

Research Article

Mixture Regression Models for Predicting the Water Absorption and Durability of Styrene-Butadiene-Styrene (SBS) Treated Soybean Oil - Warm Mix Asphalt Concrete

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Abstract

In this study, mixture regression models were developed to predict water absorption, measured by swelling index (SI), and durability, represented by retained stability index (RSI), of warm mix asphalt concrete (WMAC) modified with styrene-butadiene-styrene (SBS) and soybean oil (SO). The experimental design involved partial replacement of bitumen with SBS and SO, while the aggregate composition remained constant. These models were validated using statistical tools, including the Fisher test and R^2 values, to assess their predictive capability. The SI values, ranging from 0.76% to 1.66%, demonstrated a minimal moisture-induced expansion, indicating low susceptibility to water absorption. Meanwhile, the RSI values, spanning from 66.34% to 94.37%, confirmed that the majority of samples satisfied the AASHTO (2019) standards for moisture resistance, indicating strong durability. The incorporation of SBS significantly enhanced moisture resistance, primarily by improving the binder's elasticity and adhesion properties. Notably, the addition of soybean oil did not detract from moisture resistance; instead, it acted synergistically with SBS to improve both performance and workability. The regression models for SI and RSI accounted for 80.56% and 79.14% of the data variance, respectively, and were validated at a 95% confidence level. These results affirm the robustness and reliability of the models for predicting the behavior of SBS-SO-modified WMAC under medium traffic conditions, offering a valuable tool for future asphalt mixture design and performance prediction.

Keywords

Mixture Regression Models, Water Absorption, Durability, Styrene-Butadiene-Styrene, Soybean Oil, Warm Mix Asphalt Concrete

1. Introduction

The development of high-performance asphalt concrete mixtures remains a pivotal focus in modern pavement engineering, particularly as the demand for materials that are durable, cost-effective, and environmentally sustainable intensifies. One prominent advancement in this area is Warm

Mix Asphalt Concrete (WMAC) technology, which enables the production and application of asphalt concrete at lower temperatures compared to traditional Hot Mix Asphalt Concrete (HMAC). This shift not only facilitates energy savings but also significantly reduces the emission of harmful pollu-

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tants during production and application [1] WMAC's ability to be produced at temperatures typically 20-40 °C lower than HMAC leads to reduced fuel consumption and a smaller carbon footprint, thus making it an attractive option for environmentally conscious paving projects [2]. An innovative approach to further enhance the properties of WMAC involves the incorporation of renewable additives, such as soybean oil, which has been found to improve both the workability and the durability of asphalt mixtures. Soybean oil acts as a rejuvenator, helping to restore the binder's viscosity, thus improving its performance in high-temperature conditions and extending the lifespan of the pavement [3]. Furthermore, these renewable additives contribute to reducing the environmental impact of asphalt production by decreasing the reliance on petroleum-based products, making them a critical component in sustainable pavement engineering [4]. The ongoing research into WMAC and the use of renewable additives demonstrates a clear shift toward more sustainable, efficient, and high-performance paving materials, aligning with global trends aimed at minimizing environmental impact while maximizing infrastructure longevity.

Styrene-butadiene-styrene (SBS), a widely used polymer modifier in asphalt concrete mixtures, further improves the performance characteristics of warm mix asphalt concrete (WMAC) by enhancing its mechanical properties and resistance to aging and moisture damage [5]. The elastomeric nature of SBS enhances the flexibility and rutting resistance of asphalt, making it a preferred choice for improving pavement durability [6]. However, the combination of SBS with soybean oil in WMAC formulations has not been thoroughly investigated, particularly in terms of its effect on water absorption and overall durability. Soybean oil, a bio-based additive, has been shown to influence the rheological properties of asphalt binders, potentially affecting resistance to moisture damage and oxidative aging [7]. These two properties are critical for the long-term performance of asphalt concrete pavements, especially in regions with variable weather conditions and frequent exposure to water, where moisture-induced damage can accelerate pavement deterioration [8, 9].

To better understand the relationship between the components in SBS-treated soybean oil WMAC, mixture regression models provide a powerful tool for predicting performance outcomes based on compositional variables. Regression models have been widely used in materials science to predict the behavior of complex systems under varying conditions (Zhao & Li, 2019). In asphalt research, these models enable the evaluation of interactions among multiple modifiers and their influence on mechanical and durability properties [10]. Wang and Liu [11] conducted a study on predicting the dynamic modulus of asphalt mixtures using various regression-based models. The research critically evaluated early models such as the Witczak 1-37A and 1-40D, which rely on asphalt binder viscosity and complex shear modulus, respectively. The study highlighted the evolution of regression

