

Laboratory Study on the Optimization of Asphalt Mixing Protocols

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KEYWORDS	ABSTRACT
Mixing Protocols Asphalt Mix Design Hot Mix Asphalt Random Forest Gradient Boosting SHAP	Mixing parameters significantly influence asphalt-mixture performance, yet mixing speed, time, and temperature are commonly selected from general practice rather than optimized against performance criteria. This study evaluated the effects of these parameters on Marshall stability and semi-circular bending (SCB) fracture load. A balanced $3 \times 2 \times 2$ full-factorial design was used, comprising three temperatures (135, 150, and 165 °C), two mixing times (2 and 7 min), and two mixing speeds (1500 and 3000 rpm), with three replicate batches per treatment. The optimum binder content was 3.5% of the total mixture mass, as determined using the Marshall mix design method. The best overall performance occurred at 165 °C, 7 min, and 3000 rpm, yielding a Marshall stability of 12.9 kN and an SCB fracture load of 57.5 kN. Factorial ANOVA showed that mixing temperature, time, and speed significantly affected both responses ($p < 0.001$). Exploratory machine-learning models were developed to predict performance from the mixing parameters. Random Forest outperformed Gradient Boosting, with R^2 values of 0.794 for Marshall stability and 0.828 for SCB fracture load. The results demonstrate that coordinated optimization of mixing temperature, time, and speed can improve asphalt-mixture stability and fracture resistance, while data-driven models can support laboratory-scale protocol selection.

1. Introduction

Asphalt is among the most widely used pavement materials in the transportation industry because it is economical, workable, and capable of providing a smooth, durable riding surface [1]. Its performance under traffic loading and varying environmental conditions depends strongly on the quality and uniformity of the asphalt mixture [1,2]. Production procedures, particularly mixing temperature, time, and speed, directly affect mixture homogeneity, workability, and durability [3,4]. These parameters influence binder–aggregate adhesion, material distribution, and cracking resistance; even small variations can therefore produce substantial differences in mechanical performance [5].

Conventional hot-mix asphalt production generally heats the binder within approximately 135–160 °C to obtain sufficient fluidity for aggregate coating and mixture workability [6]. However, this range is usually applied as a broad practice rather than optimized for specific performance targets. Increasing temperature within recommended limits can reduce binder viscosity, improve aggregate coating, and promote uniform dispersion of modifiers or additives [5,8,9]. Excessive temperature, however, may accelerate binder aging, volatilize lighter fractions, increase emissions, and reduce long-term pavement durability [8,10].

Mixing time is also critical to mixture uniformity. Insufficient mixing can result in incomplete aggregate coating, whereas longer mixing can improve binder–aggregate adhesion and the distribution of additives in

modified or recycled mixtures [10]. Excessive mixing may nevertheless promote oxidative aging or damage temperature-sensitive additives. Mixing speed is another frequently overlooked variable. The applied shear energy affects fine-particle dispersion, air-void distribution, and aggregate degradation, thereby influencing the mechanical response of the mixture [11,12].

Despite their importance, precise performance-based ranges for mixing temperature, time, and speed remain insufficiently defined for many asphalt mixtures. Existing specifications generally provide broad recommendations derived from experience rather than systematic laboratory optimization. This limitation is becoming increasingly important as modified binders, reclaimed asphalt pavement (RAP), warm-mix technologies, and other innovations respond differently to mixing procedures [13,14].

Accordingly, this study systematically investigates the effects of mixing temperature, time, and speed on Marshall stability and semi-circular bending (SCB) fracture load. The objective is to quantify the individual and interactive effects of these parameters and identify a mixing protocol that improves load-bearing capacity, fracture resistance, durability, and structural integrity [15].

The findings provide a data-driven basis for refining asphalt-mixing protocols and supporting performance-based production specifications. Optimized procedures may improve quality assurance, extend pavement service life, reduce premature failure, and lower economic and environmental costs. Such guidance is particularly relevant to road agencies and practitioners operating under severe climates or high traffic volumes.

2. Materials and methods

2.1 Research Approach

This study evaluated the effects of mixing temperature, time, and speed on the mechanical performance of asphalt mixtures, following the workflow shown in Fig. 1. The factor levels were selected from published literature and common asphalt-plant practice and are listed in Table 1. A balanced $3 \times 2 \times 2$ full-factorial design was adopted, comprising three temperatures, two mixing times, and two mixing speeds. The design produced 12 treatment combinations, each represented by three replicate batches.

A locally supplied 60/70 penetration-grade bitumen from Attock Refinery Limited (ARL) was used as the binder. Its physical properties were

evaluated using the standard tests summarized in Table 3.

