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Advanced Climate-Resilient Asphalt Mixture with SBS Polymer, Anti-Stripping Agent, and Tall Oil: Comprehensive Laboratory Evaluation and Predictive ANN Modeling

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Abstract

Extreme weather and climate conditions pose significant challenges to the durability and performance of asphalt pavements, accelerating distresses such as rutting, moisture damage, and cracking. To address these challenges, this study presents the development of a climate-resilient asphalt mixture enhanced with 4% Styrene-Butadiene-Styrene (SBS) polymer, 0.5% Amine-Based Anti-Stripping Agent (AD-here® LOF 65-00 EU), and 5% Tall Oil rejuvenator (Delta-S). Laboratory experiments, involving the Hamburg wheel-track test for rutting resistance and the strain-controlled four-point bending beam test for fatigue life (Nf) evaluation and revealed important enhancements over the unmodified control mix. The modified asphalt achieved a 55% decrease in rut depth at 20,000 passes and exhibited a 50% increase in initial stiffness, reaching 720 MPa at 200 με and 700 MPa at 400 με. In terms of fatigue performance, the mix sustained 120,000 cycles at 200 με and 65,000 cycles at 400 με, nearly tripling the durability compared to the control. Moreover, Artificial Neural Network (ANN) models were employed to predict rutting depth and fatigue life up to 100,000 passes and 600 με, providing a reliable tool for performance forecasting under extreme climatic conditions. The findings reveal that the proposed amendment approach significantly enhances the structural integrity, moisture resistance, and long-term durability of asphalt pavements. This work not only bridges the gap between laboratory testing and practical implementation, but additionally establishes a new benchmark for resilient and sustainable pavement design in challenging environments by promoting longer service life and reducing maintenance needs, leading to minimizing resource consumption.

Keywords: Climate-resilient asphalt, SBS polymer modification, Anti-stripping agent, Tall oil rejuvenator, Rutting resistance, Fatigue life prediction, Artificial Neural Network (ANN)

1. Introduction

1.1 Research Background

The increased occurrence of extreme climate and weather conditions produce recurrent issues for the stability and longevity of asphalt pavement [1]. Long durations of warm weather, extensive rain, interspersed temperature shifts, and prolonged arid conditions all lead to

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pavement failure by inducing rutting, thermal cracking, cracking from repetitive usage, and water-induced damage, [2] as presented below in Figure 1.

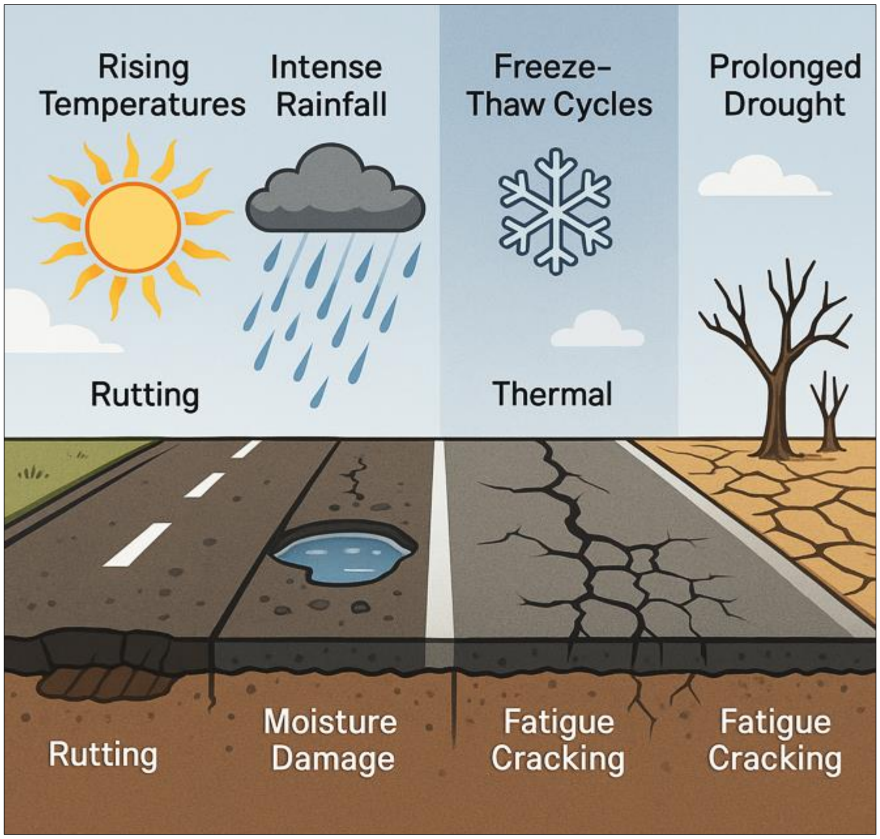

Figure 1. Impact of climatic factors on asphalt pavement distress

Typical asphalt mix, although efficient under normal environmental conditions, tends to lack the endurance needed to cope with these newer and stringent climatic requirements [3]. As such, the research into climate-resilient asphalt mixtures became a strategic concern for the world's road authorities and scientists [4]. Of all the methods uncovered, multi-component asphalt modification became a favorable method for enhancing pavement performance for a broad spectrum of climatic stresses [5]. Polymer modification, particularly with Styrene-Butadiene-Styrene (SBS), is widely recognized for its capability to enhance elasticity, high-temperature rutting resistance, and fatigue performance [6].

SBS polymers form a network inside the asphalt binder matrix that enhances its viscoelastic characteristics, allowing the pavement to accommodate traffic loading and thermal actions better [6]. However, high-temperature overall performance alone isn't sufficient for complete climate resilience. Moisture-caused failure, regularly exacerbated by increased rainfall and flooding events, represents an essential failure mechanism, especially at the asphalt-combination interface [7]. To mitigate this problem, the incorporation of amine-based anti-stripping marketers (ASA), along with AD-right here® LOF sixty-five-00 EU, has been confirmed to be enormously effective [8]. These additives chemically enhance the adhesion between the asphalt binder and the combination, notably advancing resistance to moisture damage and keeping pavement integrity below moist conditions [8].

In parallel, the aging of asphalt binders because of oxidative and thermal processes leads to embrittlement and decreased flexibility, particularly under fluctuating thermal environments [9]. The use of bio-based rejuvenators, for instance, Delta-S tall oil, offers a sustainable solution to this undertaking [9]. Tall oil rejuvenators refill the maltene fraction of aged binders, restoring ductility and increasing provider lifestyles by enhancing the binder's resistance to cracking and fatigue [10].

Recognizing the numerous effects of climate on pavement overall performance, this research suggests an integrated amendment system that includes SBS polymer, an amine-based anti-stripping agent, and a tall oil rejuvenator. Comprehensive laboratory testing, which includes rutting and fatigue resistance, was conducted into accomplished simultaneously with the construction of an ANN model for predicting each rutting and fatigue life (NF). This innovative strategy not only bolsters pavement resilience but also advances sustainability by prolonging service life and minimizing maintenance demands, ultimately reducing resource use and environmental footprint.

1.2 Literature Review

Asphalt pavements are getting more and more susceptible to climate-related issues including rutting, cracking, and moisture damage. While individual modifiers such as polymers, anti-stripping marketers, and rejuvenators have demonstrated benefits, few studies have looked at their mixed use for comprehensive climate resilience. This work fills that hole by combining numerous chemicals to improve pavement resilience underneath harsh environmental conditions. A study presented by Cong P. et al. [11] aimed to evaluate the effect of SBS polymer on rutting and fatigue overall performance below elevated temperatures.

