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TEMPERATURE PERFORMANCE AND RUTTING PREDICTION OF STEEL SLAG ASPHALT MIXTURES

VISOKO TEMPERATURNE LASTNOSTI IN NAPOVED DOBE TRAJANJA MEŠANIC ASFALTA IN JEKLARSKE ŽLINDRE

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Steel slag, an industrial by-product, can replace basalt aggregate in road construction, helping to reduce the extraction of natural resources. By combining steel slag with waste rubber powder to produce steel slag–rubber-modified asphalt mixtures, both the material performance is enhanced and resource recycling is promoted. However, due to slight differences in high-temperature behavior between steel slag–rubber-modified asphalt mixtures and traditional basalt-based mixtures, existing rutting prediction models fail to accurately characterize the rutting development of the modified materials. To address this, four different types of asphalt mixtures were prepared in this study: full steel slag–rubber-modified warm-mix asphalt (CR-WSAM), partial steel slag–rubber-modified warm-mix asphalt (CR-WSBAM), full steel slag–rubber-modified hot-mix asphalt (CR-HSAM), and partial steel slag–rubber-modified hot-mix asphalt (CR-HSBAM). Uniaxial compression, Hamburg wheel tracking, and dynamic modulus tests were conducted, and a new rutting prediction model was developed by incorporating key factors influencing the rut formation. The results show that the proposed model outperforms existing models in terms of both accuracy and applicability, providing a more precise description of the rutting behavior of steel slag–rubber-modified asphalt mixtures. Furthermore, the model's predictions show a higher correlation with measured rut depth values, indicating improved prediction accuracy.

Keywords: road engineering, performance prediction, steel slag–rubber powder-modified asphalt mixture, optimization algorithms

Z jeklarsko žlindro, ki je stranski produkt industrijske izdelave jekla, lahko zamenjamo bazaltni agregat v cestnih konstrukcijah, kar pomaga pri zmanjšanju izkoriščanja naravnih surovin. S kombinacijo asfalta, jeklarske žlindre in odpadnega prahu iz gum se lahko izdela modificirana asfaltna mešanica. Na ta način se lahko promovira recikliranje odpadnih produktov in istočasno izboljša materialne lastnosti asfalta. Vendar pa zaradi rahlih razlik med obnašanjem tega materiala pri povišanih temperaturah v primerjavi s tradicionalnimi asfaltnimi mešanicami, obstoječi modeli napovedovanja vzdržljivosti (trajnosti) zahtevajo natančno karakterizacijo razvoja poškodb in trajnosti modificiranih materialov. Zato so avtorji tega članka izvedli študijo s katero so raziskali lastnosti štirih različnih, z jeklarsko žlindro in gumarskim prahom, modificiranih toplih/vročih asfaltnih mešanic: (1) popolnoma modificirano toplo asfaltno mešanico (CR-WSAM; angl..: full steel slag–rubber-modified warm-mix asphalt) (2) delno modificirano toplo asfaltno mešanico (CR-WSBAM; angl.: partial steel slag–rubber-modified warm-mix asphalt), (3) popolnoma modificirano vročo asfaltno mešanico (CR-HSAM; angl.: full steel slag–rubber-modified hot-mix asphalt) in (4) delno modificirano vročo asfaltno mešanico (CR-HSBAM; angl.: partial steel slag–rubber-modified hot-mix asphalt). Na vzorcih iz izdelanih asfaltnih mešanic so določili enoosno tlačno trdnost, Hamburg-ški preizkus sledi koles (angl.: Hamburg wheel tracking) in dinamični modul. Nato so izdelali nov model za napoved obrabe modificiranih asfaltnih mešanic, ki je upošteval vse ključne faktorje, ki vplivajo na nastanek poškodb. Rezultati raziskave so pokazali, da predlagani model prekaša obstoječe modele tako glede točnosti, kot tudi uporabnosti. Model zagotavlja bolj natančen opis obnašanja modificiranih asfaltnih mešanic. Nadalje ima nov model večjo korelacijo napovedi globine poškodb v primerjavi z dejansko izmerjenimi, kar kaže na izboljšano natančnost napovedi.

Ključne besede: inženirstvo in gradnja cest, napoved zmogljivosti, asfaltna mešanica modificirana s prahom iz gume in jeklarsko žlindro, optimizacijski algoritmi

1 INTRODUCTION

The high-temperature performance of steel slag asphalt mixtures arises from their ability to resist high-temperature deformation, which is closely related to pavement distresses such as rutting and shoving. It is one of the most important parameters in asphalt pavement design.[1–3] Among various pavement distresses, rutting is the most common and severe form. Under high-temperature conditions in summer, with an increase in heavy-load vehicles on the road, the pavement is more susceptible to severe rutting damage. This has a detrimental impact on road performance and traffic safety, leading to significant economic losses and safety hazards.[4–6] Therefore, an increasing number of researchers both domestically and internationally are focusing on how to effectively enhance the high-temperature rutting resistance of asphalt mixtures. Research and application of new pavement materials offer better solutions to address this issue.[7,8] Steel slag exhibits high hardness, high compressive strength, and excellent high-temperature resistance, enabling it to effectively improve the rutting re-

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sistance, enhance high-temperature stability, and reduce pavement deformation in asphalt mixtures, thereby extending the service life of roads. In the 1950s, developed countries such as the United States, Germany, and Japan directly used steel slag as a road construction material, using steel slag asphalt mixtures for surface layers, thus promoting the use of steel slag in road construction projects.[9]

A rutting prediction model for asphalt mixtures can effectively assess the rutting resistance of asphalt mixtures by predicting the rutting deformation of the pavement under long-term loading.[10] The uniaxial compression test, Hamburg wheel tracking test, and dynamic modulus test provide important physical performance data for the model. The uniaxial compression test evaluates the compressive strength of asphalt, the Hamburg wheel tracking test simulates rutting behavior under high temperatures, and the dynamic modulus test reflects the elastic modulus of an asphalt mixture at different frequencies.[11,12] These experimental results provide key input parameters for a rutting prediction model. In recent years, scholars have found that when predicting rutting in asphalt mixtures, factors such as the type and quality of asphalt, aggregate gradation and properties, mix proportion, temperature, traffic load, environmental humidity, construction methods, compaction, as well as temperature changes and moisture effects during use, all play a combined role in determining the rutting resistance of a mixture.[13–16] Some researchers aim to optimize the high-temperature rutting resistance of steel slag asphalt mixtures by focusing on the mix design and additives.[17,18] Others have approached the study of asphalt mixtures' high-temperature rutting resistance from the perspective of road mechanical performance and proposed rutting prediction models based on mechanical properties. These studies focus on the stress, strain, and creep characteristics of asphalt mixtures, examining material deformation behavior under high-temperature load conditions.