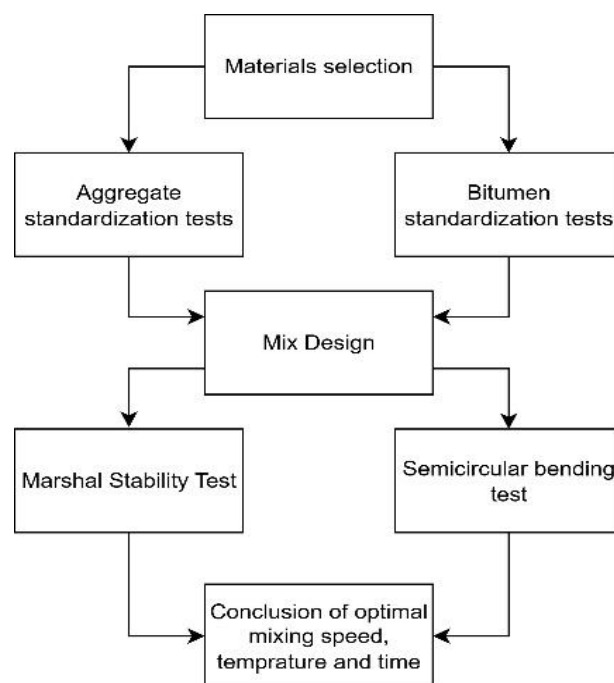


Fig. 1. Research Methodology

Table 1

Assigned Values for Parameters

Parameter	Levels
Mixing temperature	135, 150, and 165 °C
Mixing speed	1500 and 3000 rpm
Mixing time	2 and 7 min

The asphalt mixture was prepared at a binder content of 3.5% by total mixture mass. Accordingly, each 1200 g batch contained 42 g of bitumen and 1158 g of aggregate. The selected aggregate gradation satisfied the requirements for a dense-graded mixture.

2.2 Materials

Locally available crushed stone was used as the fine and coarse aggregate. Its physical properties were determined using standard characterization tests, as summarized in Table 2.

Table 2.

Aggregate Standardization Tests

Test	Standard	Acceptance criterion
Flakiness and elongation index	ASTM D4791	Flat-to-elongated ratio = 5:1

Test	Standard	Acceptance criterion
Aggregate crushing value	ASTM C131	Asphalt wearing course $\leq 30\%$
Aggregate impact value	ASTM C535	Wearing course (surface layer) $\leq 30\%$
Bulk specific gravity	ASTM C127	Dense-graded HMA: 2.20–2.50
Los Angeles abrasion	ASTM C131/C131M	Wearing course (surface): $\leq 30\text{--}35\%$

Table 3.

Bitumen Standardization Tests

Test	Standard	Acceptance criterion
Specific gravity	ASTM D70	1.01–1.06
Softening point	ASTM D36/D36M	60/70 grade bitumen: 49–56 °C
Ductility	ASTM D113	> 75 cm for paving-grade 60/70 bitumen
Flash and fire point	ASTM D92	Flash point > 220 °C; fire point typically $> 240\text{--}250$ °C
Penetration	ASTM D5/D5M	40–120, depending on bitumen grade

2.3 Mix Design

The Marshall mix design method was used for mixture preparation. An optimum binder content of 3.5% by total mixture mass was selected because it produced the highest Marshall stability among the 3.0, 3.5, and 4.0% contents evaluated. To isolate the effects of the mixing-protocol variables, the binder content was held constant for all treatment combinations. Each 1200 g batch therefore contained 42 g of bitumen and 1158 g of aggregate. The aggregate gradation is presented in Table 4.

Table 4.

Mix Design

Sieve size (mm)	Percentage passing (%)	Percentage retained (%)	Material retained (g)
19 mm	100%	0%	0
12.5 mm	82%	18%	208.44

Sieve size (mm)	Percentage passing (%)	Percentage retained (%)	Material retained (g)
9.5 mm	63%	19%	220.02
6.3 mm	54.60%	8.40%	97.272
2.36 mm	29%	25.60%	296.448
1.18 mm	18.50%	10.50%	121.59
0.6 mm	13.50%	5%	57.9
0.3 mm	10%	3.50%	40.53
0.15 mm	7.10%	2.90%	33.582
0.075 mm	5%	2.10%	24.318
Pan	0%	5%	57.9

2.4 Specimen Preparation

The aggregate and binder were heated separately to the designated mixing temperature. Mixing was performed using a laboratory mechanical mixer at 135, 150, or 165 °C; for 2 or 7 min; and at 1500 or 3000 rpm. The mixtures were then compacted using the Marshall compaction method to produce cylindrical specimens for stability testing and semi-circular specimens for SCB testing. Three replicate specimens were prepared and tested for each treatment combination to improve repeatability and reduce random experimental variation.

2.5 Testing Procedure

The Marshall stability test was performed in accordance with ASTM D6927 to determine stability (kN), flow (mm), air voids (%), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). The recommended performance ranges were used for comparison. The semi-circular bending (SCB) test was conducted in accordance with ASTM D8044 to evaluate intermediate-temperature cracking behavior. Fracture load was the primary SCB response reported in this study. Specimens 150 mm in diameter and 50 mm thick, with a 15 mm notch, were tested at a loading rate of 0.5 mm/min. The test requirements are summarized in Table 5.