analysis in modeling the mechanical behavior of asphalt mixtures, emphasizing the significance of accurate predictions in pavement design. The findings underscored the role of regression models in optimizing asphalt mixture properties and improving the reliability of predictive modeling. Zhang and Chen [12] proposed an integrated framework combining traditional regression analysis models with machine learning techniques to predict pavement deterioration, particularly focusing on the International Roughness Index (IRI). The study assessed the limitations of conventional regression models, revealing their restricted accuracy when predicting long-term pavement performance. Li and Zhao [13] explored the prediction of asphalt mixture dynamic modulus (E^*) using a combination of regression models and machine learning techniques. The study compared the performance of traditional regression models against advanced machine learning algorithms in forecasting asphalt concrete properties. Nie et al. [14] provided a comprehensive review on multiscale modeling of asphalt, discussing the development and applications of various modeling techniques. They emphasized the importance of regression models at the macroscale for describing the physical and mechanical properties of asphalt, which can be employed to analyze properties and optimize performance. Motlagh and Naghizadehrokhni [15] presented an extended multi-model regression approach for predicting and optimizing the compressive strength of concrete mixtures. They employed a combination of regression methods, including artificial neural networks, random forest regression, and polynomial regression, to enhance prediction accuracy. Although focused on concrete mixtures, their methodology offers valuable insights applicable to asphalt concrete modeling. By incorporating statistical techniques such as response surface methodology (RSM) and machine learning-based regression models, researchers can refine mixture designs to enhance performance while maintaining cost-effectiveness [16]. These models allow for the optimization of asphalt concrete mixtures, ensuring that performance criteria such as water absorption and durability are met without compromising other essential properties such as workability or cost-effectiveness [17]. Additionally, regression-based approaches can help account for environmental factors, such as temperature and moisture fluctuations, that influence long-term pavement performance [18].

Despite the use of mixture regression modeling in predicting the properties of asphalt concrete, there is a limited knowledge on the use of mixture regression modelling for the prediction of the water absorption and durability of styrene-butadiene-styrene (SBS) treated soybean oil (SO) warm mix asphalt concrete (WMAC). This study thus aims to develop and validate mixture regression models to predict the water absorption and durability of SBS-treated soybean oil WMAC, providing insights for optimizing sustainable and high-performance asphalt mixtures and also revealing the complex relationships in the asphalt matrix.

2. Materials and Methods

2.1. Research Design

This research is based on developing mixture regression models for predicting the water absorption in terms of swelling index (SI) and the durability in terms of retained stability index (RSI) of styrene-butadiene-styrene (SBS) treated soybean oil (SO) warm mix asphalt concrete (WMAC). In this research, SO and SBS partially replaced bitumen in the Warm mix asphalt concrete (WMAC) matrix with the aggregate blending remaining constant all through the investigation. Mixture regression models for predicting SI and RSI were developed from information gathered from the experimental procedures. These models were then validated and verified using the Fisher test and R^2 statistics respectively.

2.2. Materials and Equipment

Materials; This study utilizes soybean oil (SO) and styrene-butadiene-styrene (SBS) as the primary materials for producing and modifying warm mix asphalt concrete (WMAC). The coarse aggregate consists of uniformly graded granite with a maximum particle size of 12.5 mm, a specific gravity of 2.77, and a fineness modulus of 4.25. The fine aggregate is uniformly graded river sand, with a specific gravity of 2.43 and a fineness modulus of 3.54. Bitumen of PEN grade 60/70 serves as the binder for coating the aggregates, possessing a specific gravity of 1.09, a softening point of 53 °C, a penetration value of 68, and a flash point of 250 °C.

Equipment; This research utilized various laboratory equipment for accurate material preparation and testing. Aggregate gradation was performed using a set of sieves arranged according to IS: 383-(1970). Weight measurements were taken using a 40 kg sensitive weighing balance for heavy materials and a 5 kg digital balance for lighter samples. The mold assemblage included a 4.5 kg rammer, a 63.5 mm by 100 mm asphalt mold, a mold collar, and a compaction table. A muffle furnace with a 1375 °C heating capacity was used for preheating materials. Additionally, a Universal Strength Testing Machine was employed for Marshall stability and flow testing to assess the mechanical properties of asphalt mixtures.

2.3. Methods

2.3.1. Design of Experiment Formulation

In designing the experiment for SBS-SO WMAC using the mixture theory of extreme vertices, the optimum bitumen content (OBC) of 5.95%, determined from preliminary investigations, was adjusted to incorporate soybean oil (SO) and styrene-butadiene-styrene (SBS). The aggregate composition remained constant throughout the study, with

granite and sand contents fixed at 51.26% and 42.79%, respectively. The SO content was varied between 0-3.5% by weight of the bitumen, while SBS ranged from 0-5% by weight of the bitumen, resulting in an adjusted bitumen content between 5.444% and 5.95%. This adjustment translated to SO comprising 0-0.208% and SBS 0-0.298% of the total WMAC mix by weight. Based on these constraints, the lower and upper bounds for the materials are outlined in Table 1. Using Minitab software, nine different combinations of bitumen, SO, and SBS were generated, as shown in Table 2.