Research indicates that asphalt mixtures are prone to plastic deformation and rutting under high temperatures and heavy traffic loads. Therefore, rutting prediction models based on mechanical performance can accurately predict the rutting formation process by considering the stress and strain characteristics of asphalt mixtures. These models account for material constitutive relations and deformation characteristics, significantly improving prediction accuracy. For example, by modeling material creep behavior, temperature sensitivity, and performance under long-term loading, the models can more precisely predict rutting development in high-temperature environments. Compared to traditional prediction methods, the mechanical property-based models offer higher reliability and applicability, providing a more scientific basis for the selection and design of asphalt materials. These models also help optimize road material design, enhancing road service life and durability, especially under high-temperature and heavy-load conditions.[19,20]

This study investigates the high-temperature performance of asphalt mixtures obtained with different mixing processes and steel slag contents. Through uniaxial penetration, dynamic modulus, and Hamburg wheel tracking tests, the high-temperature performance of CR-HSAM, CR-WSAM, CR-WSBAM, and CE-HSBAM was comprehensively analyzed. The results showed that CR-WSAM demonstrated the best overall high-temperature deformation resistance among the four materials.

A new rutting prediction model is proposed in this study, aiming to improve the fitting accuracy of rut depth for steel slag–rubber-modified asphalt mixtures. The new model takes into account the dynamic mechanical properties, shear resistance, and external factors influencing rut formation in asphalt mixtures. A reasonable model form is established, and the coefficients of the rutting prediction are adjusted based on the experimental results mentioned earlier. The corrected model is then validated, showing that the predictions of rut depth in steel slag–rubber-modified asphalt mixtures are closer to the measured values, with a high correlation and improved prediction accuracy.

2 EXPERIMENTAL MATERIALS AND DESIGN

2.1 Experimental materials

2.1.1 Bitumen

In this study, rubber-modified asphalt with a rubber content of 20 % by mass of the base asphalt was used. The technical performance indicators of the modified asphalt were tested according to the Specification for Design and Construction of Rubber Modified Asphalt and Mixtures (DB15/T 1417-2018). The test results show that all indicators meet the specification requirements, indicating that the modified asphalt exhibits good performance and meets the application requirements of the relevant technical standards. Detailed test data and results are shown in **Table 1**.

Table 1: Technical performance indicators of rubber powder-modified asphalt

Technical index	Test results	Technical requirements	Test methods
Penetration (25 °C, 100g, 5s, 0.1 mm)	67.6	60–80	JTG E20 T 0604
Softening point (°C)	66.4	≥55	JTG E20 T 0606
Ductility (15 °C, cm)	≥15	19.7	JTG E20 T 0605

2.1.2 Aggregates and mineral powder

Steel slag has sharp edges and excellent mechanical properties. It is an alternative material to traditional mineral materials in road construction. This study used steel slag produced by Baotou Iron and Steel (Group) Co.,

Table 2: Technical indicators of steel slag

Project indicators	0–3	3–5	5–10	10–20	Technical requirements
Apparent specific gravity	3.314	3.434	3.578	3.712	≥2.6
Surface dry specific gravity	–	3.403	3.534	3.612	–
Bulk specific gravity	–	3.311	3.356	3.585	–
Absorption rate	–	1.63	1.21	0.06	≤2.0
Silt content (<0.075mm content/%)	0.18	–	–	–	≤3
Sand equivalent/%	69	–	–	–	≥60
Angularity/S	36.5	–	–	–	≥30

Table 3: Technical indicators of mineral powder

Project indicators	Experimental results	Technical requirements	
Appearance	No lumps	No lumps	
Surface dry specific gravity	2.601	≥2.5	
Particle size range/%	<0.6mm	100	100
	<0.15mm	95.2	90–100
	<0.075mm	76.1	75–100
Moisture content/%	0.7	≤1	
Hydrophilicity coefficient	0.4	<1	
Plasticity index/%	2.8	<4	

Ltd., and its particle size was divided into four ranges: 0–3, 3–5, 5–10, and 10–15 mm. According to the Highway Engineering Aggregate Test Specification (JTG E42-2005), the technical conformity of steel slag was evaluated, and all test indicators met the requirements. Detailed test data and results for steel slag are shown in **Table 2**, and detailed data for mineral powder are shown in **Table 3**.

2.1.3 Warm mix agent

The warm-mix agent used in this study was SDYK, a surfactant independently developed by the Shandong Transportation Science Research Institute. According to the research team's findings, the optimal performance of rubber powder-modified asphalt is achieved when the SDYK warm-mix agent is added at a dosage of 0.6 % of the asphalt mass.[21] Therefore, this study adopted an SDYK dosage of 0.6 %.

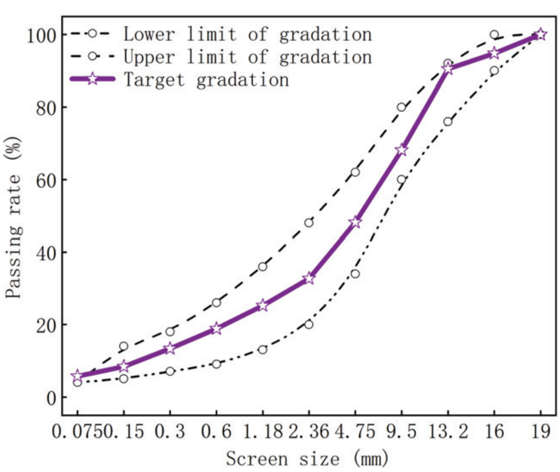

Figure 1: AC-16 steel slag gradation curve

2.2 Specimen preparation and testing

2.2.1 Ratio design

In this experiment, the mix design for the all-steel-slag rubber powder-modified asphalt mixture was based on the gradation range specified in the Technical Specifications for Highway Asphalt Pavement Construction (JTG F40-2004). The planning solution method was employed to control the synthetic gradation. The final gradation curve is presented in **Figure 1**.

Drawing on previous experience and relevant literature, 5.5 % was selected as the median value, and five asphalt-to-stone ratios ranging from 4.9 to 6.1 % were chosen at 0.3 % intervals to prepare Marshall standard specimens. Marshall tests were then conducted under different asphalt-to-stone ratios. Based on the test results, the optimal asphalt content for the all-steel-slag rubber powder-modified asphalt mixture was determined to be 5.2 % following the standard test procedures. The corresponding volumetric indicators are presented in **Table 4**.

Table 4: Volume index of hot-mix all-steel slag rubber powder-modified asphalt mixture with the optimal asphalt dosage

Project indicators	Experimental results	Technical requirements
Marshall stability (KN)	12.30	≥8
Flow value (0.1 mm)	3.39	2-4
Bulk specific gravity (g/cm³)	3.014	–
Voids in mineral aggregate (%)	17.77	≥14.5
Voids filled with asphalt (%)	75.62	70-85

The road performance of the two types of steel slag crumb rubber-modified asphalt mixtures was tested in accordance with the test methods specified in the JTG

E20-2011 standard. The test results are presented in **Table 5**.

In engineering practice, when asphalt mixtures are prepared using two or more types of aggregates, the density differences among the aggregates are often overlooked. For natural aggregates with similar densities, minor differences generally do not affect the mix design.[22,23] However, the density of steel slag is approximately 1.2 to 1.5 times that of basalt. Therefore, when partially replacing basalt with steel slag in the aggregate gradation, it is necessary to perform a volume-to-mass conversion based on the original basalt gradation to ensure that the final mix design meets engineering requirements. By conducting volume-to-mass conversions, the mass ratio of each aggregate fraction was determined. The corresponding proportions of steel slag replacing basalt for each size fraction after conversion are shown in **Table 6**.