Their results demonstrated a 45% improvement in rutting resistance and a notable increase in fatigue life compared to conventional binders. Zhang R. et al. [12] analyzed the impacts of future climate change on pavement aging, revealing that rising temperatures, increased freeze-thaw cycles, and shifting precipitation patterns accelerate pavement deterioration such as cracking and rutting. The research emphasizes the regional vulnerability differences and the significance of incorporating climate resilience into the design of pavements. Their multi-dimensional methodology emphasizes the requirement for adaptive lifecycle models to better project and control pavement performance under the changing environmental conditions.

Meanwhile, Lu Z. et al. [13] focused on enhancing the adhesive bond between binder and aggregate using amine-based additives, achieving a 28% increase in the Tensile Strength Ratio (TSR) and highlighting improved resistance to moisture-induced damage. Furthermore, Liang C. et al. [14], conducted a study aimed at restoring aged binder properties using tall oil-derived rejuvenators, reporting a 34% improvement in low-temperature cracking resistance and enhanced flexibility in aged mixtures. Although these works have demonstrated the individual effectiveness of polymers, anti-stripping agents, and rejuvenators, there remains a gap in combining these approaches into a unified, performance-optimized system.

The current study addresses this need by integrating SBS polymer, AD-here® LOF 65-00 EU anti-stripping agent, and Delta-S tall oil rejuvenator within a single asphalt mixture. Moreover, it advances previous efforts by incorporating Artificial Neural Network (ANN) models to predict long-term rutting and fatigue life (Nf), bridging the gap between laboratory innovation and field performance. This research represents a forward step in the development of next-generation, climate-resilient asphalt pavements that build upon and expand the foundation established by previous studies.

1.3 Research Novelty

This study pioneers a triple-modification system using SBS polymer, an amine-based anti-stripping agent (ASA), and a tall oil rejuvenator to create asphalt mixtures that are resilient to rutting, moisture damage, and fatigue cracking under extreme climatic conditions. By combining laboratory test results with an ANN model for predicting rutting and fatigue life, this study provides a realistic, future-oriented foundation for the development of durable, climate-resistant pavements.

1.4 Research Objectives

This study aims to improve a climate-resistant asphalt mix by incorporating an SBS polymer, an amine-based antistripping agent (AD-here® LOF 65-00 EU), and a long-oil rejuvenator (Delta-S) to improve resistance to cracking, and moisture damage. Laboratory tests including cracking, moisture sensitivity, and fatigue resistance tests were utilized using the Hamburg wheel-track test and stress-controlled four-point bending beam test to assess the efficacy of these modifications. In addition to this, an artificial neural network (ANN) model estimated the fatigue life and intensity of a crack, presenting an overall view of long-term pavement behavior under very severe climate conditions.

2. Experimental Part

2.1 The Utilized Materials

2.1.1 The Chosen Bitumen

PG 64-10 asphalt binder was chosen to act as the base material for this study owing to its general stability and performance for a variety of climatic conditions. designed to perform reliably at high pavement temperatures up to 64° C and low temperatures all the way down to −10° C, it is well-appropriate for zones experiencing warm summers and mild winters. Its stability and resistance to both rutting and thermal cracking make it a perfect baseline binder for assessing the overall performance improvements in asphalt combinations. The physical characteristics of the PG 64-10 asphalt binder were assessed in accordance with Superpave binder specifications, as revealed in Table 1. Figures 2, 3, and 4 illustrate the Dynamic Shear Rheometer (DSR), the rotational viscometer, and the Bending Beam Rheometer (BBR) utilized to determine the physical properties of the applied bitumen.

Table 1. The physical characteristics of PG 64-10 asphalt binder

Test Property	The Result	Standard	Requirement
Rotational Viscosity @135° C	2.0 Pa·s	AASHTO T316	≤ 3.0 Pa·s
G*/Sinδ (Unaged) @64° C	1.20 kPa	AASHTO T315	≥ 1.00 kPa
G*/Sinδ (RTFO-aged) @64° C	2.60 kPa	AASHTO T315	≥ 2.20 kPa
G*·Sinδ (PAV-aged) @25° C	4000 kPa	AASHTO T315	≤ 5000 kPa
Stiffness (S) @ (-10° C)	250 MPa	AASHTO T313	≤ 300 MPa

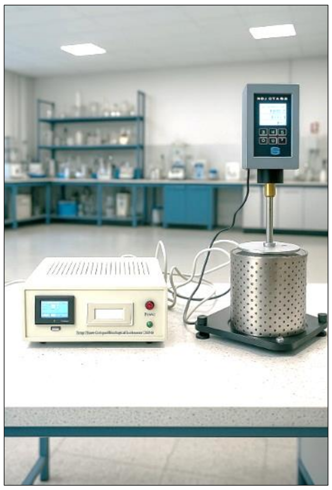

Figure 2. Rotational viscometer

Figure 3. Dynamic shear rheometer (DSR)

Figure 4. Bending Beam Rheometer (BBR)

2.1.2 The Chosen Aggregate

In this research, high-quality coarse and fine aggregates were selected to achieve an optimal performance of the asphalt mix under intense weather conditions. Crushed stone was used as a coarse aggregate because of its high angularity, advanced hardness, and coffee water absorption, which contribute to progressed rutting resistance, structural balance, and long-term durability in both hot and wet environments. For the fine aggregate, crushed sand was carried out, providing advanced particle interlock, high fine aggregate angularity (FAA), and superior moisture resistance.

The chosen aggregates conform to Superpave specifications and are well-suited for use in performance-modified mixes that are planned to resist temperature extremes, freeze-thaw cycles, and high traffic loading.

Table 2. Physical characteristics of the utilized coarse aggregate

Property	The Result	Test Method	Standard Requirement
Bulk Specific Gravity (SSD)	2.65	AASHTO T 84	2.50 – 2.80
Apparent Specific Gravity	2.70	AASHTO T 85	2.60 – 2.90
Water Absorption (%)	0.60	AASHTO T 85	≤ 2.0 %
Los Angeles Abrasion Loss (%)	18.50	AASHTO T 96	≤ 30 %
Flat and Elongated Particles (%)	7.00	ASTM D4791	≤ 10 %
Soundness Loss (Sodium Sulfate) (%)	8.20	AASHTO T 104	≤ 12 %

Table 3. Physical properties of the used fine aggregate

Property	The Result	Test Method	Standard Requirement
Bulk Specific Gravity (SSD)	2.63	AASHTO T 84	2.50 – 2.80
Apparent Specific Gravity	2.68	AASHTO T 85	2.60 – 2.90
Water Absorption (%)	1.2	AASHTO T 85	≤ 2.0 %
Fine Aggregate Angularity (%)	47.5	AASHTO T 304	≥ 45 %
Sand Equivalent (%)	78	AASHTO T 176	≥ 45 %
Material Passing No. 200 Sieve (%)	1.8	AASHTO T 11	≤ 2.0 %

To ensure optimal performance under extreme climatic conditions, a dense-graded aggregate structure was selected, conforming to Superpave specifications [15]. The chosen

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gradation aims to enhance rutting resistance, moisture susceptibility, and thermal cracking performance. Nominal Maximum Aggregate Size (NMAS) is 12.5 mm, suitable for surface wearing layer as shown below in Table 4 and Figure 5. The adopted gradation avoids the restricted zone between the 0.3 mm and 2.36 mm sieves to minimize potential issues with moisture susceptibility and to enhance rutting resistance.

