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Case study

A laboratory evaluation of factors affecting rutting resistance of asphalt mixtures using wheel tracking test

Yuanyuan Pan [a,b], Hui Guo [c], Wei Guan [d], Yongli Zhao [a,*]

[a] School of Transportation, Southeast University, Nanjing, China
[b] Faculty of Civil Engineering and Geosciences, Delft University of Technology, CN Delft, Netherlands
[c] Ningbo Tech University, Ningbo, China
[d] Research Institute of Highway Ministry of Transport (RIOH), Beijing, China

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ABSTRACT

Rutting is one of the most common distresses in early damage to asphalt pavements. It can raise the risk of ride safety issues, accelerate pavement deterioration, and increase maintenance costs. To investigate the factors that affect the rutting resistance of asphalt mixtures, internal factors (such as aggregate gradation, asphalt content, and layer thickness), external factors (including temperature and traffic loading), and human factors (such as compaction degree) were tested using wheel tracking tests. The test results showed that the rutting resistance of asphalt mixtures can be improved by designing a tightly interlocked aggregate skeleton using the Bailey method's primary control sieve, using an optimal asphalt content, achieving sufficient compaction, maintaining a layer thickness of 2.5–3 times its nominal maximum aggregate size, using an asphalt softening point higher than the pavement temperature, and avoiding overloaded vehicles. In highly rutted areas, it is recommended to use a stone mastic asphalt with a stable aggregate skeleton matrix and styrene-butadiene-styrene modified asphalt with a softening point higher than the highest pavement temperature.

1. Introduction

Rutting has become a major distress in the early deterioration of asphalt pavements due to the increase in traffic volume, axle loads, overloads, and channelization [1], [2]. It is the accumulation of viscous and plastic deformation under the simultaneous effects of repeated traffic loading and high temperatures [3], [4]. This irreversible distress not only degrades the ride quality and raises the risk of ride safety issues, but also shortens the service life of the pavement and raises maintenance costs [5], [6]. Therefore, studying the causes and mechanisms of rutting in asphalt pavement is crucial to provide design and construction recommendations for relevant agencies.

The rutting resistance of asphalt mixtures is influenced by a variety of factors, categorized as internal, external, and human-related factors as illustrated in Fig. 1 [3, [7], [8]. Internal factors comprise the properties of the constituent materials, such as the asphalt content and properties, aggregate gradation, angularity, and strength, as well as the characteristics of the pavement structure, such as the pavement structure type and surface layer thickness. Previous research has discovered that the primary aggregate physical properties that influence the rutting susceptibility of asphalt mixtures are particle shape, gradation, and asphalt absorbed by aggregate

* Corresponding author.
E-mail address: yonglizhao2016@126.com (Y. Zhao).

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[9], [10]. Chen et al. [11] found that asphalt mixtures with a low percentage of flat and elongated particles have a stable internal structure, emphasizing the importance of coarse aggregate shape properties for anti-rutting performance. Kamaruddin et al. [12] discovered that quarry sand with higher levels of angularity, rougher texture, and shear strength was more resistant to rutting through wheel tracking tests (WTTs). The stone-on-stone effect in coarse aggregate mixtures associated with Stone Mastic Asphalt (SMA) has also been linked to higher resistance to permanent deformation in asphalt mixtures [13], [14]. Numerous studies have found that coarse aggregates in asphalt mixtures form a skeleton structure to support the bearing load, and the viscoelastic-plastic asphalt slurry formed by fine aggregates and mineral powder fills the skeleton pores in the coarse aggregate to stabilize the pavement structure [3, [15], [16]. Sreedhar and Coleri [17] explored how binder content affected the rutting resistance of asphalt mixtures and discovered that increasing the binder content by 0.7% increases the measured flexibility index by 1.07–2.63 times. Airey et al. [18] also discovered that rutting damage in asphalt pavement is caused by a lack of cohesion between the aggregate and binder due to an excess of asphalt in the asphalt mixture. Polymer modification is a widely used technique to enhance the engineering properties of asphalt mixtures [19], [20], [21].