Based on the Marshall mix design method, the optimum asphalt contents for crumb rubber-modified asphalt mixtures prepared under warm mix conditions – with basalt replacing steel slag aggregates in the particle size ranges of 3–20, 5–20, and 10–20 mm – were determined to be (5.3, 5.3 and 5.2) %, respectively. It was also found that, under hot mix conditions, the mixture in which basalt replaced steel slag aggregates in the 5–20 mm size range exhibited the best road performance. Therefore, a crumb rubber-modified asphalt mixture was prepared under hot mix conditions using steel slag to partially replace basalt aggregates in the 5–20 mm range, referred to as CR-HSBAM. Its optimum asphalt content, determined using the Marshall method, was 5.4 %. The corresponding volumetric properties of the steel slag–basalt blended mixtures with the optimum asphalt content are shown in **Table 7**.

The road performance of the four asphalt mixtures with different replacement schemes was tested in accor-

Table 5: Mix ratio verification test results of four types of steel slag rubber powder-modified asphalt mixtures

Performance indicators	Project indicators	CR-HSAM	CR-WSAM	Technical requirements
High-temperature stability	Dynamic stability (Times.mm^{-1})	4846	5653	≥2400
Low-temperature crack resistance	Failure strain ($\mu\varepsilon$)	3425	3910	≥2800
Water stability	Residual strength ratio (%)	95	93	≥75

Table 6: Proportion of basalt aggregate partially replaced by steel slag

Replacement scope	10–20 mm	5–10 mm	3–5 mm	0–3 mm	Mineral powder
3–20 mm	33% (steel slag)	27% (steel slag)	9% (steel slag)	29% (basalt)	2%
5–20 mm	34% (steel slag)	28% (steel slag)	7% (basalt)	29% (basalt)	2%
10–20 mm	35% (steel slag)	24% (basalt)	7% (basalt)	31% (basalt)	3%

Table 7: Volume indicators of warm and hot mix with the optimal asphalt dosage

Project indicators	Warm mix	Hot mix	Technical requirements		
	3–20 mm	5–20 mm	10–20 mm	5–20 mm	
Marshall stability (KN)	12.01	12.88	11.22	11.15	≥8
Flow value (0.1 mm)	2.03	2.57	2.40	2.68	2-4
Bulk specific gravity (g/cm³)	2.846	2.838	2.696	2.743	–
Voids in mineral aggregate (%)	14.6	14.82	15.2	16.4	≥14.5
Voids filled with asphalt (%)	73.96	76.89	72.13	81.13	70-85

Table 8: Verification results of mix proportions in hot- and warm-mix asphalt

Performance indicators	Project indicators	CR-HSAM		Experimental results	Technical requirements
High-temperature stability	Dynamic stability (Times.mm^{-1})	3–20 mm		3956	≥2400
		5–20 mm	Warm Mix	4468	
			Hot Mix	4717	
		10–20 mm		3854	
Low-temperature crack resistance	Failure strain ($\mu\varepsilon$)	3–20 mm		5811	≥2800
		5–20 mm	Warm mix	6109	
			Hot mix	3168	
		10–20 mm		5232	
Water stability	Residual strength ratio (%)	3–20 mm		79	≥75
		5–20 mm	Warm mix	85	
			Hot mix	88	
		10–20 mm		77	

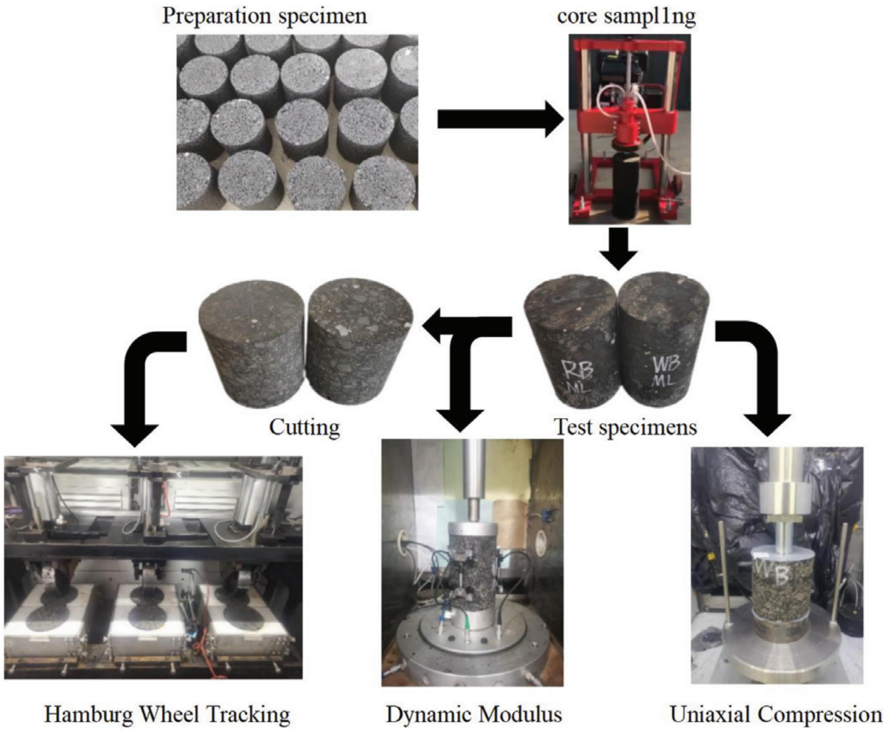

Figure 2: Experimental process

dance with the JTG E20-2011 specification. The test results are presented in **Table 8**.

As shown in **Table 8**, all test results meet the specification requirements, indicating that the mix designs of both CR-HSBAM and CR-WSBAM are compliant. In this study, the grey-target decision-making method described in reference[24] was used to analyze the crumb rubber-modified asphalt mixtures prepared under warm mix conditions, where steel slag was used to replace basalt aggregates in the particle size ranges of (3–20, 5–20 and 10–20) mm. The analysis concluded that the optimal replacement scheme under warm mix conditions is to replace basalt with steel slag in the 5–20 mm size range. Therefore, in this study, CR-WSBAM specifically refers to the asphalt mixture designed with this replacement scheme.

2.2.2 Test plan

According to the Specification for Asphalt Mixture Tests of Highway Engineering (JTGE20-2011), specimens were prepared using the gyratory compaction method; in addition, Hamburg wheel tracking tests, uniaxial compression tests, and dynamic modulus tests were conducted. The experimental process is shown in **Figure 2**.

3 RESULTS AND DISCUSSION

3.1 Impact of the asphalt mixture type on mechanical properties

At the same temperature, the shear strengths of the four asphalt mixture types, CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM, are shown in **Figure 3**.