2.6 Machine Learning

To supplement the laboratory investigation, machine-learning models were developed using mixing temperature, time, and speed as input variables and Marshall stability and SCB fracture load as output targets. Random Forest and Gradient Boosting

regression models were trained using an 80:20 train/test split. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE). Feature-importance and SHAP analyses were also conducted to interpret model behavior.

Table 5.

Performance Tests

Test	Standard	Recommended range
Marshall stability test	ASTM D6927	Stability: 8–16 kN
		Flow: 8–18 units (0.25 mm/unit)
		Air voids: 3–5%
		VMA: 14–17%
		VFA: 65–75%
Semi-circular bending (SCB) test	ASTM D8044	Fracture energy: 100–600 J/m ²
		Flexibility index: 4–12
		Critical strain-energy release rate (Jc): 0.3–1.5 kJ/m ²
		Crack-initiation load varies with mixture and specimen geometry

2.7 Statistical Analysis

Factorial analysis of variance (ANOVA) was used to evaluate the effects of mixing temperature, speed, and time on Marshall stability and SCB fracture load. The balanced $3 \times 2 \times 2$ design comprised three temperatures (135, 150, and 165 °C), two speeds (1500 and 3000 rpm), and two times (2 and 7 min), with three replicate specimens per treatment combination. Separate three-way ANOVA models were fitted to the replicate-level Marshall stability and SCB fracture-load data. The factors were treated as categorical variables, and Type II sums of squares were used to evaluate main effects and interactions. Residual normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene tests, respectively. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$), and partial eta-squared values were calculated to quantify effect sizes.

3. Results and discussion

3.1 Coarse Aggregate Standardization Test Results

3.1.1 Flakiness and elongation value

The flakiness and elongation indices were determined in accordance with ASTM D4791 using three replicate tests. The average values were 20.87 and 12.79%, respectively. A high flakiness index can hinder

compaction and reduce structural integrity, while a high elongation index may promote segregation during handling. The comparatively low values obtained indicate that the aggregate is suitable for pavement applications.

Table 6.

Aggregate Standardization Test Results

Test	Standard	Result
Flakiness and elongation index test	ASTM D4791	20.87% flakiness and 12.79% elongated particles
Aggregate crushing value test	ASTM C131	27%
Impact value test	ASTM C535	7.9%
Bulk specific gravity	ASTM C127	2.45
Los Angeles abrasion test	ASTM C131 / C131M	22.29%

3.1.2 Crushing value

The aggregate crushing value was determined in accordance with ASTM C131/C131M using three replicate tests. The average value was 27%, which is below the specified limit of 30%. This result indicates moderate strength and durability and supports the use of the aggregate in general pavement applications.

3.1.3 Impact value

The aggregate impact value was determined in accordance with ASTM C535 using three replicate tests. The average value was 7.9%. Because values below 10% indicate very strong aggregate, the result suggests high toughness and resistance to impact-induced fracture.

3.1.4 Specific gravity of aggregate

The bulk specific gravity of the aggregate was determined in accordance with ASTM C127 using three replicate tests. The average value was 2.45, which falls within the typical range of 2.4–3.0 for road-construction aggregate. This value indicates moderate density and porosity and supports the suitability of the aggregate for general pavement construction.

3.1.5 Los Angeles abrasion value

The Los Angeles abrasion value was determined in accordance with ASTM C131/C131M using three replicate tests. The average value was 22.29%, below the specified maximum of 30% for road-construction

aggregate. The result indicates adequate hardness and resistance to traffic-induced wear.

3.2 Bitumen Standardization Test Results

Table 7.

Bitumen Standardization Test Results

Test	Standard	Result
Specific gravity	ASTM D70	1.02
Softening point	ASTM D36 / D36M	53.7 °C
Ductility	ASTM D113	95 cm
Flash and fire point	ASTM D92	Flash point: 190 °C Fire point: 240 °C
Penetration	ASTM D5 / D5M	63

3.2.1 Specific gravity

The specific gravity of the bitumen was determined in accordance with ASTM D70 using three replicate tests. The average value was 1.02, within the specified range of 0.97–1.02. This result supports the suitability of the binder for pavement applications.

3.2.2 Softening point

The softening point of the bitumen was determined in accordance with ASTM D36 using three replicate tests. The average value was 53.7 °C. This value indicates thermal properties appropriate for moderate climatic conditions and suggests adequate resistance to temperature-related deformation.

3.2.3 Ductility value

Bitumen ductility was determined in accordance with ASTM D113 using three replicate tests. The average value was 95 cm, which is suitable for a 60/70 penetration-grade binder. The result indicates adequate flexibility and cohesive strength under pavement loading.