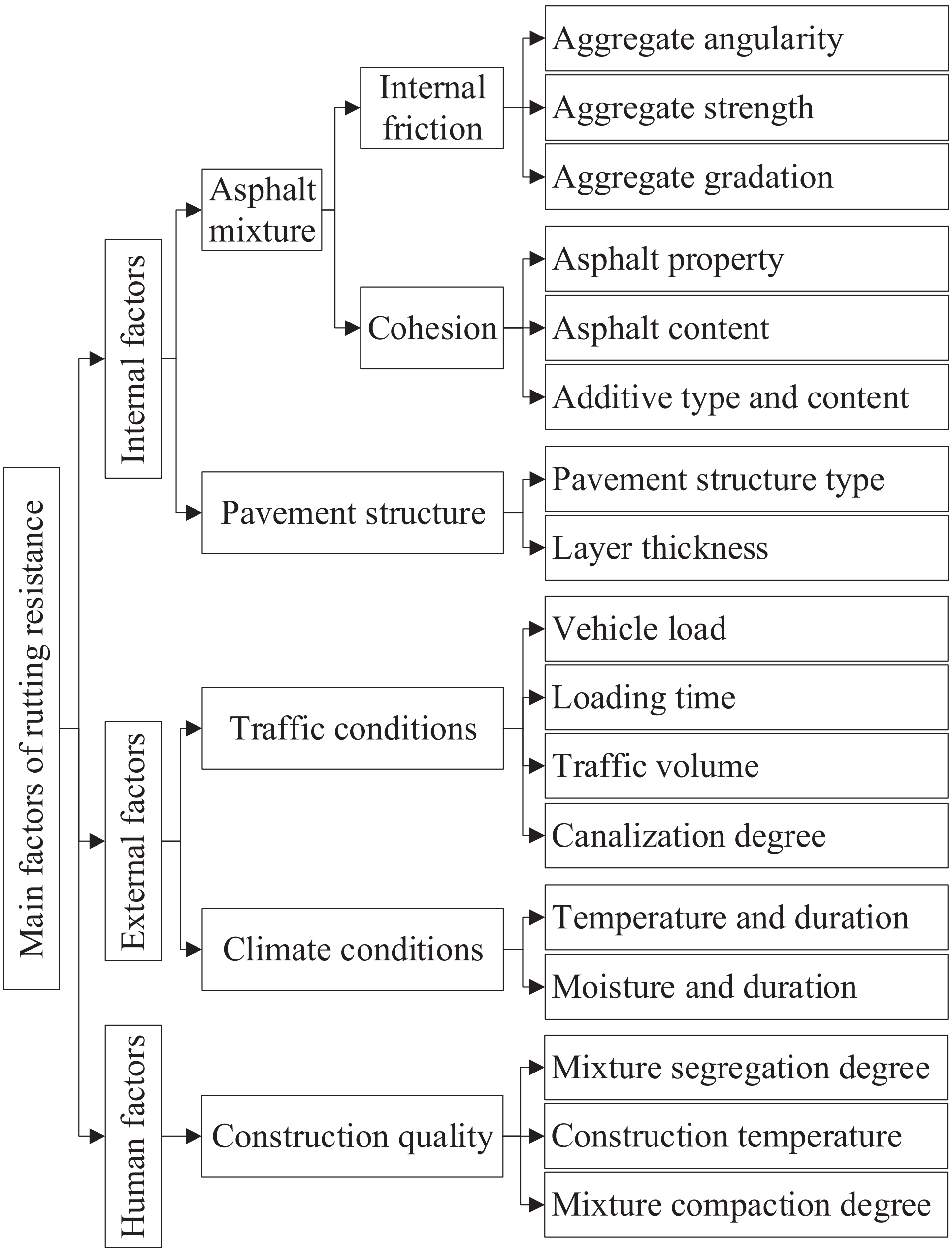

Fig. 1. Factors affecting rutting resistance of asphalt pavement.

External factors that impact the rutting resistance of asphalt mixtures include traffic-related variables, such as the traffic volume, loading magnitude, duration, and degree of channelization, as well as climate-related conditions like temperature and moisture. Several studies have indicated that the temperature, stress and loading frequency, and degree of mixture compaction all significantly impact the permanent deformation performance [22], [23]. Pouranian et al. [1] investigated the effect of temperature on the rutting resistance of SMA and discovered that the anti-rutting ability of SMA decreases with an increase in test temperature, and temperature has a significant effect on the flow number of SMA. Similarly, Wasage et al. [24] found that the rutting depth (RD) deepens as the test temperature rises, indicating that the asphalt binder is difficult to bond at higher temperatures. After investigating the subgrade vibration produced by trucks with different axle loads, Lu et al. [25] discovered that heavy vehicles caused more damage to the road structure than lighter vehicles.