As shown in **Figure 3**, for hot-mix asphalt, mixtures using full steel slag aggregate (CR-HSAM) exhibit the highest shear strength, and similarly, for warm-mix asphalt, mixtures with full steel slag aggregate (CR-WSAM) also show the highest shear strength. This indicates that the use of full steel slag aggregate signifi-

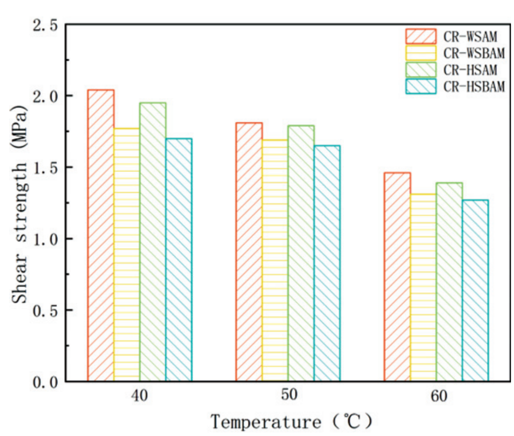

Figure 3: Shear strengths of different types of steel slag–rubber powder-modified asphalt mixtures

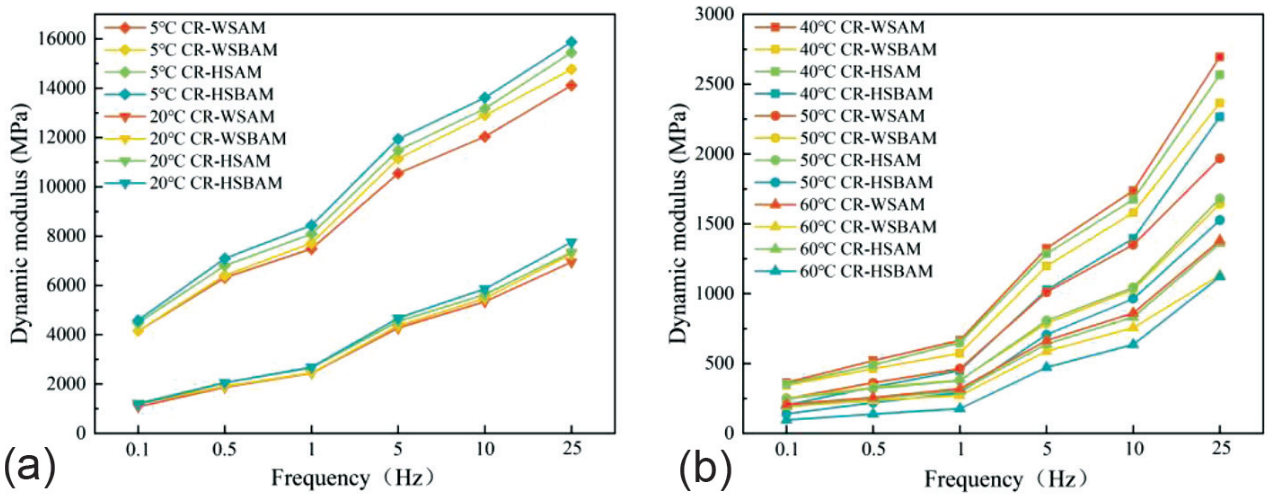

Figure 4: Dynamic modulus of different steel slag–rubber powder-modified asphalt mixtures: a) 5 °C, 20 °C, b) 40 °C, 50 °C, 60 °C

cantly improves the high-temperature shear resistance of rubber powder-modified asphalt mixtures.

Firstly, steel slag, as a high-strength aggregate with a low crushing value, exhibits excellent mechanical properties. Its rough surface texture increases friction after compaction, enhancing the aggregate's interlocking ability, which in turn strengthens the shear resistance of the mixture. This enhanced interlocking ability, especially at high temperatures, effectively reduces deformation and shear failure of the mixture, significantly improving the material's shear strength.[24] Secondly, steel slag particles have high chemical reactivity and surface energy, allowing them to form strong physical adsorption and chemical bonds with the aromatic groups in asphalt. This bonding not only improves the adhesion between the asphalt and the aggregate but also enhances the overall structural stability of the asphalt mixture, further increasing its shear strength.[25] In addition, the steel slag aggregate has a larger specific surface area and an irregular surface texture, which allows it to absorb more effective asphalt, resulting in a more uniform asphalt-aggregate bond. A higher proportion of steel slag aggregate effectively increases the adhesive properties of asphalt, enhancing its ability to resist high-temperature shear damage and further improving the shear resistance of the mixture under high-temperature conditions.[26,27]

Under the same test conditions, variations in the dynamic modulus of the four asphalt mixture types, CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM, are shown in **Figure 4**.

As shown in **Figures 4a** and **4b**, the mechanical behavior of the material can be derived and transformed based on the relationship between temperature and time (or frequency). Under low temperature and high frequency conditions, the strain in the asphalt mixture develops slowly, and the material's stress response tends toward elastic behavior. This is because, at low temperatures, the viscosity of asphalt increases, and the mobility of the molecular chains is poor, leading to weaker creep behavior, which results in the material behaving like an elastomer. It primarily relies on the storage modulus for energy storage and recovery. In contrast, under high temperature and low frequency conditions, the molecular chains in the asphalt mixture become more active, the viscosity decreases, and the flowability increases. Under these conditions, the strain changes more rapidly, and the viscous effects become more pronounced, causing the material to behave more like a viscous substance. It primarily relies on the loss modulus to

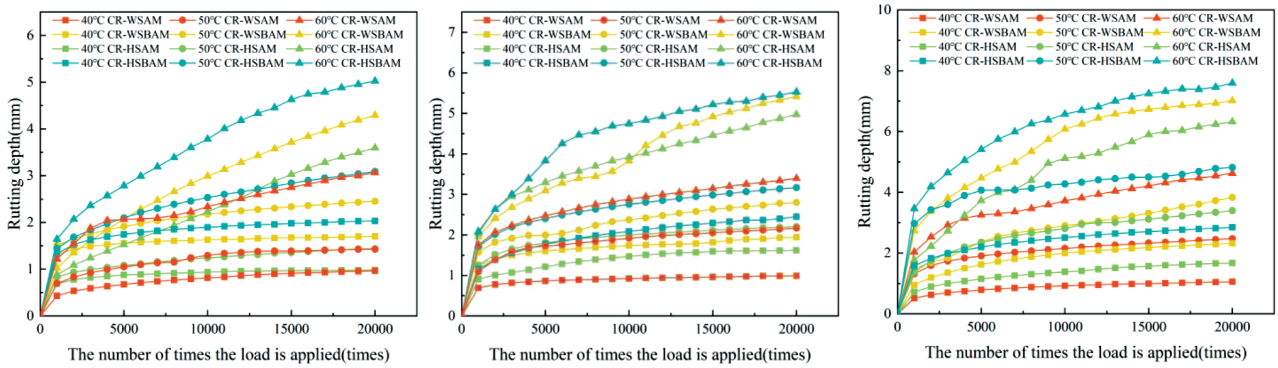

Figure 5: Rut depth of steel slag–rubber-modified asphalt mixtures at different temperatures: wheel load of: a) 0.7 MPa; b) 0.8 MPa; c) 0.9 MPa

dissipate energy. Therefore, under low temperature and high frequency conditions, the asphalt mixture exhibits elastic behavior, whereas under high temperature and low frequency conditions, it exhibits viscous behavior.

3.2 Analysis of the Hamburg rutting test

3.2.1 Analysis of rut depth in the Hamburg rutting test

Hamburg rutting tests were conducted on four types of asphalt mixtures, CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM, under specified test conditions. The variations in rut depth at different temperatures are shown in **Figure 5**.

