index (PI):** Temperature susceptibility and viscoelastic behavior
- **Flash Point (FP):** Thermal stability and safe production temperature
- **Penetration (Pen):** Hardness/consistency level of the binder

The parameters were normalized, and objective weights were calculated using the CRITIC method. The resulting BPI_{CRITIC} was defined as follows:

$BPI_{CRITIC}=0.222.SP_n+0.162.PI_n+0.436.FP_n+0.180.Pen_n$

The index in question was used to evaluate the performance of bitumen in a holistic approach within the framework of thermal stability, hardness, and temperature sensitivity parameters. A response surface analysis based on a second-order polynomial model was applied to examine the combined nonlinear effects of SBS and WMA additives on binder performance and to determine the optimum modification region. The developed model represents the change in the performance index in a continuous surface form, taking into account the SBS content, WMA dosage, and the interaction term between these two variables. Thus, it was possible to determine the optimum SBS–WMA combination in a systematic and analytical manner.

3. Results

The experimental results presented in Table 1 are summarized in the table below. Penetration tests were performed according to EN 1426, softening point (Ring and Ball) tests according to EN 1427, and flash point tests according to EN ISO 2592 (Cleveland open cup method). The PI was calculated using the Pfeiffer and Van Doormaal relationship based on the penetration and softening point values (Table 2).

Table 2. Experimental program and measured physical properties of SBS–WMA modified binders

Sample ID	SBS (%)	WMA (%)	Penetration (0.1 mm) *(EN 1426)*	Softening Point (°C) *(EN 1427)*	Flash Point (°C) *(EN ISO 2592)*	PI *(Pfeiffer & Van Doormaal)*
Control	0	0	74.7	50.8	282	0.01
M1	3	1	57.7	66.7	250	2.95
M2	3	2	80.0	55.2	250	0.30
M3	3	3	79.3	53.4	234	-0.04
M4	4	1	66.1	67.3	236	2.71
M5	4	2	77.4	57.1	240	0.47
M6	4	3	83.5	54.8	230	-0.20
M7	5	1	60.2	69.5	238	3.10
M8	5	2	72.8	60.3	235	1.20
M9	5	3	85.4	56.1	228	-0.50

To quantitatively determine the individual and combined effects of SBS and WMA additives on binding properties, a two-factor analysis of variance (ANOVA) was applied for each response variable. The total variance was decomposed into SBS, WMA, and interaction components using a sum of squares approach. Table 3 presents the relative contribution rates (%) of each factor for softening point, penetration, penetration index (PI), and flash point. These results allow for the identification of the dominant parameters driving binding behavior and the comparison of the relative importance of the modification variables.

Table 3. Two-way ANOVA results and percentage contribution of SBS, WMA and their interaction on binder properties

Response Variable	Source	df	Sum of Squares	Mean Square	Contribution (%)
Softening Point	SBS	2	60.2	30.10	24.8
	WMA	2	153.7	76.87	63.4
	SBS × WMA	4	28.6	7.15	11.8
Penetration	SBS	2	130.4	65.21	17.0
	WMA	2	373.4	186.70	48.7
	SBS × WMA	4	263.3	65.83	34.3
PI	SBS	2	4.472	2.236	28.2
	WMA	2	10.434	5.217	65.7
	SBS × WMA	4	0.973	0.243	6.1
Flash Point	SBS	2	136.2	68.11	20.6
	WMA	2	281.6	140.78	42.5
	SBS × WMA	4	244.4	61.11	36.9

Figure 1 shows the effects of SBS content and Warm Mix Asphalt (WMA) additive ratio on the penetration index, softening point, penetration, and flash point of bitumen.

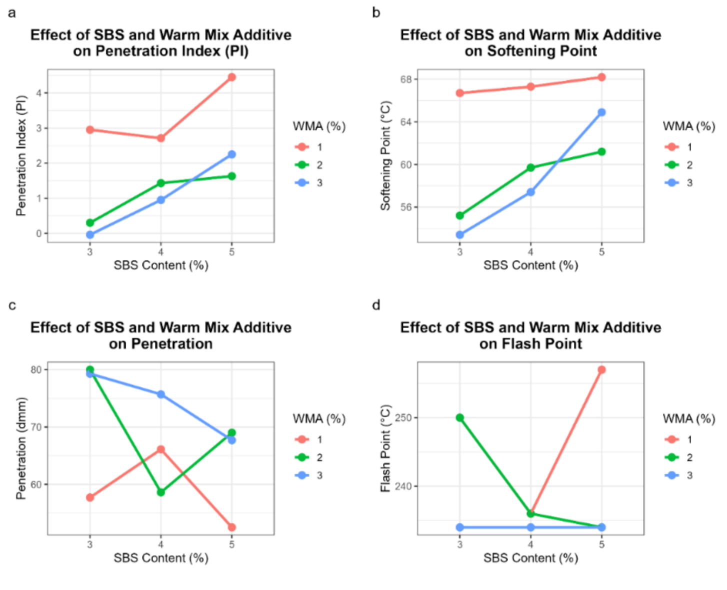

Figure 1. Effect of SBS Content and Warm Mix Additive (WMA) on Bitumen Properties