Human-related factors mostly relate to the quality of construction, such as the segregation degree of the asphalt mixture, temperature of construction, and compaction degree of the asphalt mixture. After compaction, gaps still remain in the asphalt mixture, causing further compaction of the mixture at the wheel path and leading to rutting under repeated loads [2]. The void ratio between aggregates is also crucial for asphalt pavement design as it determines the rutting resistance. The risk of poor deformation resistance can reduce by proper void design. Airey et al. [18] discovered that reducing the air-void content by 4% of its absolute value had a great effect the stiffness of the mixture.

Experiments in the laboratory are required to quantify the impact of various influential factors on the rutting resistance of asphalt mixtures. Various laboratory test methods have been developed to characterize the rutting resistance of asphalt mixtures. Table 1 lists several methods for assessing the anti-rutting ability of asphalt mixtures. Among these methods, the WTT has gained popularity as a means of evaluating the high-temperature behaviour of asphalt mixtures in the laboratory due to its simplicity, good representation of field conditions, and strong correlation with field RD. The WTT is typically conducted by applying a constant load on the specimen while rolling a steel wheel on its surface, simulating the traffic loading on the pavement. It was widely used by Ghabchi et al. [26], Shafabakhsh et al. [27], and Souliman et al. [28] to quantify the rutting resistance of asphalt mixtures.

2. Objective and scope

The objective of this study is to quantify the effects of various factors, such as aggregate properties, asphalt content, mixture compaction, etc., on the rutting resistance of asphalt mixtures. Section 3 tests the properties of selected raw materials, and Section 4 describes the mix design ratios. Section 5 discusses the factors addressed and the proposed test range of each factor, and then examines the effects of the relevant factors on the anti-rutting properties of asphalt mixtures using the WTT in laboratory. The test results about the impact of a single factor on the rutting resistance of asphalt mixtures are discussed in Section 6. Section 7 concludes the analysis by providing insights into the design and optimization of asphalt mixtures to improve anti-rutting capabilities.

Table 1
Summary of test methods used for evaluating rutting resistance of asphalt mixtures.

Test	indexes	Characteristics
Static uniaxial test [29]	Creep modulus - time; strain – time; Poisson's ratio	Widely used with simple equipment; and tress states containing shear components.
Repeated uniaxial test [30]	Fatigue strength; fatigue life; fatigue crack growth rate.	Better expression of traffic conditions but complex equipment; and large influence of the load waveform and frequency on the measured value.
Dynamic uniaxial test [31]	Dynamic modulus; damping ratio; Poisson's ratio; permanent deformation	Damping ratio as a function of frequency can be determined at different temperatures.
Marshall test [32]	Marshall stability; flow value	Simple tests; and poor correlation between stability and field RD.
Static triaxial test [33] Repeated triaxial test [34]	Creep modulus - time; Strain – time; resilient modulus; permanent deformation; period; Poisson's ratio	Multiple stress states; stress states containing shear components; better expression of traffic conditions but complex equipment; and requiring a triaxial chamber.
Dynamic triaxial test [35]	Dynamic modulus; damping ratio; Poisson's ratio; permanent deformation	Damping ratio as a function of frequency can be determined at different temperatures.
Semi-circular bending test [36]	Creep parameters	High resolution requirements of test and detection equipment.
Accelerated load testing [37], [38]	Accumulated axle load - deformation	Satisfactory field stress state simulation; and large test cost and long period.
Rutting test [39],[40]	Accumulated axle load - deformation	Low equipment accuracy requirements; satisfactory field stress state simulation; and good correlation with field RD.

3. Materials

3.1. Asphalt binders

Matrix asphalt with the penetration grade of 70# was selected in current study. To test the influence of the asphalt modifier on the rutting resistance of asphalt mixture, the Styrene-butadiene-styrene (SBS) modified asphalt with 5% of the tri-block SBS copolymer by the weight of binder was selected as well. Physical properties of the matrix binder and the modified binder were measured in accordance with specifications [41], [42] and tabulated in Table 2.

3.2. Aggregates

Natural crushed limestone was selected as coarse and fine aggregates. Hydrated lime, accounting for 4% of the total weight of the aggregate, used as an anti-strip additive, was set as the mineral powder. Conventional properties of the aggregates were measured in accordance with specifications [43], [44] and tabulated in Table 3.