Table 1. Boundary specifics for Extreme vertices design for SBS-SO WMAC.

Constraints	Factors/materials		
	Bitumen (%)	Soybean oil (%)	SBS (%)
Lower bound	5.444	0	0
Upper bound	5.950	0.208	0.298

Table 2. Extreme vertices design for SBS-SO WMAC Production.

RunOrder	Bitumen	S.oil	SBS	Total constituents
1	5.444	0.208	0.298	5.950
2	5.950	0.000	0.000	5.950
3	5.571	0.156	0.224	5.950
4	5.824	0.052	0.075	5.950
5	5.720	0.156	0.075	5.950
6	5.652	0.000	0.298	5.950
7	5.675	0.052	0.224	5.950
8	5.697	0.104	0.149	5.950
9	5.742	0.208	0.000	5.950

2.3.2. Performance Evaluation

(i). WMAC Samples Preparation

In preparing the samples, measured aggregates according to design of experiment was heated to a temperature of 140 °C and measured bitumen (modified) heated to a temperature of 110 °C. The heated aggregates and modified bitumen were thoroughly mixed at a temperature of 120 °C until a homogeneous mix was obtained. The homogeneous mix was placed in a preheated mould and compacted by a rammer with 50 blows (considering the medium traffic category) on each side at a temperature between 110 °C. The modifiers (SBS and SO) were added to the mix by adding them during the heating

process of the bitumen before combination with pre-heated aggregates.

(ii). Marshall Stability Test of WMAC Samples

The Marshall Stability test was carried out in accordance to ASTM D1559 (1989). The stability of a test specimen is the maximum load required to produce failure when the specimen is preheated to a prescribed temperature placed in a special test head and the load is applied at a constant strain (50.8 mm per minute).

(iii). Swelling Index of WMAC Samples

Swelling index (SI) of produced WMA samples were measured in accordance to Equation (1) as given by Igwe and Ottos [19]. This measurement was done after submerging the samples in water for of 24 hours at a constant temperature of 60 °C.

$$SI = \frac{V_2 - V_1}{V_1} \times 100 \quad (1)$$

Where; V_1 = Volume of sample before submergence

V_2 = Volume of sample after submergence

In this study, the volume for this analysis was computed in terms of specific volume as given by Equation (2).

$$V = \frac{W_a}{\left[\frac{W_a - W_w}{W_a} \right] \times 1000} \quad (2)$$

Where; W_a = Weight of WMAC sample in air

W_w = Weight of WMAC sample in water

(iv). Retained Stability Index of WMAC Samples

Retained strength index (RSI) was computed in accordance to Equation (3) according to Ali [20] after 24 hours of submergence in water of 60 °C to determine or check the change in stability of WMAC mixtures.

$$RSI = \frac{S_i}{S_o} \times 100 \quad (3)$$

Where; RSI = retained stability index

S_i = stability after 24 hours immersion in water

S_o = stability before immersion in water

2.3.3. Mixture Regression Model Formulation

The general second order (q, m) mixture regression model has a general form represented by Equation (4);

$$Y = b_o + \sum b_i x_i + \sum b_{ij} x_i x_j + \sum b_{ijk} x_i x_j x_k + \dots + \sum b_{i_1 i_2 \dots i_m} x_{i_1} x_{i_2} x_{i_m} \quad (4)$$

Where; $1 \leq i \leq q$, $1 \leq i \leq j \leq q$, $1 \leq i \leq j \leq k \leq q$

b_o is a constant coefficient

For (3, 2) quadratic problem as adopted in this study, the

general mixture regression model, Equation (4) becomes;

$$Y = b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \quad (5)$$

For a ternary mixture, Equation (6) is obtained;

$$X_1 + X_2 + X_3 = 1 \quad (6)$$

Multiplying through by constant b_o , yields Equation (7).

$$b_o X_1 + b_o X_2 + b_o X_3 = b_o \quad (7)$$

Again, multiplying Equation (6) by X_1 , X_2 , and X_3 in succession and rearranging, Equation (8) is produced.

$$\begin{cases} X_1^2 = X_1 - X_1 X_2 - X_1 X_3 \\ X_2^2 = X_2 - X_1 X_2 - X_2 X_3 \\ X_3^2 = X_3 - X_1 X_3 - X_2 X_3 \end{cases} \quad (8)$$

Substituting Equations (8) and (7) into Equation (5), Equation (9) was obtained after necessary transformation.