On **Figures 5a** to **5c**, it can be observed that as the temperature increases, the rut depth of the four steel slag–rubber-modified asphalt mixtures gradually increases. Under different load levels, the rut depth curve of the steel slag–rubber-modified asphalt mixture at 60 °C is significantly higher than those at 40 °C and 50 °C.

The depth of rutting is mainly affected by the viscosity and fluidity of asphalt. As the temperature rises, the movement of asphalt molecules becomes more intense, the bonds between molecules become weaker, the fluidity of the material increases, and the viscosity decreases. The viscosity of asphalt is a key factor affecting its performance, especially at high temperatures. When the viscosity decreases, asphalt is more likely to deform, thereby increasing the possibility of rutting. In addition, the chemical composition of asphalt plays an important role in determining its viscosity. Asphalt usually contains a mixture of heavy components and light components, and the light components are more volatile. At high temperatures, the light components are more likely to evaporate or decompose. This process further reduces the viscosity and may also reduce the overall performance of asphalt. The evaporation of light components changes the structure of asphalt and affects its adhesion and anti-rutting performance.

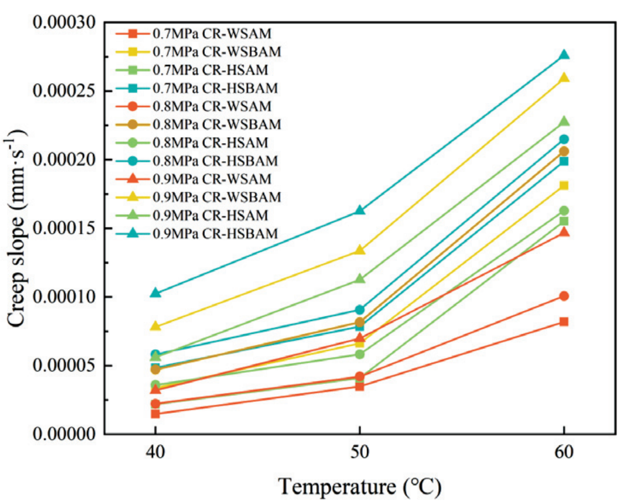

Figure 6: Creep slopes of steel slag–rubber powder-modified asphalt mixtures at different temperatures

The fluidity of asphalt is closely related to molecular structure, temperature, composition, etc. As the temperature increases, the fluidity of asphalt molecules increases, the interaction between molecules weakens, and the viscosity decreases. This is an important reason for the decrease in the viscosity of asphalt at high temperatures.

3.2.2 Creep slope analysis of Hamburg wheel tracking test

Figure 6 illustrates the variations in creep slope for four types of asphalt mixtures – CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM – at different temperatures (40, 50 and 60) °C.

As shown in **Figure 6**, the creep slopes of steel slag–rubber powder-modified asphalt mixtures exhibit a significant variation across different temperatures. Regardless of the load level, the creep slope gradually increases with rising temperature, particularly when the temperature increases from 50 °C to 60 °C, where the change becomes more pronounced. This phenomenon indicates that as the temperature rises, the rate of rut depth growth accelerates significantly, while the asphalt mixture's resistance to high-temperature rutting deformation declines. These findings further highlight the critical influence of temperature on the high-temperature rutting resistance of steel slag–rubber powder-modified asphalt mixtures. The primary reason for this phenomenon is that at high temperatures, asphalt materials gradually soften, causing a significant reduction in their inherent cohesion and viscosity. As the temperature continues to rise, asphalt becomes increasingly fluid, weakening the overall structural stability of the mixture. Under these conditions, repeated vehicle loading – especially from steel wheels – reduces the friction between particles within the asphalt mixture and diminishes the load-bearing capacity of the internal skeleton structure. This ultimately leads to substantial plastic deformation, accelerating rutting formation.[26] In particular, when the temperature exceeds a critical threshold, the fluidity of asphalt increases rapidly. This not only makes the mixture more prone to permanent deformation under wheel loads but also significantly accelerates the growth rate of rut depth. As a result, with further temperature increases, rutting accumulation follows a nonlinear growth trend, severely compromising the stability of the asphalt mixture under high-temperature conditions. Additionally, in steel slag–rubber powder-modified asphalt mixtures, the inclusion of steel slag and rubber powder enhances high-temperature stability to some extent. However, under extreme heat, this modification has its limitations. The detrimental effects of high temperatures on the asphalt matrix remain significant, especially within the 50–60 °C range, where performance degradation becomes more pronounced.[28] Therefore, controlling pavement temperature or further optimizing the steel slag–rubber powder modification ratio is crucial for improving the high-temperature rutting resistance of asphalt mixtures.

Moreover, under the same load level and varying temperatures, the creep slope of CR-WSAM consistently remains lower than that of the other three asphalt mixtures, particularly at 60 °C. This indicates that CR-WSAM exhibits superior resistance to rutting deformation under high-temperature conditions, deforms at a slower rate, and demonstrates the best high-temperature performance. This is primarily due to the synergistic effect of its material properties and warm-mix technology. On the one hand, steel slag exhibits high rigidity, strong deformation resistance, and a large internal friction angle, effectively enhancing the shear resistance of the mixture. On the other hand, warm-mix technology improves asphalt fluidity by lowering the mixing temperature, reduces asphalt aging, and creates a more uniform aggregate-asphalt interface after construction, thereby enhancing the mixture's bonding strength. Additionally, the incorporation of a warm-mix agent enhances high-temperature stability and minimizes the impact of temperature on material properties, thereby better preserving the structural stability and creep resistance under varying temperature conditions. These factors collectively contribute to reducing the rutting creep rate of warm-mix steel slag asphalt mixtures.

3.3 Establishment and modification of a rutting prediction model for asphalt mixtures

Building on existing rutting prediction models from both domestic and international research, this study integrates the dynamic mechanical properties, shear resistance, and external factors influencing rutting formation in asphalt mixtures. Drawing inspiration from the commonly used exponential model,[28] a more reasonable rutting prediction model is proposed. This model (as shown in Equation (1)) comprehensively accounts for the impact of temperature variations on asphalt mixture performance. To enhance prediction accuracy, correlation coefficients within the model are refined using experimental data from uniaxial penetration tests, dynamic modulus tests, and Hamburg wheel tracking tests. The corrected model more effectively simulates the rutting formation process and is further validated to ensure its reliability and accuracy in practical applications.

$$R_{\mathrm{d}} = \alpha N^{q} T^{t} \left(\frac{\tau}{[\tau]} \right)^{s} \left(\frac{|E^*|}{\sin\phi} \right)^{k} \tag{1}$$

Here, R_d is the estimated rut depth; N is the number of load actions; T is the temperature; τ is the pavement shear stress (MPa), solely dependent on load magnitude, as indicated in the referenced literature. When the load reaches 0.7 MPa, the corresponding shear stress value is 0.5 MPa; $[\tau]$ is the asphalt mixture shear strength; $|E^*|/\sin\phi$ is the rutting performance indicator; α, q, t, s, k are regression parameters.