4. Mix design

Types of asphalt mixtures studied included AC-13 and SBS modified AC-13. AC-13, as a standard dense asphalt mixture, has a nominal maximum aggregate size (NMAS) of 13.2 mm. The gradation selected is the median of the upper and lower limits of AC-13 in the specification [43], as shown in Fig. 2. These asphalt mixtures represented the common mixtures used in asphalt pavement engineering in China [23].

The optimal asphalt contents (OACs) of AC-13 and SBS-modified AC-13 were respectively determined by employing the Marshall mixture design method [43]. Initially, an asphalt content range of 4–6%, with a 0.5% interval, was selected for creating five parallel specimens for each asphalt content at a mixing temperature of 155 ± 5 ℃ and a compaction temperature of 145 ± 5 ℃. The volume indicators of specimens such as bulk density, theoretical maximum relative density, volume of air voids (VV), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) were measured and calculated. The mechanical indexes of specimens including Marshall stability and flow value were measured using Marshall tests. The OAC_1 was determined by averaging the asphalt content corresponding to the maximum bulk density, maximum Marshall stability, target VV (4%), and VFA median value from the relationship curve between the asphalt content and physical-mechanical indexes. The OAC_2 was determined by averaging the minimum and maximum asphalt contents that ensured all the above physical-mechanical indicators satisfied the standards [43]. The OACs were then determined by averaging OAC_1 and OAC_2. After that, performance tests such as rutting test, Immersion Marshall test, freeze-thaw splitting test, and three-point bending test were conducted to verify the feasibility of the OAC. Finally, the OACs for AC-13 and SBS-modified AC-13 were determined as 4.9% and 5.0%, respectively. The corresponding physical-mechanical indicators of two types of mixtures are listed in Table 4.

5. Experimental methodology

5.1. Influencing factors

The study selected and tested various factors to evaluate their impact on the rutting resistance of asphalt mixtures using the WTT method. These factors included aggregate gradation, asphalt content, mixture layer thickness, temperature, traffic loading, and compaction degree, as illustrated in Fig. 3. The following sections provide a detailed discussion of the selected range for each factor.

5.1.1. Aggregate gradation

The rutting resistance of asphalt mixture is affected by various factors, including aggregate gradation, asphalt content, mixture layer thickness, temperature, traffic loading, and compaction degree. Among these factors, aggregate gradation is particularly important and has received a lot of attention in terms of improving the anti-rutting performance of asphalt pavements [10,12]. Two commonly used methods for designing asphalt mixtures are the Bailey method and the Superpave method [45]. The former focuses on aggregate packing and separates coarse and fine aggregates using a primary control sieve (PCS) [46], [47]. The PCS is related to the NMAS and is calculated using Eq.(1) [47]. Eq.(1) yields a PCS of 2.904 mm for an NMAS of 13.2 mm for AC-13, which falls between

Table 2
Physical properties of matrix and modified asphalt.

Test	Matrix asphalt		SBS modified asphalt		Test method
	Test result	Standard	Test result	Standard	
Density/($g·cm^{-3}$)	1.0415	/	1.0354	/	T 0603
Penetration (25 °C, 100 g, 5 s)/0.1 mm	63.4	60–80	71.1	60–80	T 0604
Penetration index	-0.88	-1.5–1.0	1.13	≥ −0.4	T 0604
Equivalent softening point/°C	48.6	/	56.4	/	T 0606
Softening point/°C	47.6	≥ 46	58.3	≥ 55	T 0606

Table 3
Conventional properties of aggregates.

Item	Test	Test result	Standard	Test method
Aggregate	Apparent density/(g·cm^{-3})	2.658	≥ 2.6	T 0304
	Water absorption/%	0.48	≤ 2	T 0304
	Los Angeles abrasion/%	11.3	≤ 28	T 0317
Mineral powder	Moisture content/%	0.27	≤ 1	T0103
	Apparent density/(g·cm^{-3})	2.831	≥ 2.5	T 0352
	hydrophilic coefficient	0.45	< 1	T0353
	Heating stability	Not metamorphic	/	T0355