Table 4. Superpave adopted gradation for surface wearing course

Sieve Size (mm)	Superpave Control Points (% Passing)	Adopted Gradation (% Passing)
19.0	90 – 100	100
12.5	90 – 100	95
9.5	0 – 90	85
4.75	39 – 69	60
2.36	23 – 49	40
1.18	—	30
0.600	—	22
0.300	—	15
0.150	—	8
0.075	2 – 10	5

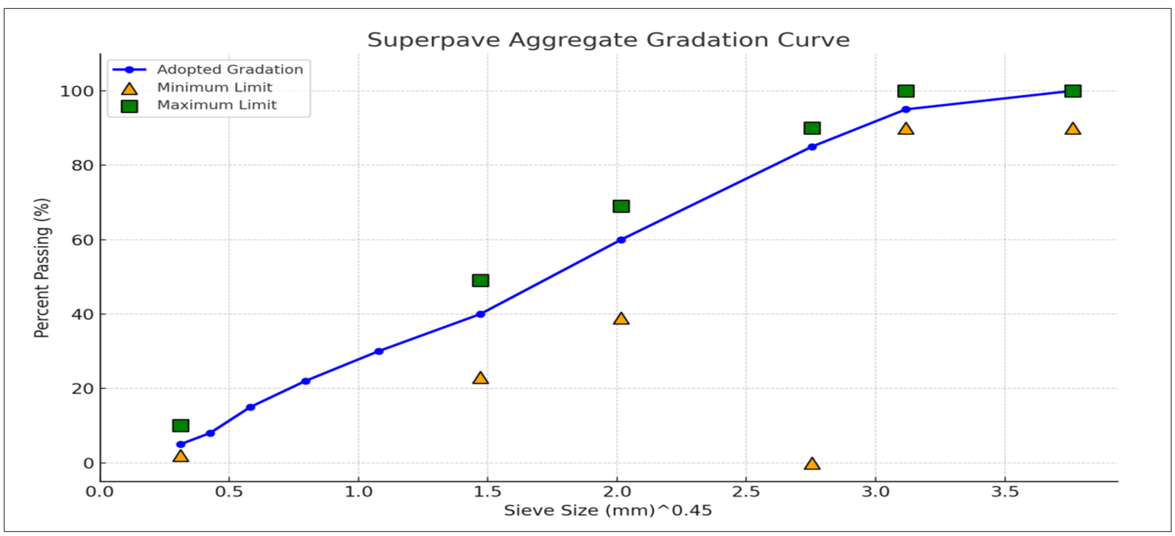

Figure 5. Superpave aggregate gradation curve for surface wearing layer

2.1.3 The Chosen Filler

Portland cement was used as a mineral filler in this study to improve mixture stability, reduce moisture damage, and enhance overall performance under extreme climatic conditions. Its mechanical properties are shown below in Table (5).

Table 5. Portland cement mechanical properties

Property	The Result	Test Method	Standard Requirement
Specific Gravity	3.15	ASTM C188	2.90 – 3.20
Fineness (by Blaine method)	380 m²/kg	ASTM C204	≥ 280 m²/kg

2.1.4 Styrene-Butadiene-Styrene (SBS)

Styrene-Butadiene-Styrene (SBS), as shown in Figure 6, is a block copolymer composed of two polystyrene end blocks and a polybutadiene mid-block. In this study, SBS was incorporated into the asphalt binder to enhance its elasticity, thermal stability, and resistance to deformation. Table 6 represents the main physical properties of the SBS.

Figure 6. SBS

Table 6. Physical properties of the used SBS

Property	The Result	Test Method	Standard Requirement
Appearance	White solid granules	Visual	Uniform solid granules
Density	0.95 g/cm³	ASTM D792	0.93–0.97 g/cm³
Tensile Strength	25 MPa	ASTM D412	≥ 20 Mpa
Elongation	700 %	ASTM D412	≥ 500 %
Softening Point	200° C	ASTM D36	≥ 180° C

2.1.5 Amine-Based Anti-Stripping Agent (ASA) (AD-here ® LOF 65-00 EU)

AD-here® LOF 65-00 EU as shown below in Figure (7), is a liquid amine-based anti-stripping agent specifically formulated to improve the adhesion between asphalt binder and aggregate. Composed primarily of fatty amines and polar organic compounds, it enhances the

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chemical bonding at the asphalt–aggregate interface, thereby reducing moisture susceptibility and stripping potential. Table 6 represents the main physical properties of the used anti-stripping agent.

Figure 7. AD-here ® LOF 65-00 EU anti-stripping agent

Table 7. The main physical properties for the used anti-stripping agent

Property	**The Result**	**Test Method**	**Standard Requirement**
Appearance	Dark brown liquid	Visual	Uniform dark liquid
Specific Gravity (25° C)	0.92	ASTM D1298	0.85 – 0.98
Viscosity (25° C)	420 cP	ASTM D445	100 – 800 cP
Flash Point	200° C	ASTM D92	≥ 180° C

2.1.6 Tall Oil (Delta-S)

Delta-S, as shown below in Figure 8, a commercially available tall oil-derived rejuvenator, is a bio-based additive used to restore the flexibility and workability of aged asphalt binders. It is primarily composed of fatty acids, rosin acids, and other organic compounds derived from the distillation of crude tall oil, a byproduct of the kraft pulping process. Table 7 represents the main physical properties of the used tall oil.

Figure 8. Tall oil (Delta-S)

Table 8. The main physical properties for the used tall oil

Property	The Result	Test Method	Standard Requirement
Appearance	Amber liquid	Visual	Clear, uniform liquid
Specific Gravity (25° C)	0.94	ASTM D1298	0.90 – 0.97
Viscosity (25° C)	380 cP	ASTM D445	200 – 700 cP
Flash Point	220° C	ASTM D92	≥ 200° C

2.2 Laboratory Performance Assessment

2.2.1 The Modification Process of the Used Bitumen

Based on previous studies in asphalt binder modification and practical experience, the selected dosages of the additives used in this study are as follows:

- The SBS polymer, typically dosed at 4% by weight of the bitumen [16].
- The amine-based liquid anti-stripping agent ASA (AD-here ® LOF 65-00 EU) is incorporated at a dosage of 0.5% by weight of binder [17].
- The tall oil (Delta-S), commonly dosed at 5% by weight of bitumen [18].

To prepare SBS-modified bitumen incorporating an amine-based anti-stripping agent and a tall oil-based rejuvenator, the base bitumen (PG 64-10) is first preheated to approximately 160° C–170° C to achieve adequate fluidity. Once the temperature reaches the target mixing range of 175° C–185° C, it is maintained at an optimal level of 180° C throughout the process. The SBS polymer is then gradually introduced into the bitumen using a high-shear mixing blender, as shown in Figure 9, under slow agitation at 500–1000 rpm, to ensure uniform dispersion and prevent clumping.

After the complete addition of the polymer, the high-shear blender is operated at 3000–5000 rpm, and mixing is continued for 60 to 90 minutes to ensure full polymer swelling and dispersion. Once the SBS is thoroughly blended and the binder exhibits a homogeneous, elastic texture, a pre-measured quantity of tall oil-based rejuvenator is added while maintaining high-shear mixing for an additional 10–15 minutes. Finally, the amine-based liquid anti-stripping agent (ASA) is incorporated under gentle stirring (approximately 500 rpm) for a further 5–10 minutes to ensure uniform distribution without introducing air entrainment. Throughout the entire mixing process, strict temperature control is essential to prevent thermal degradation of the SBS polymer and to maintain binder consistency. Figure 10, shows the production workflow of the modified binder.