Compared with commonly used models, this model incorporates shear stress and shear strength parameters, providing a more comprehensive reflection of the shear resistance of asphalt mixtures. Additionally, it accounts for the viscoelastic properties of asphalt mixtures under dynamic loads, allowing for a more accurate representation of material deformation behavior under varying conditions. By comprehensively considering temperature, vehicle load characteristics, and material properties, the model enhances the prediction of permanent deformation in asphalt pavement. Furthermore, it systematically describes the formation mechanisms and influencing factors of rutting, thereby improving both the accuracy and applicability of the predictions.

Based on the data from the uniaxial penetration test, Hamburg wheel tracking test, and dynamic modulus test, the parameters of the rutting prediction model were fitted using SPSS software. According to the asphalt pavement design specifications in China, a standard axle load of 100 kN for a single-axle dual-wheel group and a tire contact pressure of 0.7 MPa are used. Therefore, the regression fitting was performed using the Hamburg wheel tracking test, data of CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM at 40 °C and 50 °C under 0.7 MPa, the uniaxial penetration test data at 40 and 50 °C, and the dynamic modulus test data at 10 Hz, and 40 °C and 50 °C. The final fitted parameters are presented in **Table 9**.

Table 9: Results of model-related parameters

Parameters	Results
α	$5.735*10^3$
q	0.343
t	-0.68
s	1.792
k	-0.824

The revised rutting prediction model is shown in Equation (2).

$$R_{\mathrm{d}} = 5375 \times 10^{3} N^{0.343} T^{-0.68} \left(\frac{\tau}{[\tau]} \right)^{1.792} \left(\frac{|E^*|}{\sin\phi} \right)^{-0.824} \tag{2}$$

The regression results of the revised rutting prediction model show that the correlation coefficient R^2 reaches 0.91, indicating high accuracy. This suggests that the model effectively predicts the rutting deformation behavior of asphalt mixtures with good reliability and predictive performance. The reliability and accuracy of the rutting prediction model determined in the previous section were further validated. The Hamburg rutting test results for CR-WSAM, CR-WSBAM, CR-HSAM, and CR-HSBAM at 60 °C were compared with the predicted values obtained from the model. Additionally, a commonly used rutting prediction model was modified and

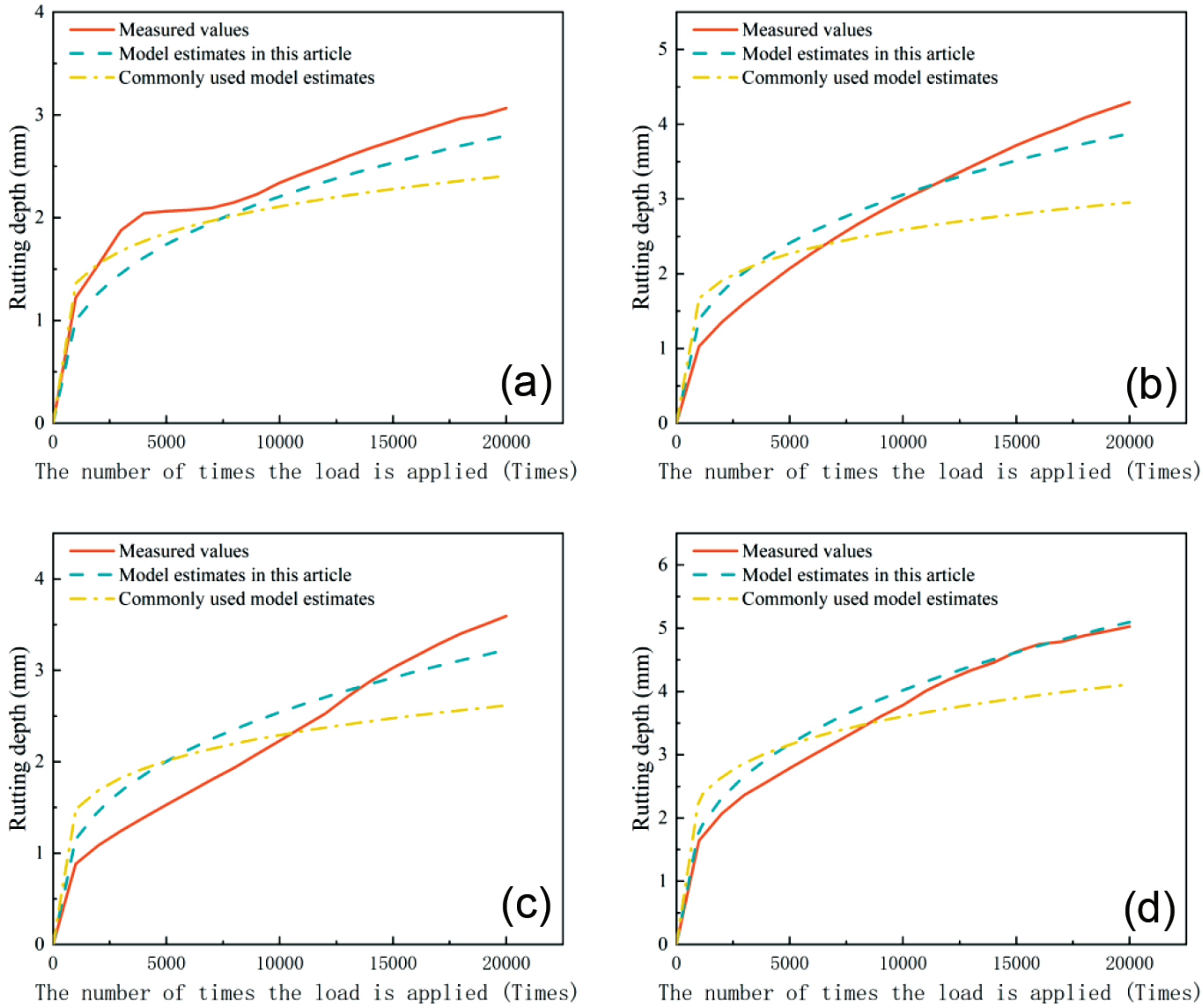

Figure 7: Comparison of measured and predicted rutting values for different steel slag–rubber powder-modified asphalt mixtures (60 °C, 0.7 MPa): a) CR-WSAM, b) CR-WSBAM, c) CR-HSAM, d) CR-HSBAM

Table 10: Comparison of predicted values from the revised model and measured values from the Hamburg rutting test (60 °C, 0.7 MPa)

Asphalt mixture type	Measured value	Predicted value of this model (mm)	Error (%)	Common model predicted value (mm)	Error (%)
CR-WSAM	3.066	2.798	8.74	2.406	21.53
CR-WSBAM	4.292	3.878	9.65	2.953	31.20
CR-HSAM	3.595	3.223	10.35	2.615	27.26
CR-HSBAM	5.027	5.097	-1.39	4.112	18.20

compared with the revised model proposed in this study. The verification and comparison results are presented in **Figure 7**, while the final prediction results are summarized in **Table 10**.