3.2.4 Flash and fire point

The flash and fire points of the bitumen were determined in accordance with ASTM D92 using three replicate tests. The measured flash and fire points were 190 and 240 °C, respectively. These temperatures define the safe handling and heating limits of the binder during laboratory and production operations.

3.2.5 Penetration test

The penetration value was determined in accordance with ASTM D5 using three replicate tests. The measured value was 63, confirming that the binder

falls within the 60/70 penetration grade. This grade provides a balance between hardness and flexibility for moderate climatic conditions.

3.3 Marshall Stability Test Results

Table 8.

Marshall Stability Test Results

Treatment combinations			
Time (min)	Temperature (°C)	Speed (rpm)	Stability (kN)
2	135	1500	5.5
2	150	1500	8.24
2	165	1500	8.91
2	135	3000	7.33
2	150	3000	10.8
2	165	3000	11.2
7	135	1500	6.24
7	150	1500	9.57
7	165	1500	11.59
7	135	3000	8.26
7	150	3000	11.8
7	165	3000	12.9

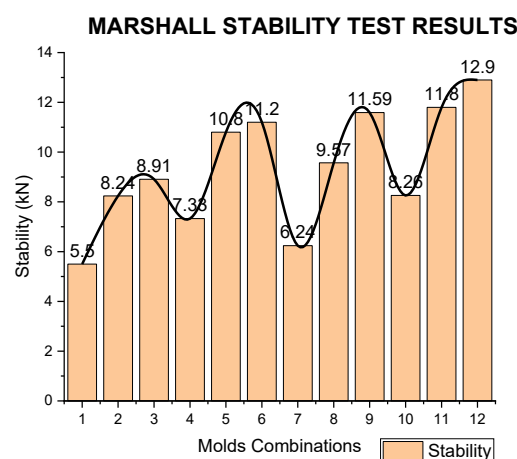


Fig. 2. Marshall Stability Test Results

3.3.1 Effect of changing mixing time on performance

Mixing time had a positive, although generally smaller, effect on Marshall stability than temperature or speed. At 135 °C and 1500 rpm (combinations 1 and 7), increasing the mixing time from 2 to 7 min raised stability from 5.50 to 6.24 kN (13.45%). At 150 °C

and 1500 rpm (combinations 2 and 8), stability increased from 8.24 to 9.57 kN (16.14%).

At 165 °C and 1500 rpm (combinations 3 and 9), stability increased from 8.91 to 11.59 kN (30.08%). At 165 °C and 3000 rpm (combinations 6 and 12), the corresponding increase was from 11.20 to 12.90 kN (15.18%).

At 135 °C and 3000 rpm (combinations 4 and 10), stability increased from 7.33 to 8.26 kN (12.69%). At 150 °C and 3000 rpm (combinations 5 and 11), it increased from 10.80 to 11.80 kN (9.26%). These results indicate that longer mixing improves binder–aggregate blending, aggregate coating, and temperature uniformity, thereby increasing stability.

3.3.2 Effect of changing mixing temperature on performance

Marshall stability increased consistently with mixing temperature. At 2 min and 1500 rpm, stability increased from 5.50 to 8.24 kN between 135 and 150 °C (49.82%), from 8.24 to 8.91 kN between 150 and 165 °C (8.13%), and from 5.50 to 8.91 kN across the full temperature range (62.00%). At 2 min and 3000 rpm, stability increased from 7.33 to 10.80 kN between 135 and 150 °C (47.34%).

At 2 min and 3000 rpm, stability increased from 10.80 to 11.20 kN between 150 and 165 °C (3.70%) and from 7.33 to 11.20 kN between 135 and 165 °C (52.80%). At 7 min and 1500 rpm, the corresponding increases were 53.37% (135–150 °C), 21.11% (150–165 °C), and 85.74% (135–165 °C). At 7 min and 3000 rpm, stability increased by 42.86, 9.32, and 56.17% over the same temperature intervals, respectively.

The temperature effect is attributed primarily to reduced binder viscosity, which improves aggregate coating and compaction. Higher temperatures may also reduce residual moisture and strengthen binder–aggregate adhesion. Within the investigated range, these effects collectively increased Marshall stability.

3.3.3 Effect of changing mixing speed on performance

Increasing mixing speed from 1500 to 3000 rpm increased Marshall stability under every temperature–time combination. At 2 min, stability increased by 33.27% at 135 °C, 31.07% at 150 °C, and 25.70% at 165 °C. At 7 min and 135 °C, the increase was 32.37%.

At 7 min, stability increased by 23.30% at 150 °C and 11.30% at 165 °C. These results suggest that higher mixing speed improves binder dispersion, mixture homogeneity, and compaction, thereby reducing air voids and increasing stability.

3.4 Semi-Circular Bending (SCB) Test Results

Table 9.