Figure 9. Bitumen Blender

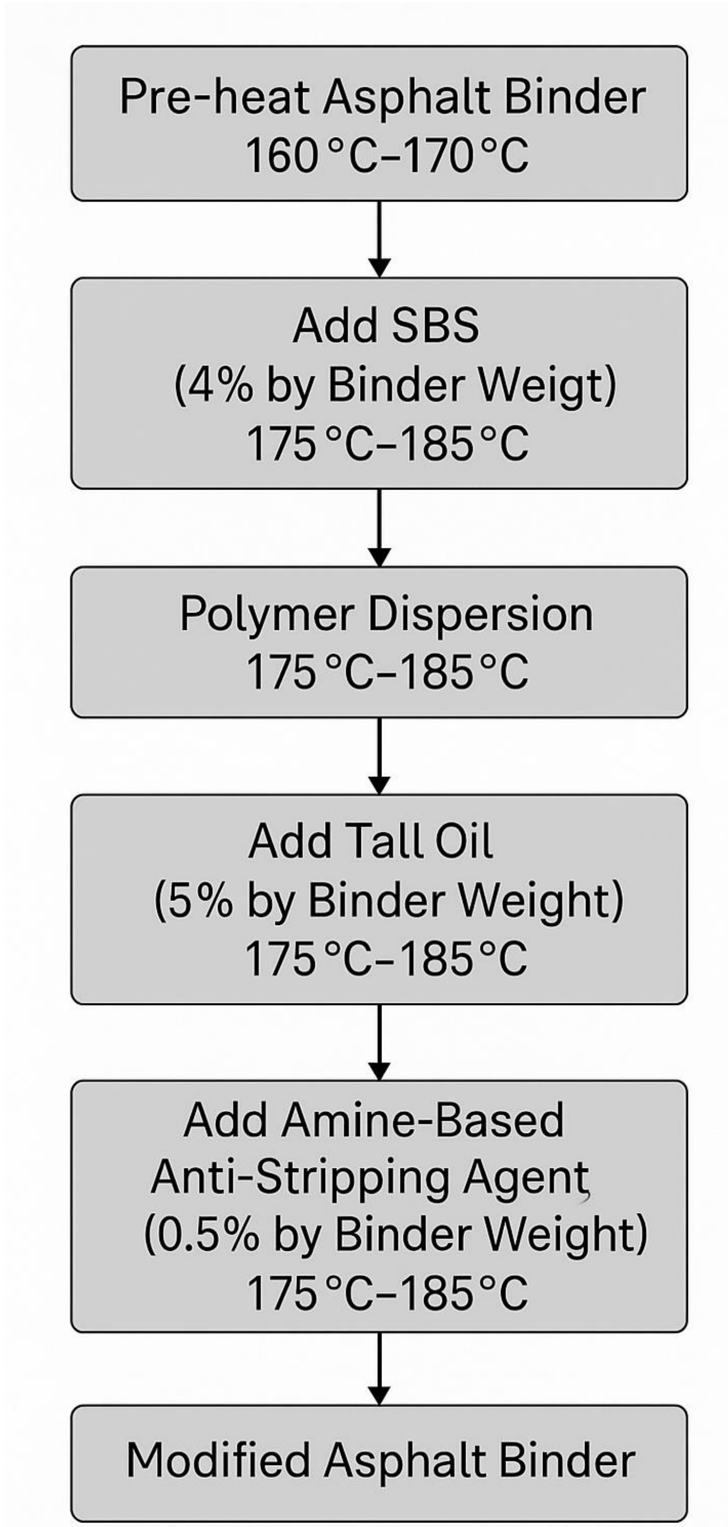

Figure 10. Modified Asphalt Binder Production Workflow

2.2.2 Determination of the Optimum Bitumen Content

The optimum bitumen content for the designed control mixture was determined to be 4.8%, corresponding to a target air void content of 4.0%, as required by the Superpave mix design method [19]. This optimum value was identified through volumetric analysis of trial mixtures compacted using a Superpave Gyratory Compactor (SGC), as shown in Figures 11 & 12, at the designated N_{design} level of 100 gyrations, which is appropriate for medium- to high-volume traffic levels ranging from 10 to 30 million ESALs, typical of roadways in Iraq [20]. The selected bitumen content not only satisfied the air void requirement at N_{design} but also met the minimum VMA, acceptable VFA, and complied with Superpave criteria at $N_{initial}$ (8 gyrations) and $N_{maximum}$ (160 gyrations), as shown in Table (9), ensuring adequate resistance to early densification and over-compaction. This design is expected to provide enhanced performance under the climatic and traffic loading conditions prevalent in the region.

Figure 11. SGC apparatus

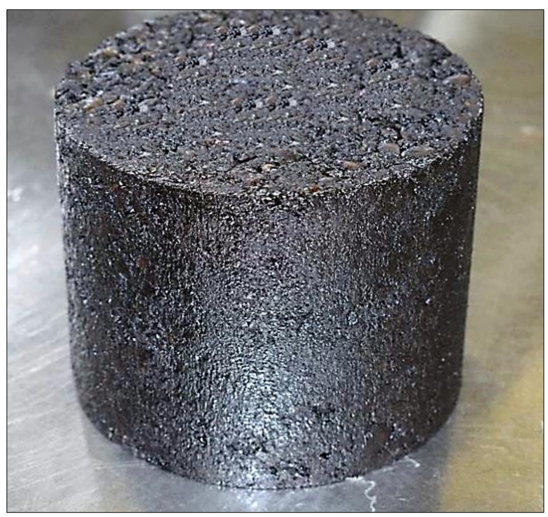

Figure 12. The generated specimen

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Table 9. Superpave volumetric properties of the control asphalt mixture

Volumetric Property	@ $N_{initial}$= 8 gyrations	@ N_{design}= 100 gyrations	@ $N_{maximum}$= 160 gyrations
Air Voids	—	4.0 %	—
Voids in Mineral Aggregate (VMA)	—	14.5 %	—
Voids Filled with Asphalt (VFA)	—	72.4 %	—
Density (% of Gmm)	88.6 %	96.0 %	97.8 %

2.2.3 Rutting Resistance

The Hamburg Wheel-Track Test, outlined in EN 12697-22 [21], is a key European standard for assessing the rutting performance and moisture susceptibility of asphalt mixtures under simulated traffic and environmental conditions, as shown in Figure (13). This method employs slab specimens, typically sized at 300 × 200 × 60 mm, which are compacted using a pneumatic roller compactor in accordance with EN 12697-33 to replicate field compaction [21], as shown in Figure 14. During testing, a steel or rubber wheel applies a controlled load of 705 ± 10 N as it repeatedly traverses the water-submerged specimen, maintained at an elevated temperature of 50 °C. The test monitors rut depth development over time and continues for up to 20,000 passes, or until a predefined rutting threshold is reached. This procedure provides key insights into the mixture's resistance to deformation and moisture damage, supporting the design of durable pavements in climate-sensitive areas. Figure 15 reveals the generated slab specimens of asphalt.

Figure 13. Hamburg wheel-track apparatus **Figure 14. Pneumatic roller compactor**

Figure 15. Asphalt slab specimens

2.2.4 Fatigue Resistance

In this study, the fatigue resistance of the asphalt mixtures was evaluated using the strain-controlled four-point bending beam test in accordance with AASHTO T321 [22], as shown in Figure (16). Rectangular beams with dimensions of 63 × 50 × 380 mm were prepared from laboratory-compacted specimens and tested at a temperature of 20 °C, as shown in Figure 17. A sinusoidal loading pattern was applied at a frequency of 10 Hz with constant strain amplitudes ranging from 200 to 400 microstrain, depending on the mixture stiffness as shown in Figure 18. The test was continued until the flexural stiffness of each specimen dropped to 50% of its initial value, and the corresponding number of load cycles was recorded as the fatigue life (Nf). This method allowed for a reliable assessment of the cracking resistance of the modified asphalt mixtures under repeated loading conditions.