Table 4. Relative contribution of SBS and WMA on binder properties based on ANOVA (sum-of-squares method)

Response Variable	SBS (%)	WMA (%)	SBS × WMA (%)	Interpretation
Softening Point	24.8	63.4	11.8	WMA dominant, SBS secondary
Penetration	17.0	48.7	34.3	WMA dominant, strong interaction
PI	28.2	65.7	6.1	WMA dominant, low interaction
Flash Point	20.6	42.5	36.9	WMA dominant, strong interaction

Additive analysis reveals that WMA is the dominant factor determining penetration and temperature sensitivity, while SBS plays a secondary but still significant role. The relatively low interaction effect observed for the PI suggests that SBS and WMA influence temperature sensitivity through partially independent mechanisms (Table 4).

➢ **BPI_{CRITIC} – Definition and Physical Interpretation**

In this study, a CRITIC-based BPI_{CRITIC} was developed to evaluate the combined effects of SBS and WMA additives on bitumen performance. Using the objective weights obtained by the CRITIC method, the performance index was defined as follows:

$BPI_{CRITIC}=0.222\ SP_n+0.162\ PI_n+0.436\ FP_n+0.180\ Pen_n$

Where:

- SP_n : normalized softening point
- PI_n : normalized penetration index
- FP_n : normalized flash point
- Pen_n : normalized penetration value (reverse normalized)

Table 5. CRITIC weights and their physical meanings

Parameter	Symbol	Weight (w)	Physical Meaning	Effect on Performance
Softening Point	SP	0.222	High-temperature stiffness and deformation resistance	Positive
Penetration Index	PI	0.162	Temperature susceptibility and viscoelastic behavior	Positive
Flash Point	FP	0.436	Thermal stability and production safety	Positive
Penetration	Pen	0.180	Binder hardness / consistency	Inverse (lower is better)

➢ Physical and Engineering Interpretation

The weights obtained from the CRITIC analysis show that in this study, bitumen performance is most strongly represented by the flash point (FP) (w=0.436)(Table 5). This finding reveals that thermal stability and volatile component behavior in WMA-modified systems constitute a more independent and dominant performance component compared to conventional rheological parameters.

The softening point (w=0.222) was determined as the second most effective parameter, consistent with the known effect of SBS modification in increasing high-temperature hardness. Penetration (w=0.180) and penetration index (w=0.162) contributed to the performance index as complementary parameters representing the consistency and temperature sensitivity of the binder(Table 5).

These results show that SBS primarily improves mechanical performance; while the WMA additive has a significant effect, particularly on thermal and production-related behaviors. Therefore, the developed BPI_{CRITIC} index evaluates bitumen performance holistically, not only in terms of hardness and deformation resistance, but also in terms of production safety and thermal stability. In conclusion, the CRITIC-based performance index revealed that thermal stability (flash point) is the parameter with the highest independent information content in determining bitumen performance. This finding highlights that WMA additive is a critical factor to consider in performance evaluation.

Table 6. Ranking of SBS–WMA modified binders based on the CRITIC-based Binder Performance Index (BPI_{CRITIC})

Sıra	Grup	SBS (%)	WMA (%)	BPI_{CRITIC}	Interpretation
1	M 7	5	1	0.752	Highest performance
2	M 1	3	1	0.585	High performance
3	M 4	4	1	0.560	Balanced performance
4	M 9	5	3	0.512	Upper–moderate performance
5	M 8	5	2	0.487	Moderate performance
6	M 5	4	2	0.442	Moderate performance
7	Control	0	0	0.418	Reference
8	M 6	4	3	0.401	Lower–moderate performance
9	M 2	3	2	0.386	Low performance
10	M 3	3	3	0.350	Lowest

The ranking results obtained with CRITIC-based BPI_{CRITIC} clearly reveal the combined effects of SBS and WMA additives on binder performance. In this analysis, the highest performance was obtained in combination M7 containing 5% SBS and 1% WMA (BPI_{CRITIC} =0.752). This is followed by combinations of 3% SBS–1% WMA (M1) and 4% SBS–1% WMA (M4), respectively; this shows that increasing SBS content with a lower WMA dosage improves binder performance. Moderate performance was observed in groups containing 5% SBS but with increased WMA content (M8 and M9), and it appears that higher WMA doses have a limiting effect on performance. The lower-to-moderate ranking of the control binder (BPI_{CRITIC} =0.418) confirms the overall performance-enhancing effect of the modification. The lowest performance was obtained in M3 (3% SBS–3% WMA); This result reveals that high WMA doses negatively affect performance, especially with low SBS content(Table 6).