Semi-Circular Bending (SCB) Test Results

Treatment combinations			
Time (min)	Temperature (°C)	Speed (rpm)	Fracture load (kN)
2	135	1500	28.5
2	150	1500	31.75
2	165	1500	33
2	135	3000	29.2
2	150	3000	35.2
2	165	3000	37
7	135	1500	30.5
7	150	1500	42.7
7	165	1500	45.2
7	135	3000	39
7	150	3000	52.7
7	165	3000	57.5

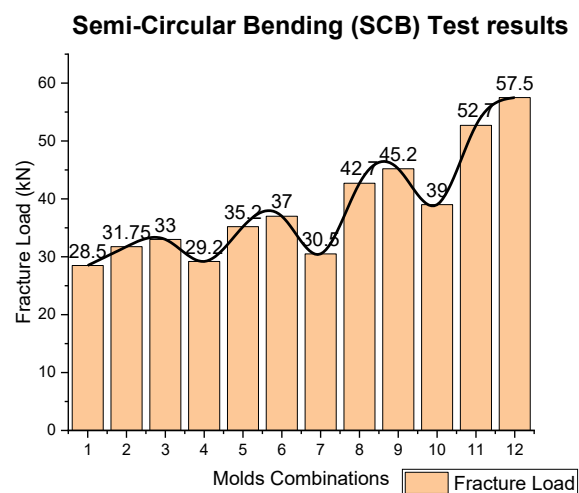


Fig. 3. Semi-Circular Bending (SCB) Test Results

3.4.1 Effect of changing mixing time on performance

Increasing the mixing time from 2 to 7 min increased SCB fracture load for every temperature–speed combination. At 1500 rpm, fracture load increased by 7.02% at 135 °C, 34.49% at 150 °C, and 36.97% at 165 °C.

At 3000 rpm, the corresponding increases were 33.56% at 135 °C, 49.72% at 150 °C, and 55.41% at 165 °C. The greater gains at higher temperatures and speeds indicate that mixing time interacted with the other processing variables.

3.4.2 Effect of changing mixing temperature on performance

Mixing temperature was evaluated at 135, 150, and 165 °C. At 2 min and 1500 rpm, fracture load increased by 11.40% between 135 and 150 °C, 3.94% between 150 and 165 °C, and 15.79% across the full range. At 2 min and 3000 rpm, the increase between 135 and 150 °C was 20.55%.

At 2 min and 3000 rpm, fracture load increased from 35.2 to 37.0 kN between 150 and 165 °C (5.11%) and from 29.2 to 37.0 kN between 135 and 165 °C (26.71%).

At 7 min and 1500 rpm, fracture load increased from 30.5 to 42.7 kN between 135 and 150 °C (40.00%) and from 42.7 to 45.2 kN between 150 and 165 °C (5.85%).

Across the full temperature range at 7 min and 1500 rpm, fracture load increased from 30.5 to 45.2 kN (48.20%). At 7 min and 3000 rpm, the increases were 35.13% between 135 and 150 °C, 9.11% between 150 and 165 °C, and 47.44% across the full range.

3.4.3 Effect of changing mixing speed on performance

Increasing mixing speed from 1500 to 3000 rpm increased SCB fracture load under every condition. At 2 min, fracture load increased by 2.46% at 135 °C, 10.87% at 150 °C, and 12.12% at 165 °C. At 7 min, the corresponding increases were 27.87% at 135 °C, 23.42% at 150 °C, and 27.21% at 165 °C.

Overall, increasing mixing time from 2 to 7 min raised fracture load by 7.02–55.41%, increasing temperature from 135 to 165 °C raised it by 15.79–48.20%, and increasing speed from 1500 to 3000 rpm raised it by 2.46–27.87%. These results demonstrate that coordinated optimization of time, temperature, and speed can substantially improve the fracture resistance of the asphalt mixture.

3.5 Machine Learning Results

Random Forest (RF) and Gradient Boosting (GB) models were used to predict Marshall stability and SCB fracture load from mixing time, temperature, and speed. Performance was assessed using R^2 , RMSE, MAE, and MAPE, as summarized in Table 10. Random Forest achieved the highest R^2 values: 0.794 for Marshall stability and 0.828 for SCB fracture load.

Table 10.

Random Forest and Gradient Boosting Model Performance

Model	Random Forest	Gradient Boosting
R^2 (Stability)	0.794	0.752
RMSE (Stability)	1.388	1.672
MAE (Stability)	1.127	1.198
MAPE (Stability)	0.145	0.140
R^2 (Fracture Load)	0.828	0.824
RMSE (Fracture Load)	13.498	13.852
MAE (Fracture Load)	2.728	3.180
MAPE (Fracture Load)	0.062	0.072

Both models captured the experimental trends to a reasonable extent, but Random Forest performed better overall. It produced higher R^2 values and lower RMSE and MAE values for both response variables. The results indicate that Random Forest can represent nonlinear relationships between mixing parameters and asphalt-mixture performance; however, validation using a larger dataset is required before practical deployment.