As shown in **Figure 7** and **Table 10**, the calculation results of the revised rutting prediction model closely match the measured values, with the final rut depth error controlled within ±11 %. In contrast, the errors between the estimated results of the commonly used model and the measured values are larger than those of the revised model proposed in this study. This discrepancy is primarily due to the commonly used model's failure to fully account for the actual mechanical behavior of asphalt mixtures under dynamic loads, particularly in describing shear stress, shear strength, and viscoelastic properties. Furthermore, commonly used models provide a relatively simplistic consideration of influencing factors such as temperature and loading cycles, making it difficult to accurately capture the deformation behavior of asphalt mixtures under actual working conditions. In contrast, the revised model presented in this study incorporates shear performance parameters and integrates test temperature, loading cycles, and material mechanical properties to comprehensively characterize the

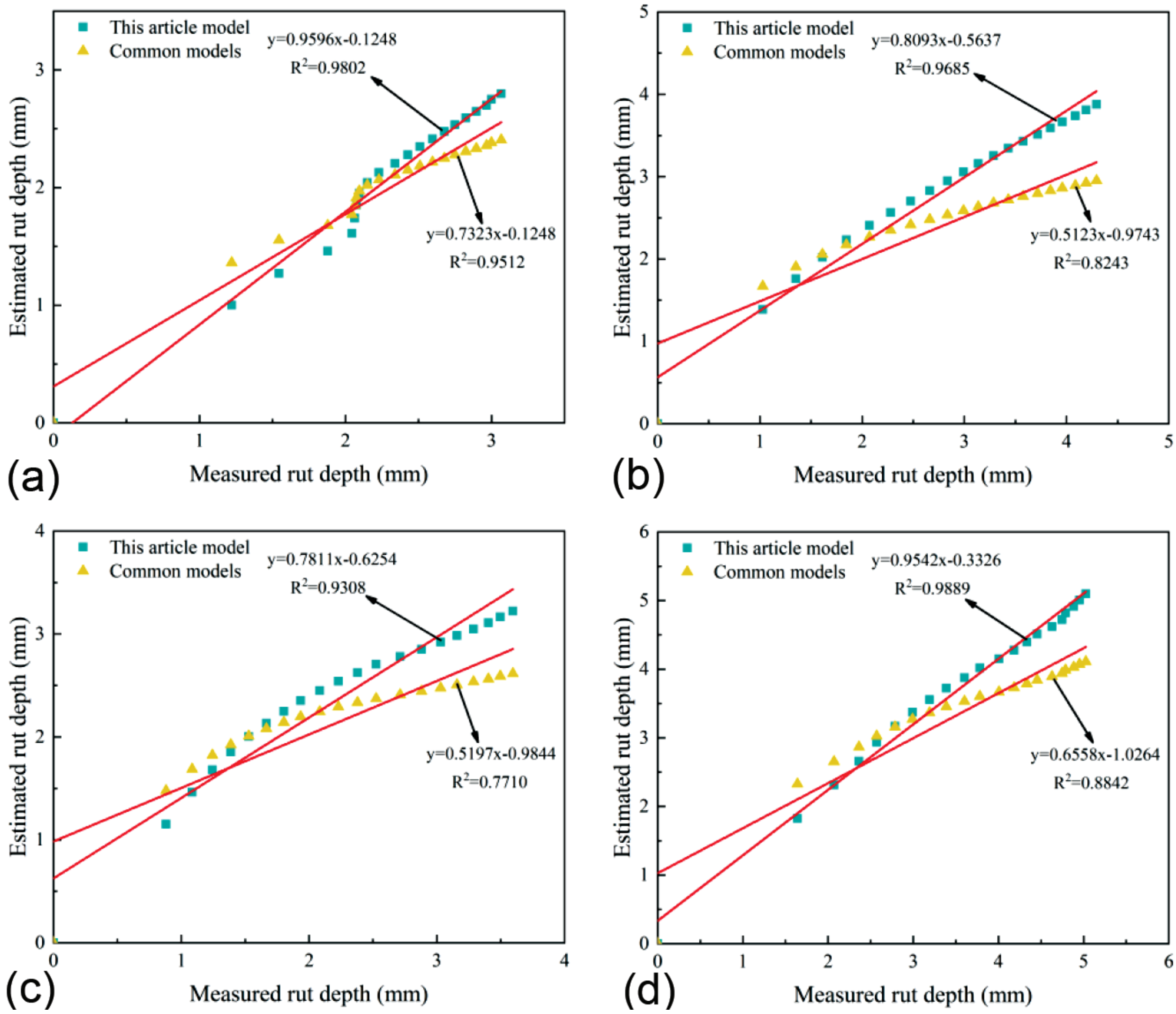

Figure 8: Correlation between the estimated values of the corrected model and measured values from the Hamburg rutting test: a) CR-WSAM, b) CR-WSBAM, c) CR-HSAM, d) CR-HSBAM

rutting deformation of asphalt mixtures. This revised model demonstrates superior mechanistic rationality and applicability, enabling more accurate rut depth predictions. It significantly reduces the error between estimated and measured values, thereby enhancing the model's reliability and accuracy.

As shown in **Figure 8**, the revised rutting prediction model presented in this paper exhibits a high correlation with the actual rut depth. In particular, the correlation coefficient R^2 for CR-WSAM and CR-HSBAM is 0.9802 and 0.9889, respectively. These values are significantly higher than those of the commonly used model before correction. This demonstrates that the rutting prediction model (Equation 10), established and refined in this study, is highly reliable for predicting the rut depth of steel slag rubber–powder-modified asphalt mixtures.

4 CONCLUSIONS

The article analyzes the high-temperature dynamic mechanical properties of four types of steel slag–rubber-modified asphalt mixtures and proposes a new rutting prediction model, which effectively enhances the rutting prediction ability for these mixtures. Based on the research findings, the following conclusions are drawn:

The integration of steel slag in asphalt mixtures has a greater impact on temperature sensitivity than the mixing method. Specifically, the warm-mix process improves the shear resistance of steel slag–rubber powder-modified asphalt mixtures by approximately 8 %.

The high-temperature rutting resistance of asphalt mixtures with full steel slag and rubber powder modification is 10 % better than that of mixtures with partial steel slag and rubber powder modification. Additionally, warm-mix steel slag–rubber powder-modified asphalt mixtures exhibit superior high-temperature rutting resistance.

A rut depth prediction model for steel slag–rubber powder-modified asphalt mixtures was developed and improved. This model accurately predicts the rutting behavior of the mixtures under various temperature and loading conditions.

Considering the impacts of traffic, climate conditions, pavement shear stress, asphalt mixture shear strength, and mechanical response under dynamic loading, a flexible data processing approach was used. A rutting prediction model was established through multivariate fitting, with a correlation coefficient (R^2) exceeding 0.93, significantly enhancing the model's prediction accuracy.