In general, the findings clearly show that the best performance is achieved with a combination of high SBS and low WMA content. Figure 2 shows the performance scores obtained according to the multi-criteria performance evaluation of SBS–WMA modified binders. The results reveal that different combinations of SBS and WMA create significant differences in overall binder performance.

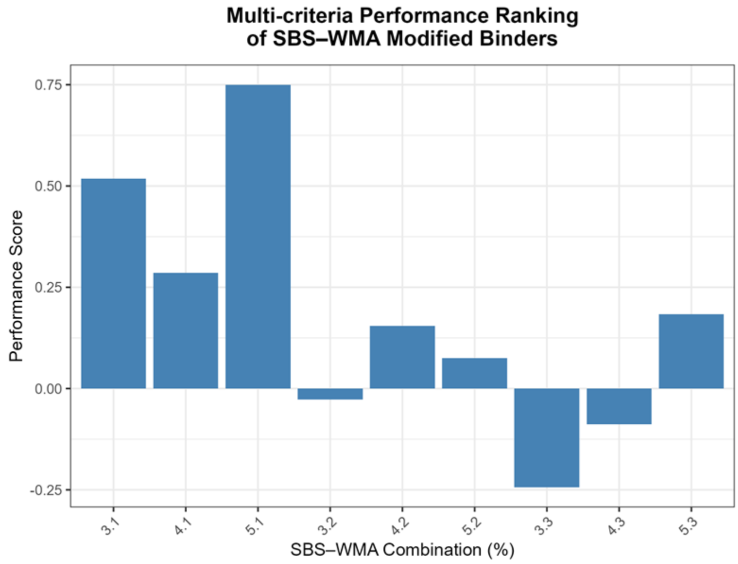

Figure 2. Multi-criteria performance ranking of SBS–WMA modified binders based on the CRITIC-derived Binder Performance Index (BPI_{CRITIC})

Figure 3 shows the change in the BPI_CRITIC performance index as a three-dimensional response surface graph, depending on the combined change of the SBS ratio and the WMA contribution percentage.

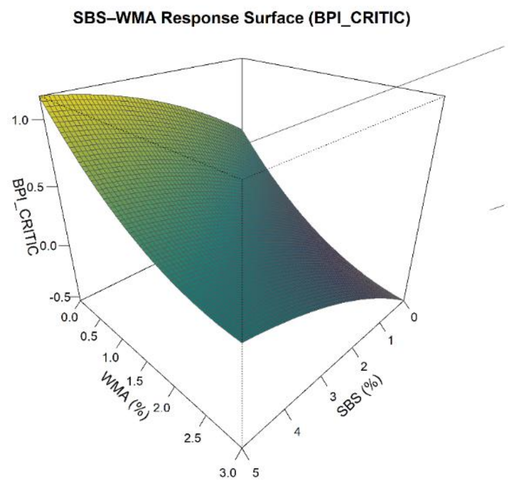

Figure 3. 3D performance ranking of SBS–WMA modified binders using the CRITIC-based Binder Performance Index (BPI_{CRITIC})

4. Discussion

Experimental findings provide a comprehensive assessment of how SBS polymer and WMA additives together affect the thermomechanical behavior of B 70/100 bitumen. Variance decomposition analysis shows that the vast majority of variations in binder properties are dependent on WMA dosage, while SBS provides a secondary but still significant contribution. Two-factor ANOVA results reveal that the largest portion of the total variance for softening point, penetration, PI, and flash point is attributed to the WMA additive. This finding is consistent with previous research demonstrating the significant effect of WMA additives on binder viscosity and temperature sensitivity (5,6).

The observed increase in softening point with increasing SBS content is consistent with literature findings showing that elastomeric polymer modification increases high-temperature stiffness and resistance to permanent deformation. Within the binder matrix, SBS forms an elastomeric network structure that provides resistance to permanent deformation at high temperatures (1,2). However, the addition of WMA additives partially offsets the hardening increase caused by SBS by reducing the viscosity of the binder. At higher WMA doses (2–3%), the hardening effect provided by SBS is significantly reduced. This indicates that the two modifiers act through different and partially balancing mechanisms; SBS increases hardness while WMA reduces viscosity.

The relatively low interaction effect observed for PI suggests that the contributions of SBS and WMA to temperature sensitivity occur largely through independent mechanisms rather than synergistic ones. SBS improves the viscoelastic behavior of the binder towards a more elastic response, while WMA additives reduce viscosity primarily through lubrication and chemical effects. Similar results have been reported in previous studies examining SBS–WMA combinations, notably noting that the hardening effect of SBS weakens at higher WMA doses (14).