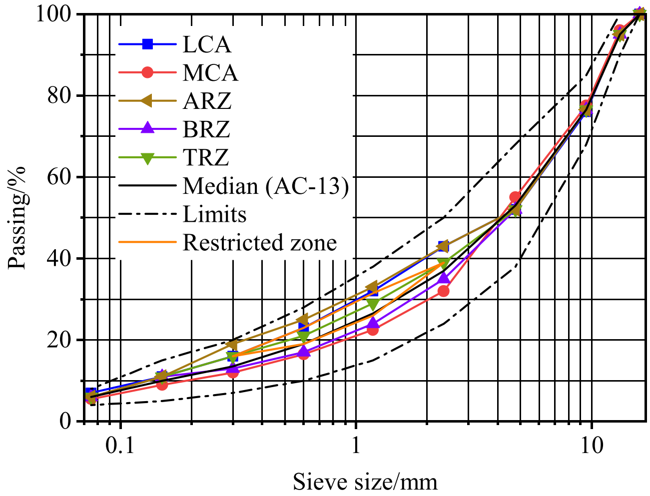

Fig. 2. Aggregate gradation curves. Note: LCA = gradation curve with less coarse aggregates with sieve size between 2.36 mm and 4.75 mm; MCA = gradation curve with more coarse aggregates with sieve size between 2.36 mm and 4.75 mm; ARZ = gradation curve above restricted zone; BRZ = gradation curve below restricted zone; TRZ = gradation curve through restricted zone; Median (AC-13) = median gradation curve of AC-13 as a reference group; and Limits = upper and lower gradation limits of AC-13 as a boundary.

Table 4
Marshall test results.

Item	Type of asphalt mixture		Standard
	AC-13	SBS modified AC-13	
OAC/%	4.9	5.0	/
Bulk density/(g·cm^{-3})	2.581	2.563	/
Theoretical maximum relative density/(g·cm^{-3})	2.687	2.685	/
VV/%	3.9	4.5	3–5
VMA/%	15.7	16.3	≥ 14
VFA/%	74.9	72.2	65–75
Marshall stability/KN	9.2	15.3	≥ 8
Flow value/0.1 mm	22.5	47.7	15–40 (appropriately relaxed for SBS modified AC-13)

Note: VV = abbreviation for volume of air voids, percentage of the volume outside the mineral aggregate and asphalt to the total volume of the specimen; VMA = abbreviation for voids in mineral aggregate, percentage of the volume outside the mineral aggregate to the total volume of the specimen; and VFA = abbreviation for voids filled with asphalt, percentage of effective asphalt volume in compacted asphalt mixture specimen to space volume outside mineral aggregate skeleton.

2.36 mm and 4.75 mm sieves. To investigate the effect of aggregate interlock on high-temperature stability, the current study considered two gradations with different coarse aggregate dosages: less coarse aggregates (LCA) and more coarse aggregates (MCA) with sieve sizes ranging from 2.36 mm to 4.75 mm.

$$PCS = 0.22 \times NMAS \tag{1}$$

The Superpave method uses a restricted zone to achieve maximum density gradation with increased contacts between coarse aggregates and reduced air void space within mineral aggregates [48]. This method specifies that asphalt mixtures with gradations crossing the restricted zone have excessive natural sand and are thus more susceptible to rutting. To explore the effect of the restricted

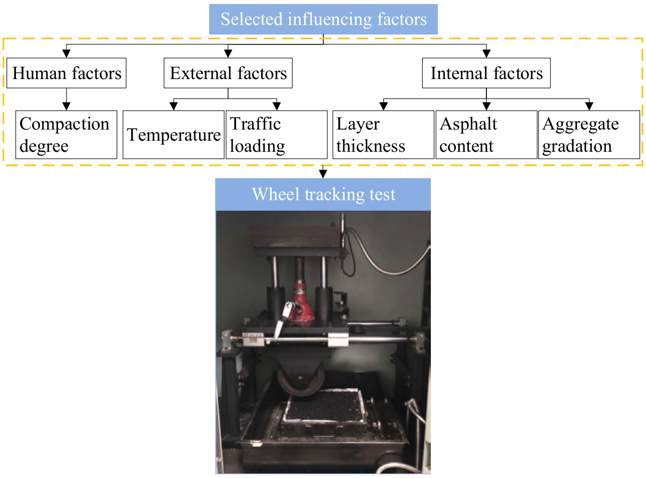

Fig. 3. Experimental framework.

zone on rutting susceptibility, this study employed three gradations: above, below, and through the restricted zone (ARZ, BRZ, and TRZ). The gradations of ARZ, BRZ and TRZ all follow the same trend from 16 mm to 4.75 mm sieve and from 0.15 mm to 0.75 mm sieve. From 4.75–0.15 mm sieve, the gradation of ARZ passes above the restricted zone and below the upper gradation limit while the gradation of BRZ passes below the restricted zone and above the lower gradation limit. The gradation of TRZ runs almost directly along the restricted zone's median.