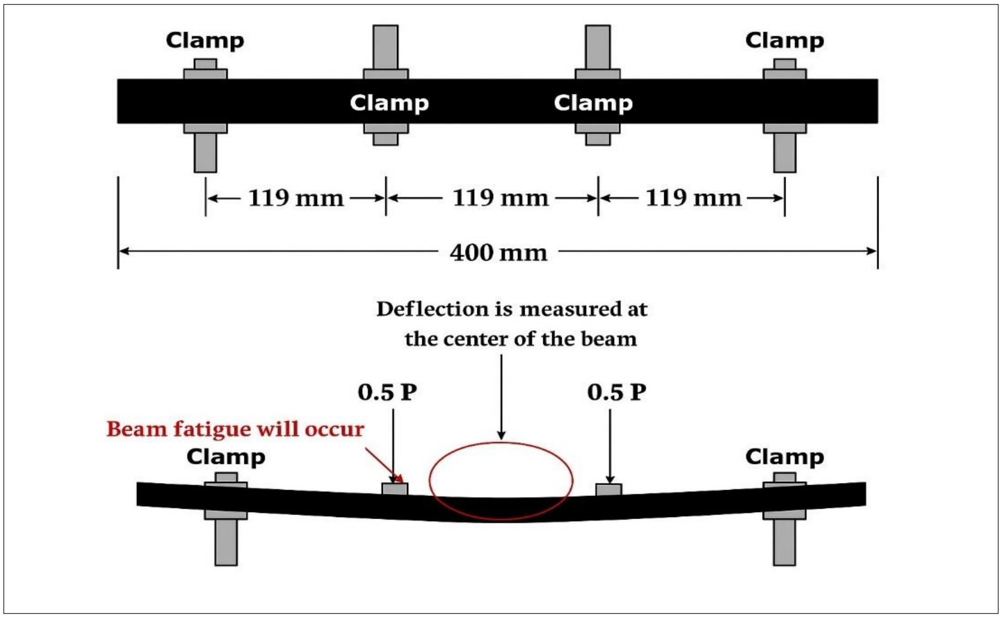

Figure 16. Flexure beam setup for fatigue evaluation

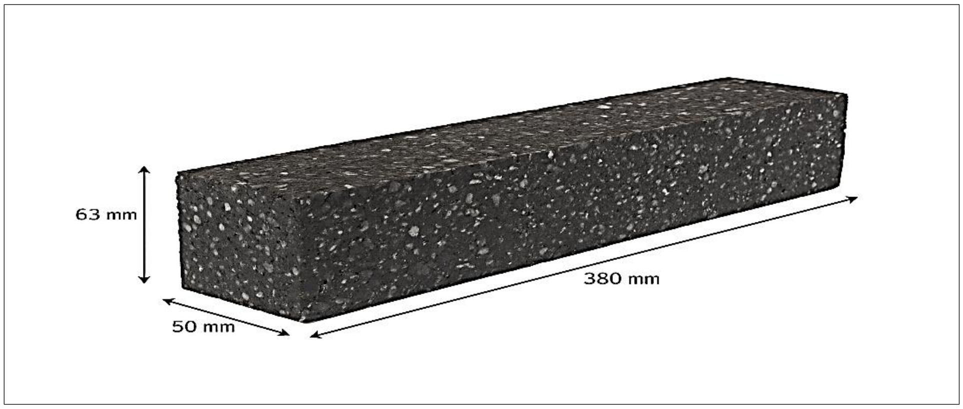

Figure 17. Asphalt beam specimen

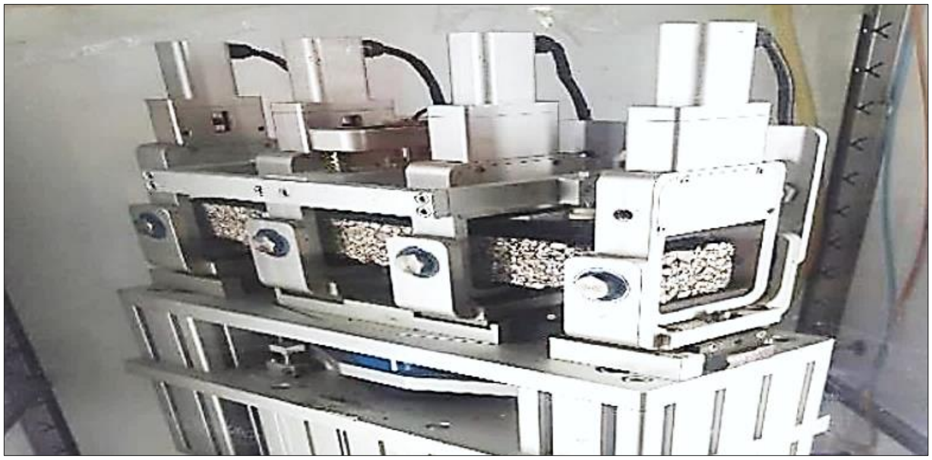

Figure 18. Fatigue testing apparatus for flexural behavior

2.3 ANN Model for Asphalt Rutting and Fatigue Prediction

In this study, the prediction of rutting and fatigue life (Nf) for asphalt pavement was carried out using an ANN model. ANNs are models of computation based on human brain architecture that can learn complicated, nonlinear relationships among inputs and outputs. Statistical analysis and prediction were conducted by the ANN model by learning complicated, nonlinear association that may elude conventional statistical techniques. In this analysis, the ANN model was trained to forecast rutting depth and fatigue life depending on the number of load passes applied to the asphalt pavement surface and the corresponding strain levels. The asphalt mixtures utilized in the research were modified with SBS polymer, an amine-based anti-stripping agent (ASA) known as AD-here® LOF 65-00 EU, and Delta-S rejuvenator.

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2.3.1 Input Parameters

The input values for both rutting and fatigue life (Nf) ANN models are presented in Tables (10 and 11). The values were assumed on the basis of results acquired in this study, earlier research, and common practice.

Table 10. Asphalt rutting prediction model input values

Parameter	Value/Range	Description
Number of Passes (N)	5,000 to 100,000	The number of load applications on the pavement.
Rutting Depth (mm)	0.8mm, 2.0mm, 3.2mm, and 4.1mm	Experimental data were collected for the observed rutting depths in the current study
Hidden Layers	Three hidden layers with: - 16 neurons in the first layer. - 32 neurons in the second layer. - 16 neurons in the third layer	Rectified Linear Unit (ReLU) to introduce non-linearity
Activation Function	ReLU	Rectified Linear Unit for non-linear transformations.
Solver	Adam	Optimizer for weight updates during training.
Regularization (L_2)	0.001	Applied to prevent overfitting.

Table 11. Asphalt fatigue life model input values

Parameter	Value/Range	Description
Strain Level (ε)	200 to 400 (με)	Experimental data was collected for the appeared fatigue life in the current study
Cycles to Failure (Nf)	120,000 cycles 65,000 cycles	The number of cycles the asphalt can withstand before fatigue in the current study
Input Layer	1 neuron (strain level)	Represents the applied strain level (με)
Hidden Layers	16 → 32 → 16 neurons	Captures non-linear relationships.
Activation Function	ReLU	Introduces non-linearity to the model
Output Layer	1 neuron	Predicts the fatigue life (Nf).
Optimizer	Adam	Efficient gradient-based optimizer
Loss Function	Mean Squared Error (MSE)	Measures prediction accuracy
Epochs	2000 iterations	Number of times the model is trained over the dataset
Regularization (L_2)	0.001	Prevents overfitting by controlling weight size.

2.3.2 Calculation Stage and the Used Equations

- Rutting

$$y^{\wedge 1} = f(W_3 \times f(W_1 \times X \times b_1) + b_2) + b_3)$$

$y^{\wedge 1}$: represents the predicted rutting depth generated by the ANN model.

f: is the ReLU activation function.

Wi: are the weight matrices for each layer.

bi: are the bias terms for each layer.