$$Y = (b_o + b_1 + b_{11}) X_1 + (b_o + b_2 + b_{22}) X_2 + (b_o + b_3 + b_{33}) X_3 + (b_{12} - b_{11} - b_{22}) X_1 X_2 + (b_{13} - b_{11} - b_{33}) X_1 X_3 + (b_{23} - b_{22} - b_{33}) X_2 X_3 \quad (9)$$

Denoting; $\beta_i = b_o + b_i + b_{ii}$ and

$$\beta_{ij} = b_{ij} - b_{ii} - b_{jj}$$

The reduced second-degree mixture regression model in 3 variables is shown by Equation (10).

$$Y = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (10)$$

The number of coefficients has reduced from 10 in Equation (5) to (6) in Equation (10). Thus, the reduced second-degree polynomial in q-variables is as shown by Equation (11).

$$Y = \sum_{1 \leq i \leq q} \beta_i X_i + \sum_{i \leq j \leq q} \beta_{ij} X_i X_j \quad (11)$$

Where;

Y = Expected response

β_i , β_{ij} = Coefficients of the mixture quadratic regression model

X_i , X_j = Proportions of bitumen, SO and SBS respectively

2.3.4. Model Coefficients Determination

In a short mathematical or matrix form, Equation (10) becomes;

$$y = [X_i][\beta_i] \quad (12)$$

Where;

$[X_i]$ = shape function vector showing interaction between constituents

$[\beta_i]$ = model coefficient vector function

The coefficient function is represented by Equation (13)

$$[\beta_i] = [\beta_1, \beta_2, \beta_3, \beta_{12}, \beta_{13}, \beta_{23}]^T \quad (13)$$

The shape function is also represented by Equation (14).

$$[X_i] = [X_1, X_2, X_3, X_1X_2, X_1X_3, X_2X_3]^T \quad (14)$$

The special consideration here is that Equation (10) is subjected to the constraints whereby summation of all component proportion is 5.95%, hence, the case of a constrained mixture regression model suffices. Hence, the coefficients in the constrained mixture regression model were estimated or determined using mixture regression model enabled in MINITAB software.

2.3.5. Model Validation and Verification

All developed models were validated using the Fisher test (F-test) to assess their adequacy. The F-statistic is the ratio of variance between predicted model responses and experimental values.

The hypotheses for validation were:

Null Hypothesis (H_0): No significant difference exists between experimental and predicted responses.

Alternate Hypothesis (H_1): A significant difference exists between experimental and predicted responses.

The F-test was conducted using the formula:

$$F = \frac{S_1^2}{S_2^2} \quad (15)$$

Where; S_1^2 = Larger of both variances, S_2^2 = Smaller of both variances, calculated as:

$$S^2 = \frac{1}{n-1} [\sum (Y - \bar{Y})^2] \quad (16)$$

A model was considered adequate if the calculated F-value was lower than the critical value from the F-distribution table. At a 5% significance level, with 8 degrees of freedom, the critical F-value was 3.438. If the calculated F-value was below 3.438, the null hypothesis was accepted, confirming model adequacy. Otherwise, the alternate hypothesis was accepted, indicating model inadequacy.

All mixture regression models were also subjected to R^2 statistics for verification testing. The R^2 values were calculated in accordance to Equation (17).

$$R^2 = \frac{\sum (y_{est} - \bar{y})^2}{\sum (y - \bar{y})^2} \quad (17)$$

Where; y_{est} = model or estimated value,

y = experimental value and

\bar{y} = mean experimental value

3. Results and Discussion

3.1. Swelling Index (SI) and Retained Stability Index (RSI) Results of SBS-SO WMAC

The swelling index (SI) and retained stability index (RSI) are critical parameters for evaluating the moisture resistance and durability of asphalt mixtures, particularly in warm mix asphalt concrete (WMAC) incorporating polymer and bio-based modifiers. Figures 1 and 2 illustrate the SI and RSI results of styrene-butadiene-styrene (SBS)-treated soybean oil (SO) WMAC in comparison to the AASHTO [21] standards. The SI values ranged from 0.76% to 1.66%, while the RSI varied between 66.34% and 94.37%. According to AASHTO [21], a minimum RSI of 80% is required for asphalt concrete used in paving applications. This suggests that a significant portion of the tested samples met or exceeded the required specification, indicating good resistance to moisture-induced damage.

The swelling index (SI) quantifies the degree of expansion or volume increase in asphalt mixtures due to moisture absorption, which directly affects pavement durability. High SI values indicate excessive moisture susceptibility, leading to stripping, binder-aggregate debonding, and reduced structural integrity [22]. In this study, the SI values remained relatively low, between 0.76% and 1.66%, suggesting that the SBS-treated SO WMAC exhibited minimal moisture-induced expansion. This aligns with previous research indicating that SBS-modified asphalt mixtures generally demonstrate reduced water absorption due to the polymer's ability to enhance binder elasticity and adhesion [23].