Figs. 4 and 5 compare predicted and experimental values for Marshall stability and SCB fracture load, respectively. The data generally follow the ideal diagonal trend, indicating that Random Forest captured the overall experimental response. Some deviations are evident at the extremes, but the agreement supports the use of mixing parameters as quantifiable predictors of stability and fracture resistance.

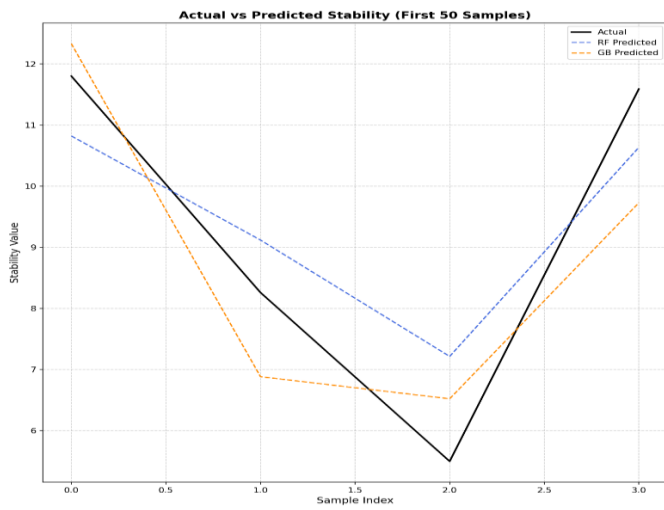


Fig. 4. Comparison Between Predicted and Experimental Marshall Stability

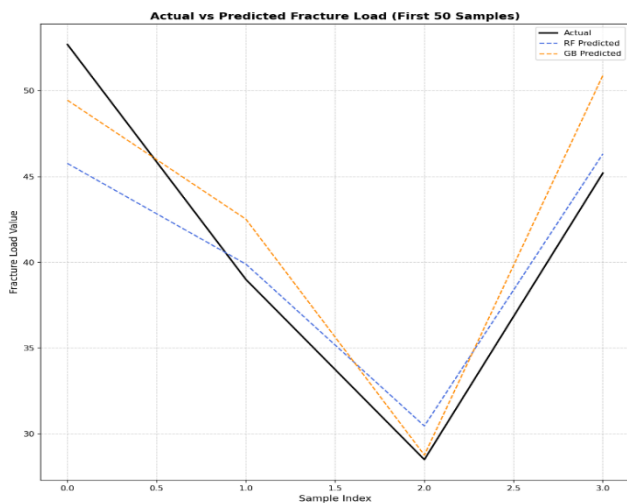


Fig. 5. Comparison Between Predicted and Experimental SCB Fracture Load

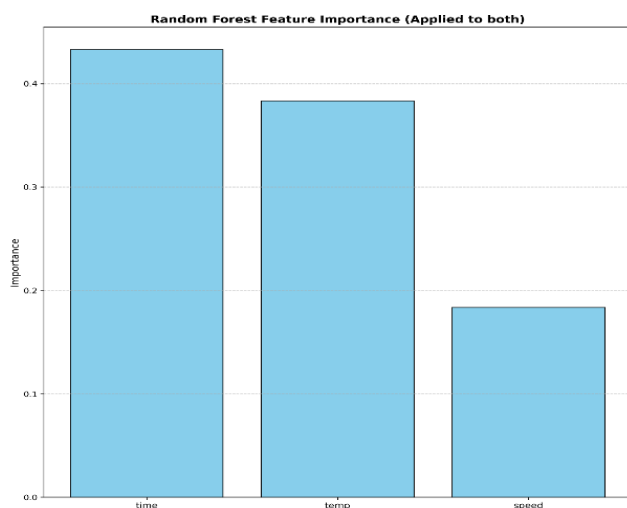


Fig. 6. Random Forest Feature Importance

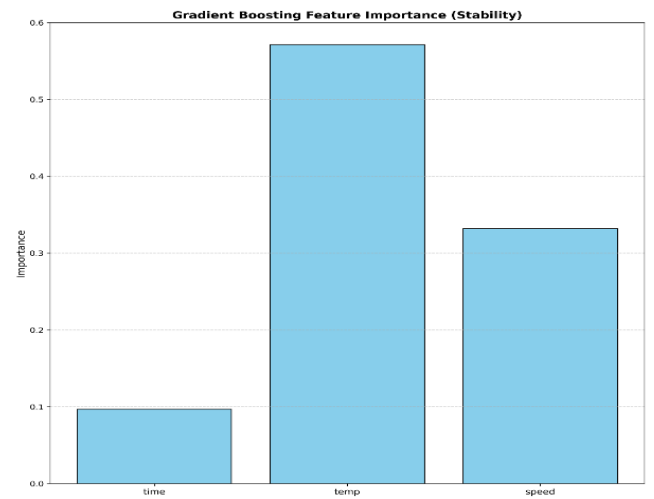


Fig. 7. Gradient Boosting Feature Importance for Marshall Stability

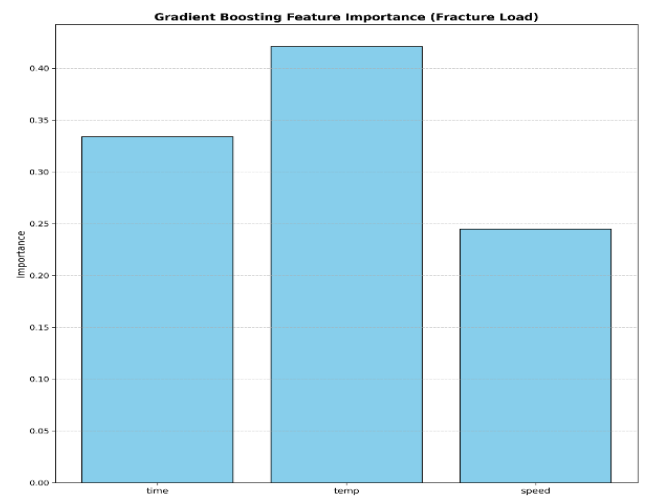


Fig. 8. Gradient Boosting Feature Importance for SCB Fracture Load

Figs. 6–8 present the feature-importance results. Gradient Boosting identified temperature as the strongest predictor of both Marshall stability and SCB fracture load, whereas Random Forest assigned substantial importance to both time and temperature. Mixing speed contributed less, but remained relevant. These patterns broadly agree with the laboratory and ANOVA results: temperature dominated Marshall stability, while SCB fracture load was strongly influenced by mixing time and interactions among the processing variables.

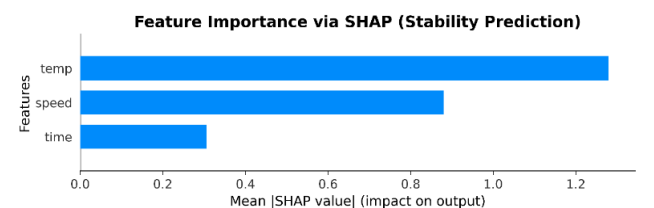