X: is the Number of Passes applied to the asphalt pavement.

- Fatigue

$$h_1 = ReLU(W_1 \times X_{scaled} + b_1)$$

$$h_2 = ReLU(W_2 \times h_1 + b_2)$$

$$h_3 = ReLU(W_3 \times h_2 + b_3)$$

$$y^{\wedge 2} = W_4 \times h_3 + b_4$$

W: weight matrix for the intended layer

b: bias term for the intended layer

h1, *h2*, *h3* represent the outputs of the hidden layers

X_{scaled}: is the normalized version of the original input data

$y^{\wedge 2}$: represents the predicted fatigue life

3. Results and Discussions

3.1 Asphalt Rutting Results

The results of the Hamburg wheel tracking test clearly show that the modified asphalt mixture (with 4% SBS, 0.5% amine-based anti-stripping agent, and 5% tall oil) performs significantly better than the unmodified control mix in terms of rutting resistance and moisture susceptibility. At 20,000 passes, the control specimen reached a rut depth of 9.2 mm, while the modified mix exhibited only 4.1 mm, representing a 55% reduction in rutting, as shown in Figure 19. This demonstrates a substantial improvement in the mixture's ability to resist permanent deformation under repeated loading. Moreover, the control mix showed progressive moisture-related damage through an increasing rut depth, while the modified mix maintained a stable, gradual deformation trend, with no visible signs of stripping throughout the test.

The improved performance is credited to the elastic network formed by SBS, enhanced binder–aggregate adhesion due to the anti-stripping agent, and the flexibility and cohesion restoration provided by tall oil, collectively making the modified mix more suitable for high-performance, climate-resilient pavement applications.

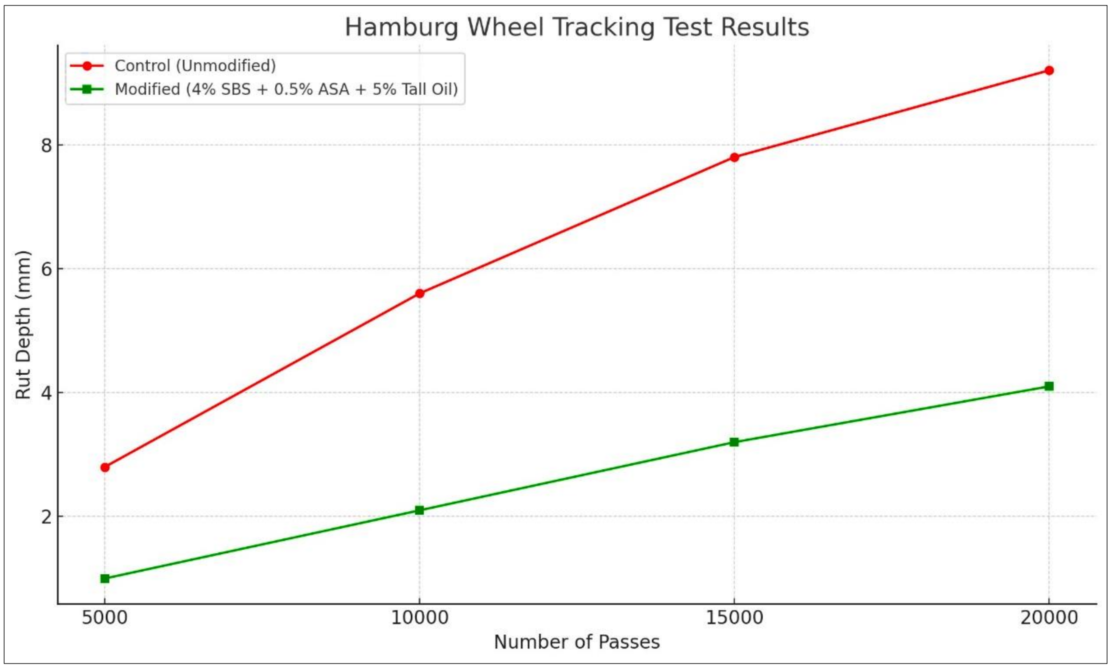

Figure 19. The attained findings of Hamburg wheel tracking test

A recent study by Calabi-Floody A, et al. [23], planned to improve the mechanical characteristics of hot mix asphalt by jioning polymer fibres derived from end-of-life tyres. The study focused on assessing the rutting resistance of these modified asphalt mixtures utlizing the Hamburg Wheel Tracking Test (HWTT) at 50° C. The results indicated improved rutting resistance when matched against conventional mixes, and this illustrated the viability of end-of-life tyres (ELT) fibre as asphalt pavements' sustainable additives. Expanding on earlier methods, this study moved an important step ahead by incorporating a powerful mix of SBS polymer, an amine antistripping agent, and tall oil to deal directly with rutting and moisture damage. HWTT measurements at 50° C demonstrated a significant reduction in rut depth and 0% stripping for up to 20,000 passes, exceeding previous polymer-based treatments. This innovative combination distinguishes our study as a forward-thinking contribution to the creation of long-lasting, climate-resistant asphalt pavement.

3.2 Asphalt Fatigue Results

The results of the strain-controlled four-point bending beam test revealed significant improvements in both fatigue life (Nf) and initial stiffness for the modified asphalt mixture incorporating 4% SBS, 0.5% Amine-Based Anti-Stripping Agent, and 5% Tall Oil compared to the unmodified control mixture.

At 200 με strain, the modified mixture achieved an initial stiffness of 720 MPa, significantly higher than the 480 MPa observed in the control mixture. Similarly, at 400 με strain, the modified mixture maintained a stiffness of 700 MPa, compared to 450 MPa for the control, as shown in Figure 20. In terms of fatigue life (Nf), the modified combination displayed extraordinary durability, reaching 120,000 cycles at 200 με and 65,000 cycles at 400 με, whereas the control mixture only lasted 35,000 cycles and 15,000 cycles, respectively, as shown in Figure 21. These results evidently reveal that combined change increases the elastic properties and cracking resistance of the mixture and greatly elevates its service life when it is subject to repeated loading conditions.