The incorporation of soybean oil (SO) as a bio-based modifier also influences moisture resistance. While bio-based additives can improve workability and reduce production temperatures, their hydrophilic nature may raise concerns regarding increased water susceptibility [24]. However, the results indicate that the tested SBS-SO WMAC formulations maintained low SI values, likely due to the synergistic effect of SBS, which counteracted any potential moisture sensitivity of SO [25]. These findings suggest that appropriate SO proportions, combined with SBS modification, can optimize the balance between moisture resistance and performance.

The retained stability index (RSI) measures the ability of asphalt mixtures to retain their structural integrity after exposure to moisture. It is a critical indicator of resistance to stripping and moisture-induced deterioration, particularly for pavements subjected to wet climates or freeze-thaw cycles [26]. According to AASHTO [21], an RSI of at least 80% is required to ensure sufficient strength retention for asphalt pavements.

In this study, RSI values ranged from 66.34% to 94.37%,

with a significant number of samples meeting or exceeding the 80% threshold. This indicates that SBS-treated SO WMAC possesses satisfactory moisture resistance, comparable to or better than conventional asphalt mixtures. The variation in RSI values suggests that certain formulations performed better than others, highlighting the importance of optimizing SBS and SO content to achieve consistent durability [27].

Polymer-modified asphalt, particularly with SBS, has been extensively studied for its role in improving moisture resistance by enhancing the cohesion of the binder and adhesion to aggregates [28]. Additionally, soybean oil's effect on asphalt binder properties has been explored in recent research, showing that, when used in appropriate dosages, it can en-

hance flexibility without significantly compromising moisture resistance [24]. The results of this study further support these findings, demonstrating that SBS-SO WMAC formulations can achieve RSI values well within acceptable limits.

The observed SI and RSI values provide insights into the long-term performance of SBS-treated SO WMAC in real-world pavement applications. Low SI values suggest reduced susceptibility to moisture-related expansion, which can help mitigate the risk of cracking, rutting, and premature pavement failure [29]. Meanwhile, RSI values above 80% indicate that the material can maintain sufficient stability even after moisture exposure, making it suitable for use in areas with variable weather conditions and frequent precipitation.

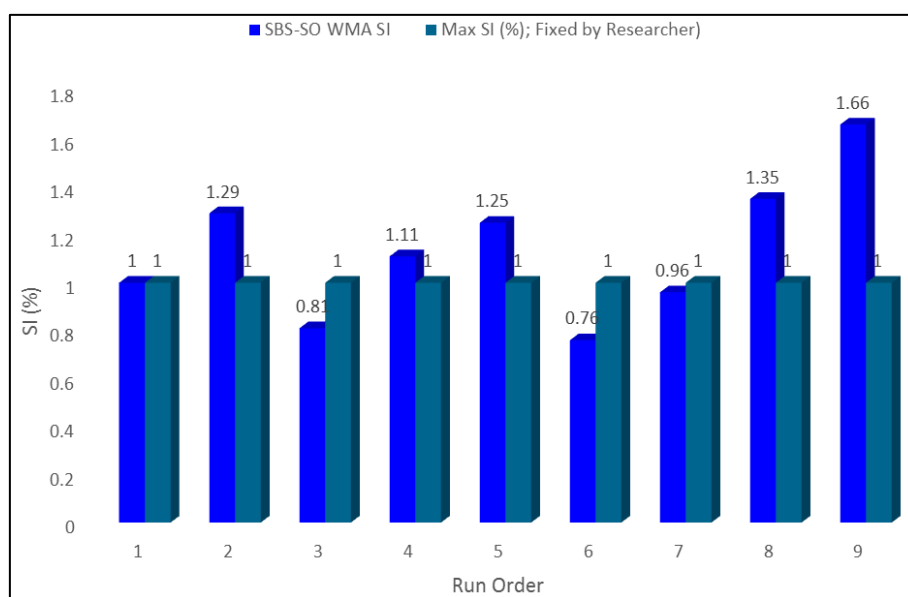


Figure 1. SI of SBS treated SO WMAC for Different Experimental Runs.