Fig. 9. SHAP Feature Importance for Marshall Stability

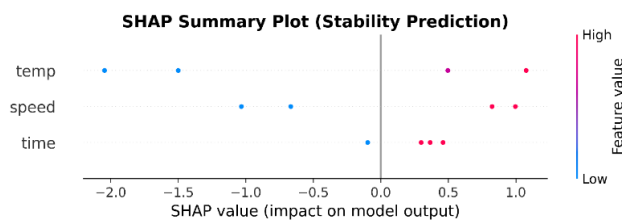


Fig. 10. SHAP Summary Plot for Marshall Stability

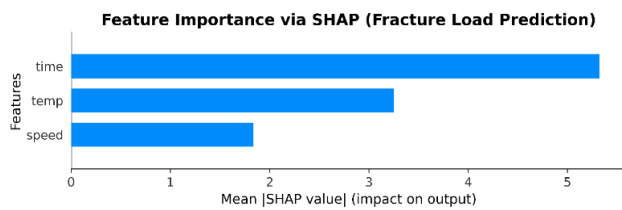


Fig. 11. SHAP Feature Importance for SCB Fracture Load

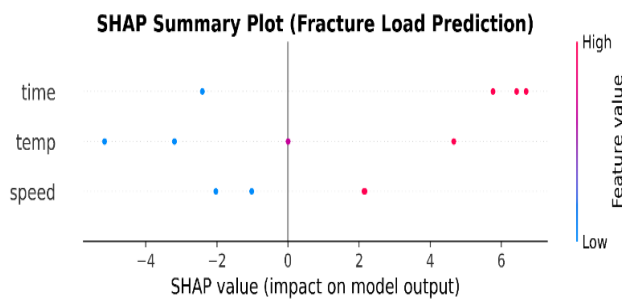


Fig. 12. SHAP Summary Plot for SCB Fracture Load

The SHAP analyses in Figs. 9–12 explain the direction and magnitude of each variable's contribution to the model predictions. Positive SHAP values increase the predicted response, whereas negative values decrease it. For Marshall stability, temperature had the largest overall contribution,

followed by speed and time. For SCB fracture load, mixing time had the greatest contribution, followed by temperature and speed. Higher temperature, longer mixing time, and higher speed generally produced positive contributions within the investigated ranges, consistent with the laboratory results.

3.6 Factorial ANOVA for Marshall Stability

The factorial ANOVA results for Marshall stability are presented in Table 11. Mixing time, temperature, and speed each had a statistically significant main effect ($p < 0.001$). Temperature produced the highest F-value and partial eta-squared value, identifying it as the dominant factor. The time $\times$ temperature interaction was also significant ($p = 0.001$), indicating that the effect of mixing duration varied across temperature levels. The time $\times$ speed, temperature $\times$ speed, and three-way interactions were not significant ($p > 0.05$).