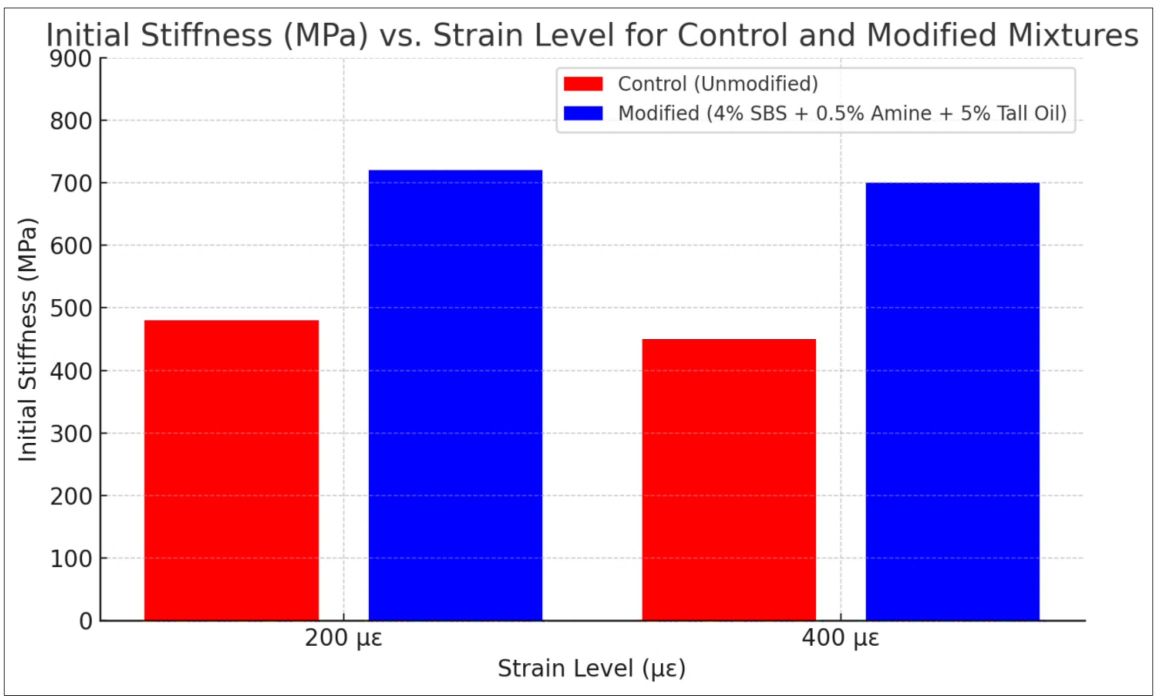

Figure 20. The initial stiffness values for both control and modified mixtures

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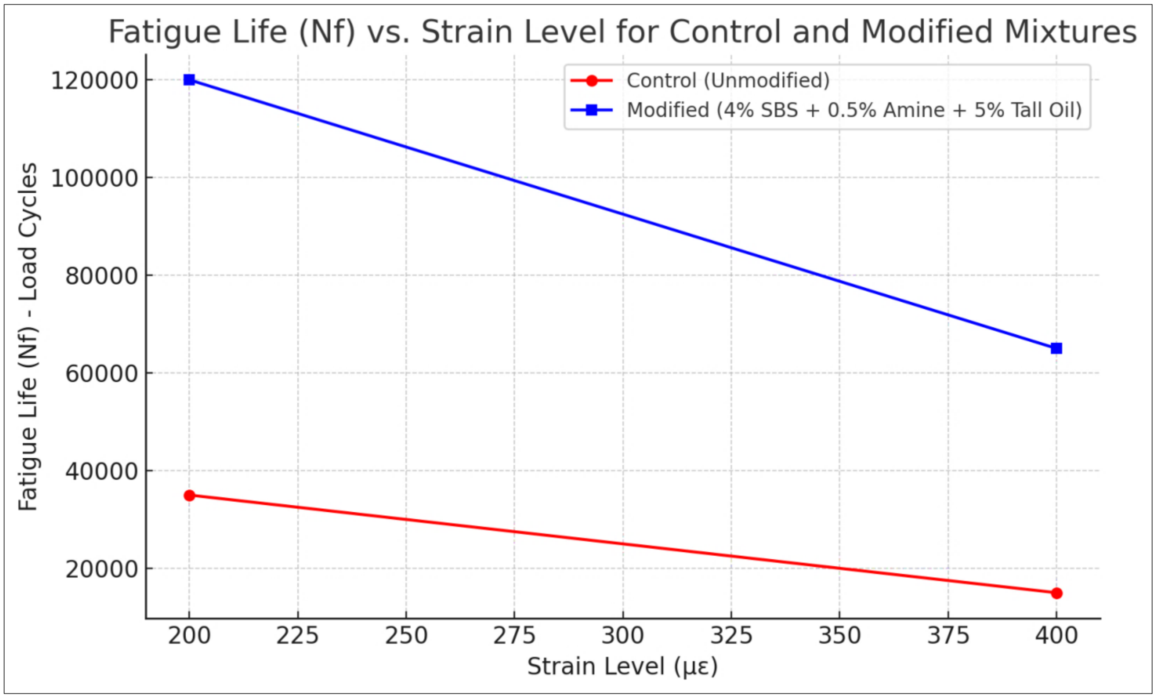

Figure 20. The fatigue life, Nf values for both control and modified mixtures

Lucas Junior JL et al. [24] aimed to assess the influence of incorporating an amine-based anti-stripping agent on the fatigue performance of asphalt mixes. In extensive laboratory testing, it was determined that addition of the agent substantially enhanced the fatiguing lives of the mixtures, offering enhanced resistance to cracking with repeated loading. These findings show the ability of anti-stripping compounds to extend the service life of asphalt pavements, making them a possible alternative for more durable and robust road surfaces. On the other hand, the current data show a significant increase in fatigue life compared to the unmodified control mixture. Furthermore, the modified mixture showed a significant 50% to 60% improvement in early stiffness over the control. These advances not only correlate with earlier research, but they also advance our understanding of material behavior by combining SBS, anti-stripping agents, and rejuvenators. This combination alteration effectively closes gaps in previous research, establishing a new standard for durability and crack resistance under repeated loads.

3. ANN Model Results

- In Terms of Rutting

Rutting is a prevalent defect in asphalt pavements, categorized by permanent deformation under repeated traffic loads. Accurate rutting prediction is crucial for maintenance planning and durability assessment. Figure 21 shows that the ANN model successfully learnt rutting behavior and delivered realistic predictions for up to 100,000 passes. Regularization and data augmentation increased stability, whereas normalization facilitated efficient learning.

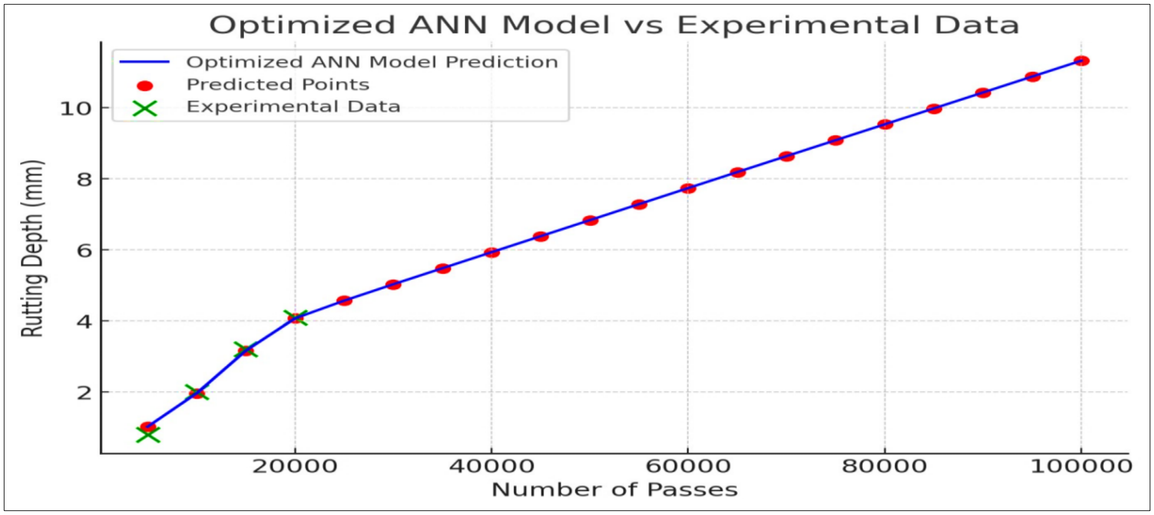

Figure 21. The ANN model for rutting prediction aligns with the experimental data

During the initial passes, the ANN model predictions match the experimental data closely, and the growth rate remains reasonable as the number of passes grows. The trend is smooth and continuous, representing genuine pavement behavior under loading conditions.

- **In Terms of Fatigue**

The calculation of fatigue life (Nf) for asphalt mixtures under repetitive loading is vital for determining pavement durability. The trained ANN can now forecast fatigue life across a wide range of strain levels, making it an effective tool for pavement design and maintenance planning. Figure 22 shows that the model effectively predicted strain levels ranging from 100 to 600 με.