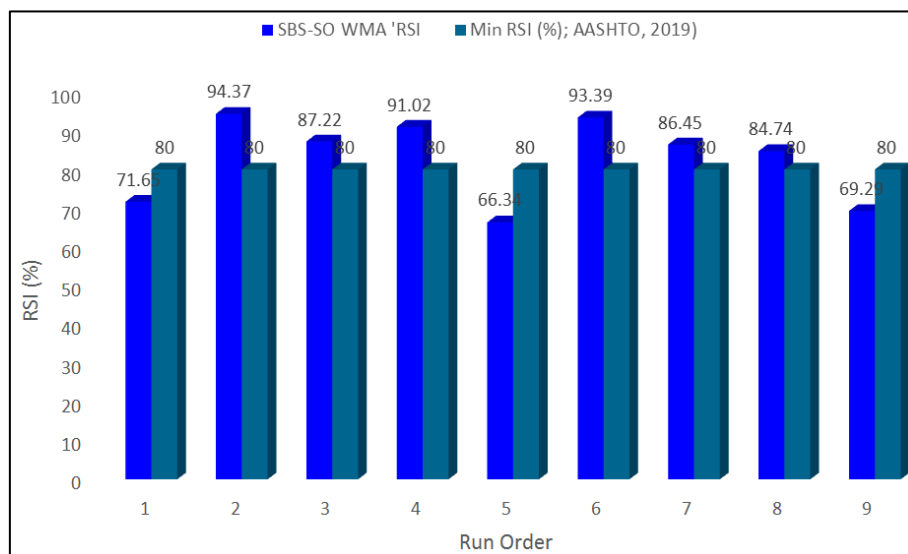


Figure 2. RSI of SBS Treated SO WMAC for Different Experimental Runs in Comparison to AASHTO (2019) Specification.

The combination of SBS and SO in WMAC formulations presents a promising approach for sustainable and durable asphalt pavement design. SBS enhances binder elasticity, reducing moisture-related damage, while SO improves workability and reduces mixing and compaction temperatures, contributing to energy efficiency and environmental benefits (Hassan et al., 2022). However, careful proportioning is necessary to ensure that moisture resistance is not compromised, as excessive SO content may negatively impact adhesion properties [25].

3.2. Mixture Regression Model for Predicting the Swelling Index (SI) and Retained Stability Index (RSI) of SBS-SO WMAC

3.2.1. SI Predictive Model for SBS-SO WMACs

SI predictive model for SBS-SO WMACs was developed by calibration of Equation (10) using the mixture regression theory enabled in Minitab software. The column vector of the coefficients $[\beta]$ was obtained as presented in Equation (18).

$$[\beta] = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_{12} \\ \beta_{13} \\ \beta_{23} \end{bmatrix} = \begin{bmatrix} 0.216 \\ -57.2915 \\ 40.1355 \\ 10.2947 \\ -7.3609 \\ 0 \end{bmatrix} \quad (18)$$

Substituting these coefficient values into Equation (10), the model for predicting the SI of SBS-SO WMACs was obtained as presented in Equation (19).

$$SI_{SBS-SO} = 0.216 X_1 - 57.2915 X_2 + 40.1355 X_3 + 10.2947 X_1 X_2 - 7.3609 X_1 X_3 \quad (19)$$

Table 3 presents the F-Statistics results for the validation of Equation (19) at 5% level of significance or 95% confidence level. From the analysis as presented in Table 3, a F-calculated value of 1.241 was obtained. Because the calculated F-value of 1.241 is smaller than the F-tabulated value of 3.438, the null hypothesis is accepted and the model for predicting the swelling index of SBS-SO WMAC (Equation 19) is considered adequate.

Moreover, Figure 3 which presents the verification statistics of the derived model reveals an R^2 value of 80.56%. This indicates that over 80% of the data within the design space considered is explained by the derived model. Equation (19) can thus be used for adequately predicting the SI of SBS-SO WMACs under medium traffic conditions. In comparison to previous studies, the obtained R^2 value aligns with findings from similar predictive models in asphalt mixture analysis. For instance, Zhang et al. [30] reported an R^2 value of 78.5% for their regression model used in predicting the moisture susceptibility of polymer-modified asphalt mixtures. Simi-

larly, a study by Kim et al. [31] on the performance modeling of warm mix asphalt (WMA) incorporating recycled materials achieved an R^2 value of approximately 82%, demonstrating comparable predictive accuracy. Additionally, the F-statistic result in this study follows a pattern observed in earlier works, where models validated through F-tests with calculated values lower than the critical tabulated values were deemed statistically sound [32]. This reinforces the robustness of Equation (19) as a predictive tool for SBS-SO WMAC behavior. Thus, the present model (Equation 19) contributes to the growing body of knowledge on predictive modeling for modified asphalt mixtures, offering an approach that is statistically validated and comparable to established models in the field.