A significant outcome of this research is the development of a CRITIC-based Binder Performance Index, BPI_{CRITIC}, for multi-criteria performance evaluation. CRITIC weighting results revealed that flash point (FP) had the highest independent information content among the evaluated parameters. The dominance of flash point indicates that thermal stability and fabrication safety represent the most informative performance dimensions in WMA-modified binders. Softening point, penetration, and PI were included in the index as complementary parameters representing the mechanical and rheological behavior of the binder.

According to the BPI_{CRITIC} ranking results, the optimum modification combination was determined to be 5% SBS and 1% WMA. This modifier combination exhibits balanced performance in terms of hardness, thermal sensitivity, and machinability. In contrast, increasing the WMA content to 3% lowered the performance index, especially at low SBS ratios, indicating that excessive viscosity reduction can negatively affect structural performance. These findings suggest that using SBS modification with low WMA doses is appropriate in cold climate regions such as Eastern Anatolia.

From an applied engineering perspective, the BPI_{CRITIC} framework allows for the analysis of binder performance from a simultaneous multi-criteria perspective instead of a single-parameter evaluation. In this context, the study offers a more comprehensive and applicable performance evaluation method compared to traditional single-parameter approaches.

However, some limitations should also be considered. Firstly, since each experimental combination is represented by a single measurement, the ANOVA results were interpreted based on the contribution ratios of variance rather than statistical significance. Also, only traditional binder tests were applied, and advanced rheological tests (Dynamic Shear Rheometer, Multiple Stress Creep Recovery, Bending Beam Rheometer) were not performed. To expand and validate the proposed index, it is suggested that these advanced rheological tests be included in future studies. In conclusion, this study demonstrates that the combined use of SBS and WMA additives can be optimized using multi-criteria analysis methods, and that the CRITIC-based performance index offers a practical and applicable approach for binder design under cold climate conditions.

5. Conclusions

This study investigated how SBS polymer and WMA additives altered the physical behavior and temperature sensitivity of B 70/100 bitumen obtained from Batman Refinery by combining laboratory tests with statistical and multi-criteria evaluation methods.

The analysis shows that WMA dosage plays a leading role in determining the binder response. Variance-based ANOVA results reveal that the majority of variation in softening point, penetration, penetration index, and flash point is associated with the WMA additive. This finding confirms that WMA's role in reducing viscosity and influencing thermal behavior drives the overall behavior of the modified binders.

Increasing SBS content increased high-temperature hardness and reduced temperature sensitivity. However, this improvement was partially reduced when the WMA dosage exceeded 2–3%, indicating that excessive viscosity reduction may weaken the structural contribution of the polymer network.

The interaction between SBS and WMA is not homogeneous for all parameters. While a strong interaction was observed for penetration and flash point, the interaction for penetration index remained limited; this suggests that the two modifiers influence temperature sensitivity through partially independent mechanisms.

A CRITIC-based BPI_{CRITIC} was developed to combine softening point, penetration, penetration index, and flash point into a single performance metric. The weighting scheme revealed that flash point had the highest independent information content among the evaluated parameters.

As a result of the multi-criteria ranking, the combination of 5% SBS and 1% WMA provides the most balanced performance in terms of hardness, temperature sensitivity, and thermal stability. In contrast, higher WMA contents, especially at low SBS levels, lead to a decrease in overall performance. These findings indicate that SBS modification should be combined with limited WMA dosage to achieve an effective balance between machinability and mechanical performance.

The proposed BPI_{CRITIC} framework offers a practical and objective tool for comparing binder alternatives based on multiple criteria. However, it should be noted that the study was conducted based on unaged binders and single measurements for each experimental combination. Therefore, the results obtained represent comparative laboratory-level findings. In the future, repeated tests and advanced rheological characterization methods (Dynamic Shear Rheometer, Multiple Stress Creep Recovery, Bending Beam Rheometer) should be applied to more reliably and comprehensively validate the proposed performance index.

Nomenclature

Abbreviation: Definition
SBS: Styrene–Butadiene–Styrene
WMA: Warm Mix Asphalt
PI: Penetration Index
SP: Softening Point
FP: Flash Point
BPI: Binder Performance Index
BPI_{CRITIC}: CRITIC-based Binder Performance Index
ANOVA: Analysis of Variance
CRITIC: Criteria Importance Through Intercriteria Correlation

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to Cite This Article

Atalay, A., Öksüz, S., Multicriteria Evaluation of SBS–WMA Modified Bitumen Using the CRITIC-Based Performance Index, Civil Engineering Beyond Limits, 2(2026), 11127.
https://doi.org/10.36937/cebel.2026.11127