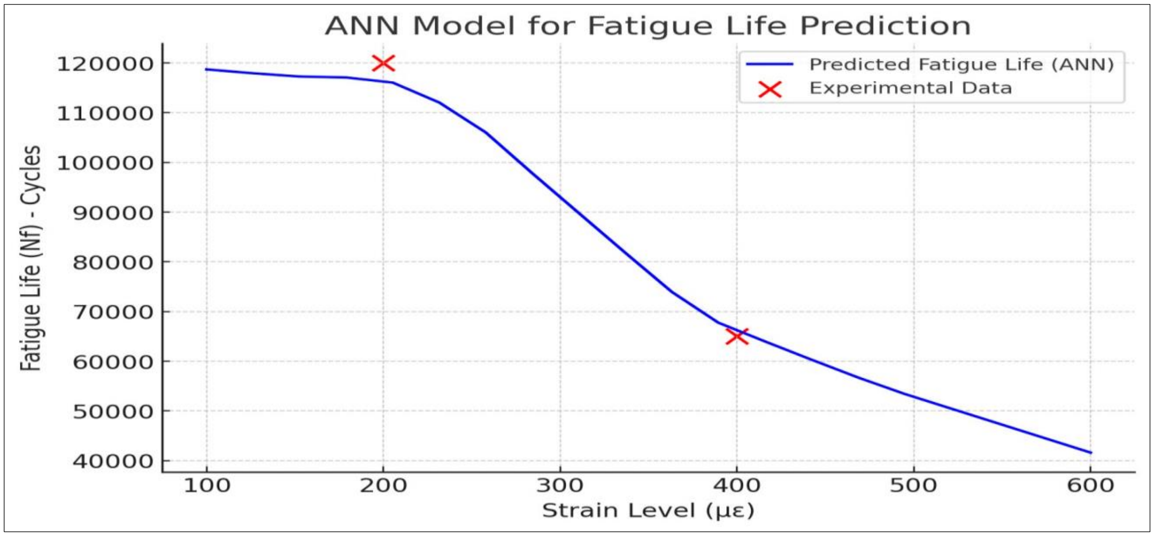

Figure 22. The ANN model for fatigue life prediction aligns with the experimental data

The ANN model accurately reflects the overall pattern, showing a gradual reduction in fatigue life as strain increases. The projections closely match the actual results, accurately representing the anticipated decrease in fatigue life at higher strain values.

4. Conclusions

This study successfully created a climate-resilient asphalt mixture with the aid of combining SBS polymer, an amine-based anti-stripping agent(AD-here® LOF 65-00 EU), and a tall oil rejuvenator (Delta-S).Comprehensive laboratory studies, inclusive of rutting and fatigue resistance tests using the Hamburg wheel-track test and the stress-controlled four-factor bending beam take a look at, showed the brand new combination's progressed overall performance. Furthermore, Artificial Neural Network (ANN) models had been used to forecast rutting depth and fatigue life (Nf), presenting important insights into long-term pavement durability in unfavorable weather situations. The following conclusions are formed from the study's findings and previous discussions: -

1- The modified asphalt aggregate exhibited a 55% decrease in rut depth related to the manage at 20,000 passes, highlighting its advanced resistance to rutting and moisture susceptibility.
2- The modified asphalt aggregate attained a 50% increase in initial stiffness at each 200 με and400 με strain levels associated with the manage, demonstrating better structural support and resistance to deformation.
3- The modified asphalt mixture exhibited a threefold increase in fatigue life, reaching 120,000 cycles at 200 με and 65,000 cycles at 400 με, compared to only 35,000 cycles and 15,000 cycles for the control, highlighting its enhanced durability under repeated loading.
4- The ANN model accurately captured pavement behavior, aligning well with experimental data for both rutting and fatigue life. It successfully predicted rutting up to 100,000 passes and fatigue life up to 600 με, demonstrating reliability and consistency with the study's experimental results.

The modified asphalt mixture demonstrated significant improvements in initial stiffness, fatigue life, and rutting resistance, with ANN models confirming its durability up to 100,000 passes and 600 με. These findings not only identify superior resilience to weather and climate conditions, but also point to a sustainable progression by lengthening lifespan of pavements, minimizing repair requirements, and hence reducing the environmental impact created by material production and maintenance processes. However, the current study was limited by the absence of long-term field validation, testing across diverse climates, and accelerated aging assessments. Future work should focus on real-world performance monitoring, broader climatic evaluations, enhanced ANN model training, and cost-benefit analysis to fully understand its practical application and durability.

Availability of Data and Materials: The datasets used and analyzed in this study are available from the corresponding author upon reasonable request.

Conflict of interest: The authors declare that they have no conflicts of interest to report.

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تطوير خلطة إسفلتية متقدمة مقاومة للظروف المناخية باستخدام بوليمر ستيرين–بوتادين–ستيرين ، ومادة مضادة للانفصال، وزيت الصنوبر كعامل مجدد: دراسة مختبرية شاملة ونمذجة تنبؤية بالشبكات العصبية الاصطناعية

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الخلاصة

تشكل الظروف الجوية والمناخية القاسية تحديات كبيرة أمام متانة وأداء الرصف الاسفلتي، حيث تعجل في حدوث التشوهات مثل التخدد، وأضرار الرطوبة، والتشقق. وللتصدي لهذه التحديات، تقدم هذه الدراسة طرق فعالة لتطويرخلطة أسفلت مقاومة لتأثيرات المناخ، محسنّة بإضافة 4% من بوليمر ستيرين–بوتادين–ستيرين(SBS) ، و0.5% من عامل اميني مضاد للانفصال (AD–here® LOF 65–00 EU)، و5% عامل مجدد من زيت الصنوبر (Delta–S). أُجريت تجارب مختبرية شملت اختبار مسار عجلة هامبورغ لمقاومة التخدد، واختبار انحناء العتب المسند رباعيا لتقييم عمر الكلل (Nf) ، حيث اظهرت النتائج تحسينات كبيرة في الخلطات المعدلة مقارنة بالخلطة الرئيسية غير المعدلة. حققت الخلطة المعدلة انخفاضًا بنسبة 55% في عمق التخدد عند 20,000 دورة، وزيادة بنسبة 50% في الصلابة الابتدائية، حيث وصلت إلى 720 ميجا باسكال عند 200 ميكرو انفعال و700 ميجا باسكال عند 400 ميكرو انفعال. وفيما يتعلق بأداء الكلل، استمرت الخلطة في تحمل 120,000 دورة عند 200 ميكرو انفعال و65,000 دورة عند 400 ميكرو انفعال، أي ما يقرب من ثلاثة أضعاف متانة الخلطة الرئيسية. علاوة على ذلك، تم استخدام نماذج الشبكة العصبية الاصطناعية (ANN) لتوقع عمق التخدد وعمر الكلل حتى 100,000 دورة و600 ميكرو انفعال، مما يوفر موثوقية لتوقع الأداء تحت ظروف مناخية قاسية. كشفت النتائج أن النهج المقترح في التعديل يعزز بشكل كبير السلامة الهيكلية، ومقاومة الرطوبة، والمتانة طويلة الأمد لأرصفة الأسفلت. لا يقتصر هذا العمل على سد الفجوة بين الاختبارات المخبرية والتطبيق العملي فحسب، بل يؤسس أيضًا معيارًا جديدًا لتصميم الأرصفة المرنة والمستدامة في البيئات الصعبة من خلال تعزيز عمر الخدمة وتقليل متطلبات الصيانة، مما يؤدي إلى تقليل استهلاك الموارد

الكلمات الدالة: الإسفلت المقاوم للظروف المناخية، بوليمر ستيرين–بوتادين–ستيرين، معامل مضاد للانفصال، زين الصنوبر كعامل مجدد، مقاومة التخدد، التنبؤ بعمر الكلل، الشبكات العصبية الاصطناعية