3.2.2. RSI Predictive for SBS-SO WMACs

RSI predictive model for SBS-SO WMACs was developed by calibration of Equation (10) using the mixture regression theory enabled in Minitab software. The column vector of the coefficients $[\beta]$ was obtained as presented in Equation (20).

$$[\beta] = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_{12} \\ \beta_{13} \\ \beta_{23} \end{bmatrix} = \begin{bmatrix} 15.83 \\ 2263.69 \\ -1499.21 \\ -414.99 \\ 267.61 \\ 0 \end{bmatrix} \quad (20)$$

Substituting these coefficient values into Equation (10), the model for predicting the RSI of SBS-SO WMACs was obtained as presented in Equation (21).

$$RSI_{SBS-SO} = 15.83 X_1 + 2263.69 X_2 - 1499.21 X_3 - 414.99 X_1 X_2 + 267.61 X_1 X_3 \quad (21)$$

Table 4 presents the F-Statistics results for the validation of Equation (21) at 5% level of significance or 95% confidence level. From the analysis as presented in Table 4, a F-calculated value of 1.263 was obtained. Because the calculated F-value of 1.263 is smaller than the F-tabulated value of 3.438, the null hypothesis is accepted and the model for predicting the retained strength index of SBS-SO WMAC (Equation 21) is considered adequate.

Moreover, Figure 4 which presents the verification statistics of the derived model reveals an R^2 value of 79.14%. This indicates that over 79% of the data within the design space considered is explained by the derived model. Equation (21) can thus be used for adequately predicting the RSI of SBS-SO WMACs under medium traffic conditions. When compared to other modeling efforts in the asphalt concrete domain, the R^2 value obtained in this study is consistent with previous findings. For example, a study by Choi et al. [33] achieved an R^2 value of 78.2% when predicting the performance of polymer-modified asphalt mixtures under varying traffic conditions. Similarly, a work by Lee and Park [34] on the long-term

performance of warm mix asphalt (WMA) mixtures achieved an R^2 value of 80.5%, demonstrating similar predictive accuracy for material properties.

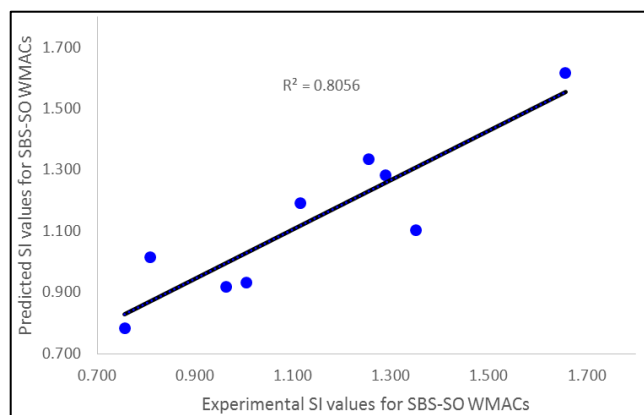


Figure 3. R^2 Statistics of SI Model for SBS-SO WMACs.

The F-statistic results also align with typical findings in the field, where a calculated F-value lower than the tabulated value suggests that the model is valid and appropriately fits the data. This result is consistent with previous studies, such as that of Guo et al. [35], who validated their models using an

F-test and concluded that the models were statistically sound when the F-calculated values were smaller than the F-tabulated values. This supports the reliability of Equation (21) as a robust predictive tool for the retained strength index of SBS-SO WMA. Thus, the present model (Equation 21) further adds to the growing body of knowledge on the modeling of modified asphalt mixtures, offering a validated approach for predicting the RSI under medium traffic conditions.

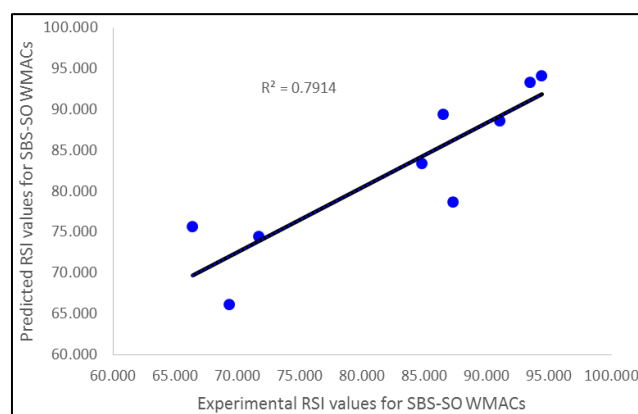


Figure 4. R^2 Statistics of RSI Model for SBS-SO WMACs.

Table 3. F-Statistics for the Validation of Swelling Index (SI) Predictive Model of SBS-SO WMACs.