5 REFERENCES

[1] W. Lu, X. Peng, S. Lv, Y. Yang, J. Wang, Z. Wang, N. Xie, High-temperature properties and aging resistance of rock asphalt ash modified asphalt based on rutting index, Construction and Building Materials, 363 (**2023**), 129774, doi:10.1016/j.conbuildmat.2022.129774

[2] M. Fakhri, A. Ahmadi, Recycling of RAP and steel slag aggregates into the warm mix asphalt: A performance evaluation, Construction and Building Materials, 147 (**2017**), 630–638, doi:10.1016/j.conbuildmat.2017.04.117

[3] Z. Liu, L. Sun, J. Li, L. Liu, Effect of key design parameters on high temperature performance of asphalt mixtures, Construction and Building Materials, 348 (**2022**), 128651, doi:10.1016/j.conbuildmat.2022.128651

[4] Y. Luan, Y. Ma, T. Ma, C. Wang, F. Xia, Research on the effects of asphalt performance on rutting resistance and its correlation with rutting performance indicators, Construction and Building Materials, 400 (**2023**), 132773, doi:10.1016/j.conbuildmat.2023.132773

[5] Q. Guo, H. Xu, J. Wang, J. Hang, K. Wang, P. Hu, H. Li, Gradation optimization based on micro-analysis of rutting behavior of asphalt mixture, Coatings, 13 (**2023**), 1965, doi:10.3390/coatings13111965

[6] B. Javilla, L. Mo, F. Hao, S. An, S. Wu, Systematic comparison of two-stage analytical rutting models of asphalt mixtures, Construction and Building Materials, 153 (**2017**), 716–727, doi:10.1016/j.conbuildmat.2017.07.083

[7] G. Prakash, S. K. Suman, Rutting characteristics evaluation and prediction model development for warm mix asphalt, International Journal of Pavement Engineering, 24 (**2023**), 2165656, doi:10.1080/10298436.2023.2165656

[8] S. Kocak, M. E. Kutay, Effect of devulcanized rubber modification on the performance grade, fatigue cracking resistance, and rutting resistance of asphalt binders, J. Mater. Civ. Eng., 33 (**2021**), 04021248, doi:10.1061/(ASCE)MT.1943-5533.0003830

[9] C. Yang, Z. Huang, S. Wu, X. He, Y. Su, Z. Zhao, H. Xu, F. Wang, L. Zhang, Recycling steel slag as aggregate in developing an ultra-thin friction course with high comprehensive road performance, Construction and Building Materials, 449 (**2024**), 138539, doi:10.1016/j.conbuildmat.2024.138539

[10] X. Hu, A. Ishaq, A. Khattak, F. Chen, Assessment of factors affecting pavement rutting in Pakistan using finite element method and machine learning models, Sustainability, 16 (**2024**), 2362, doi:10.3390/su16062362

[11] H. Chen, M. M. Alamnie, D. M. Barbieri, X. Zhang, G. Liu, I. Hoff, Comparative study of indirect tensile test and uniaxial compression test on asphalt mixtures: Dynamic modulus and stress-strain state, Construction and Building Materials, 366 (**2023**), 130187, doi:10.1016/j.conbuildmat.2022.130187

[12] H. Wang, Z. Zhou, W. Huang, X. Dong, Investigation of asphalt mixture permanent deformation based on three-dimensional discrete element method, Construction and Building Materials, 272 (**2021**), 121808, doi:10.1016/j.conbuildmat.2020.121808

[13] J. Li, J. Yu, S. Wu, J. Xie, The mechanical resistance of asphalt mixture with steel slag to deformation and skid degradation based on laboratory accelerated heavy loading test, Materials, 15 (**2022**), 911, doi:10.3390/ma15030911

[14] P. Dong, X. Cao, B. Tang, Analysis of the mechanical behavior of asphalt pavement under multiple coupling effects, Construction and Building Materials, 449 (**2024**), 138409, doi:10.1016/j.conbuildmat.2024.138409

[15] Y. Luan, W. Zhang, Y. Zhao, Z. Pan, Z. Niu, K. Zeng, X. Chen, L. N. Mohammad, Mechanical property evaluation for steel slag in asphalt mixture with different skeleton structures using modified marshall mix design methodology, J. Mater. Civ. Eng., 34 (**2022**), 04021382, doi:10.1061/(ASCE)MT.1943-5533.0004014

[16] Z. Zhou, J. Cao, X. Shi, W. Zhang, W. Huang, Probabilistic rutting model using NGBoost and SHAP: Incorporating other performance indicators, Construction and Building Materials, 438 (**2024**), 137052, doi:10.1016/j.conbuildmat.2024.137052

[17] C. K. Akisetty, S.-J. Lee, S. N. Amirkhanian, High temperature properties of rubberized binders containing warm asphalt additives, Construction and Building Materials, 23 (**2009**), 565–573, doi:10.1016/j.conbuildmat.2007.10.010

[18] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Construction and Building Materials, 49 (2013), 611–617, doi:10.1016/j.conbuildmat.2013.08.034.

[19] K. Chen, C. Zhuang, J. Zhang, Y. Hao, Modification of rutting prediction model for with semi-rigid base in service based on accelerated loading test, Case Studies in Construction Materials, 17 (**2022**), e01704, doi:10.1016/j.cscm.2022.e01704

[20] W. Chuhong, W. Zhichao, Prediction model for rutting of asphalt concrete pavement considering temperature influence, Case Studies in Construction Materials, 22 (**2025**), e04831, doi:10.1016/j.cscm.2025.e04831

[21] Lan Wang, Ji Li, Gui Wanmei, Effect of surfactant on high and low temperature properties of warm mix rubber powder modified asphalt, Materials Reports, 33 (2019), 986–990, https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFQ&dbname=CJFDLAST2019&filename=CLDB201906016 (accessed April 7, 2025)

[22] H. Yu, S. Shen, G. Qian, X. Gong, Packing theory and volumetrics-based aggregate gradation design method, J. Mater. Civ. Eng., 32 (**2020**), 04020110, doi:10.1061/(ASCE)MT.1943-5533.0003192

[23] Hao Qi, Yingying Guo, Lan Wang, Research on the optimal content of steel slag asphalt mixture based on gray target decision theory, Highway, 68 (**2023**), 265–273, https://link.cnki.net/urlid/11.1668.U.20230209.0921.081 (accessed April 7, 2025)

[24] Z. Yan, Z. Hao, Study on preparation and performance of steel slag asphalt mixture based on steel slag aggregate, IOP Conf. Ser.: Mater. Sci. Eng., 631 (**2019**), 022067, doi:10.1088/1757-899X/631/2/022067

[25] Z. Zhang, X. Zheng, J. Li, G. Xu, L. Tan, Mechanism of reinforced interfacial adhesion between steel slag and highly devulcanized waste rubber modified asphalt and its influence on the volume stability in steel slag asphalt mixture, Construction and Building Materials, 447 (**2024**), 138129, doi:10.1016/j.conbuildmat.2024.138129

[26] H. Xu, Y. Zou, G. Airey, H. Wang, H. Zhang, S. Wu, A. Chen, J. Xie, Y. Liang, Interfacial characteristics between bitumen and corrosion products on steel slag surface from molecular scale, Construction and Building Materials, 417 (**2024**), 135324, doi:10.1016/j.conbuildmat.2024.135324

[27] Y. Yan, H. Zhang, M. Bekoe, C. Allen, J. Zhou, R. Roque, Effects of asphalt binder type, aggregate type, and gradation characteristics on fracture properties and performance of asphalt mixtures at intermediate temperatures, Construction and Building Materials, 409 (**2023**), 133801, doi:10.1016/j.conbuildmat.2023.133801

[28] G. Liu, L. Chen, Z. Qian, Y. Zhang, H. Ren, Rutting prediction models for asphalt pavements with different base types based on RIOHTrack full-scale track, Construction and Building Materials, 305 (**2021**), 124793, doi:10.1016/j.conbuildmat.2021.124793