The dominance of temperature is consistent with the role of binder fluidity and aggregate coating in stability development. As temperature increases, binder viscosity decreases, aggregate wetting improves, and denser compaction becomes possible. The significant time $\times$ temperature interaction further suggests that longer mixing is most beneficial when sufficient thermal energy is available to promote uniform coating and binder–aggregate bonding. Although higher speed improved stability, its nonsignificant interactions indicate a predominantly direct rather than synergistic effect.

Table 11.

Factorial ANOVA Results for Marshall Stability

Source	df	SS	MS	F-value	p-value	Significance	Partial η^2
Mixing time	1	17.556	17.556	105.132	<0.001	***	0.814
Mixing temperature	2	121.724	60.862	364.461	<0.001	***	0.968
Mixing speed	1	37.454	37.454	224.289	<0.001	***	0.903
Time $\times$ Temperature	2	2.996	1.498	8.969	0.001	**	0.428
Time $\times$ Speed	1	0.314	0.314	1.878	0.183	ns	0.073
Temperature $\times$ Speed	2	0.591	0.295	1.768	0.192	ns	0.128
Time $\times$ Temperature $\times$ Speed	2	0.515	0.258	1.543	0.234	ns	0.114
Error	24	4.008	0.167	—	—	—	—

3.7 Factorial ANOVA for SCB Fracture Load

The factorial ANOVA results for SCB fracture load are presented in Table 12. Mixing time, temperature, and speed each had a highly significant main effect ($p < 0.001$). All two-way interactions—time $\times$ temperature, time $\times$ speed, and temperature $\times$ speed—were also significant ($p < 0.001$), whereas the three-way interaction was not significant ($p = 0.320$). Mixing time produced the strongest main effect, followed by temperature and speed; all three factors had very large effect sizes.

These results indicate that SCB fracture resistance was more sensitive than Marshall stability to the combined action of the mixing variables. The significant two-way interactions show that the effect of one factor depended strongly on the levels of the others. This response is consistent with the influence of coating uniformity, mixture homogeneity, and the internal aggregate–binder structure on cracking resistance. The nonsignificant three-way interaction indicates that pairwise coupling was important, but the simultaneous interaction of all three factors did not provide an additional detectable effect within the investigated design space.

Table 12.

Factorial ANOVA Results for SCB Fracture Load

Source	df	SS	MS	F-value	p-value	Significance	Partial η^2
Mixing time	1	1330.426	1330.426	2609.874	<0.001	***	0.991
Mixing temperature	2	853.224	426.612	836.814	<0.001	***	0.986
Mixing speed	1	379.276	379.276	743.898	<0.001	***	0.969
Time $\times$ Temperature	2	183.024	91.512	179.568	<0.001	***	0.937
Time $\times$ Speed	1	128.256	128.256	251.633	<0.001	***	0.913
Temperature $\times$ Speed	2	19.149	9.574	18.787	<0.001	***	0.610
Time $\times$ Temperature $\times$ Speed	2	1.219	0.609	1.196	0.320	ns	0.091
Error	24	12.232	0.510	—	—	—	—

Conclusion

This study demonstrates that the mixing protocol is a critical determinant of asphalt-mixture performance. Mixing temperature, time, and speed were evaluated simultaneously, and all three factors significantly affected Marshall stability and SCB fracture load. The best overall performance occurred at 165 °C, 7 min, and 3000 rpm, yielding a Marshall stability of 12.9 kN and an SCB fracture load of 57.5 kN. Marshall stability was governed primarily by temperature, whereas fracture performance was more strongly influenced by the combined effects of time, temperature, and speed. These improvements are attributed to lower binder viscosity, more uniform

aggregate coating, greater mixture homogeneity, and improved compaction.

The factorial ANOVA results confirmed the experimental trends. All three main effects were significant for both responses ($p < 0.001$). Temperature was the dominant factor for Marshall stability, and the time $\times$ temperature interaction was significant. For SCB fracture load, all three two-way interactions were significant, demonstrating that cracking resistance depends more strongly than stability on coupled processing effects. Consequently, a protocol optimized for stability alone may not provide the greatest fracture resistance; the processing variables should be optimized jointly.

The exploratory machine-learning analysis further demonstrated that processing variables can be used to estimate asphalt-mixture performance. Random Forest outperformed Gradient Boosting, with R^2 values of 0.794 for Marshall stability and 0.828 for SCB fracture load. The results provide a performance-based framework in which temperature, time, and speed are treated as interacting design variables rather than isolated plant settings. Future work should extend the investigation to modified binders, recycled materials, larger datasets, and field-scale validation to translate the laboratory findings into durable and practical production guidelines.

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