S/N	SI Experimental Value= Y_e	SI Predicted or Model Value= Y_m (Equation 19)	$Y_e - \hat{Y}_e$	$Y_m - \hat{Y}_m$	$(Y_e - \hat{Y}_e)^2$	$(Y_m - \hat{Y}_m)^2$
1	1.004	0.935	-0.128	-0.197	0.01648	0.03894
2	1.288	1.285	0.156	0.153	0.02433	0.02331
3	0.807	1.018	-0.325	-0.115	0.10551	0.01317
4	1.114	1.193	-0.019	0.060	0.00035	0.00363
5	1.253	1.337	0.121	0.204	0.01455	0.04177
6	0.756	0.783	-0.376	-0.349	0.14157	0.12197
7	0.963	0.919	-0.169	-0.213	0.02864	0.04557
8	1.350	1.104	0.217	-0.029	0.04728	0.00084
9	1.656	1.619	0.523	0.486	0.27390	0.23664
	$\hat{Y}_e = 1.132$	$\hat{Y}_m = 1.133$			$\Sigma = 0.65262$	$\Sigma = 0.52583$
Square of deviation of experimental SI values from mean SI value (Equation 16), S_e^2				$S_e^2 = 0.081577064$		
Square of deviation of predicted SI values from mean SI value (Equation 16), S_m^2				$S_m^2 = 0.065728679$		
F- Calculated value, ratio of the two deviations (Equation 15), F-cal				F-cal = 1.241118258		

Table 4. F-Statistics for the Validation of Retained Strength Index (RSI) Predictive Model of SBS-SO WMACs.

S/N	RSI Experimental Value= Y_e	RSI Predicted or Model Value= Y_m (Equation 21)	$Y_e - \hat{Y}_e$	$Y_m - \hat{Y}_m$	$(Y_e - \hat{Y}_e)^2$	$(Y_m - \hat{Y}_m)^2$
1	71.647	74.494	-11.071	-8.209	122.57422	67.39220
2	94.372	94.189	11.654	11.486	135.81030	131.91917
3	87.223	78.794	4.505	-3.909	20.29214	15.27947
4	91.019	88.641	8.301	5.939	68.89923	35.26631
5	66.344	75.742	-16.374	-6.961	268.12081	48.45362
6	93.389	93.441	10.671	10.738	113.86344	115.30764
7	86.447	89.410	3.729	6.707	13.90425	44.97997
8	84.737	83.510	2.019	0.807	4.07575	0.65132
9	69.286	66.106	-13.432	-16.597	180.40934	275.46073
	$\hat{Y}_e = 82.718$	$\hat{Y}_m = 82.703$			$\Sigma = 927.94948$	$\Sigma = 734.71043$
Square of deviation of experimental RSI values from mean RSI value (Equation 16), S_e^2				$S_e^2 = 115.9936854$		
Square of deviation of predicted RSI values from mean RSI value (Equation 16), S_m^2				$S_m^2 = 91.8388042$		
F- Calculated value, ratio of the two deviations (Equation 15), F-cal				F-cal = 1.263013891		

4. Conclusions

The results and analysis of this study offer valuable insights into the performance of this novel asphalt formulation under moisture exposure. The following key conclusions can be drawn:

The SI and RSI results indicate that SBS-SO WMAC has good moisture resistance and durability. The SI values, ranging from 0.76% to 1.66%, suggest minimal moisture-induced expansion, meaning the material is less likely to suffer from damage like stripping or binder-aggregate debonding. The RSI values, between 66.34% and 94.37%, show that most samples met or exceeded the 80% threshold required by AASHTO (2019), confirming that SBS-SO WMAC maintains adequate strength after moisture exposure, making it suitable for pavements in diverse climates.

The addition of SBS, a polymer modifier, greatly improved the moisture resistance of the asphalt mixtures by enhancing binder elasticity and adhesion between binder and aggregates, reducing water susceptibility. Despite soybean oil's hydrophilic nature, it did not harm the moisture resistance and actually worked synergistically with SBS. This combination optimized both performance and workability, with soybean oil also lowering production temperatures and providing environmental benefits. Careful proportioning of soybean oil with SBS can achieve a good balance between moisture resistance and other performance traits.

The predictive models for SI and RSI, developed using

mixture regression analysis, were validated using F-statistics. The models showed an R^2 value of 80.56% for SI and 79.14% for RSI, indicating that both models explain a substantial portion of the data within the design space. This high explanatory power suggests that the models can be reliably used to predict the performance of SBS-SO WMAC under medium traffic conditions. The validation of these models at a 95% confidence level further strengthens their applicability in real-world scenarios. However, the developed models are only applicable to medium traffic roads.

Abbreviations

SI	Swelling Index
RSI	Retained Stability Index
WMAC	Warm Mix Asphalt Concrete
SBS	Styrene-Butadiene-Styrene
SO	Soybean Oil
SBS-SO-modified WMAC	Styrene-Butadiene-Styrene Modified Soybean Oil Warm Mix Asphalt Concrete
AASHTO	American Association of State Highway and Transportation Officials

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Conflicts of Interest

The authors declare no conflicts of interest.

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