Consequently, the five gradation types selected for this study were LCA, MCA, ARZ, BRZ and TRZ, with the AC-13 median gradation curve (Median) used as a reference group. The gradation curves are depicted in Fig. 2. OAC was measured for each aggregate gradation using the Marshall test, as shown in Table 5. Three identical specimens with each aggregate gradation were then fabricated for rutting test.

5.1.2. Asphalt content

The properties and dosages of asphalt binder have a significant impact on the rutting resistance of asphalt mixtures [3]. To investigate this factor, five different asphalt contents, OAC $\pm$ 1, OAC $\pm$ 0.5 and OAC, were tested for AC-13 with median gradation in Fig. 2, as shown in Table 6. The selected range covers the commonly used asphalt content range in the construction of asphalt pavements. Asphalt mixtures with a low asphalt content may result in insufficient asphalt binder to coat the aggregate particles, leading to poor workability and reduced durability, whereas mixtures with a high asphalt content may result in excessive bleeding and rutting. Therefore, it is essential to evaluate the influence of asphalt content within this range on the rutting resistance of asphalt mixtures to determine the allowable variability of asphalt content in construction. Three identical specimens with each asphalt content and the same AC-13 and SBS modified AC-13 dense gradation were then fabricated for rutting test.

5.1.3. Layer thickness

The standard test method for evaluating the rutting resistance of asphalt pavement involves using a 5-cm-thick rutting plate to test the dynamic stability of asphalt mixture [43]. However, asphalt pavement is a multi-layer structure, and permanent deformation is formed by the accumulation of multi-layer plastic deformation, which makes it challenging for a single-layer rutting plate to reflect the multi-layer state of the asphalt pavement. Moreover, the layer thickness is an essential control parameter in construction as it affects not only the composition state of the asphalt mixture's internal skeleton but also the structural performance of the pavement [49]. To validate the effect of layer thickness on the rutting resistance of asphalt mixture, rutting plates with different thicknesses were selected.

To ensure that the skeleton structure can be formed within the mixture, the current specification in China specifies that the layer thickness should be set at 2.5–3 times the NMAS of the asphalt mixture [43]. The Superpave method recommends the layer thickness to be three times the NMAS of the asphalt mixture, and the Australia specification provides the layer thickness of 2.5 times the NMAS of the asphalt mixture. The compaction degree should also be considered in the selection of layer thickness. The Asphalt Institution proposes an upper limit of 10 cm for layer thickness, and the Japanese specification provides a general threshold of 7 cm. Therefore, in this study, four rutting plate thicknesses were selected with a ratio of rutting plate thickness to NMAS (($L/NMAS$) no less than 2.5 and a maximum layer thickness no more than 7 cm. These thicknesses were 3.3 cm, 4.0 cm, 5.3 cm, and 6.6 cm, corresponding to the $L/NMAS$ ratio of 2.5, 3, 4, and 5, respectively, as shown in Table 7. Three identical specimens with each layer thickness and the same

Table 5
OAC of each aggregate gradation.

Item	LCA	MCA	ARZ	BRZ	TRZ	Median
OAC/%	4.77	4.98	4.83	4.61	4.54	4.90

Table 6
Asphalt content of each asphalt mixture type.

Item	OAC-1	OAC-0.5	OAC	OAC+ 0.5	OAC+ 1
AC-13	3.9	4.4	4.9	5.4	5.9
SBS modified AC-13	4.0	4.5	5.0	5.5	6.0

AC-13 and SBS modified AC-13 dense gradation were then fabricated for rutting test.

5.1.4. Temperature

As a typical viscoelastic-plastic material, temperature is one of the most influential factors impacting the high temperature stability of asphalt mixtures [3,23]. The higher the temperature, the lower the modulus of the asphalt mixture and the weaker the resistance to rutting. Numerous studies have shown that in the temperature range of 40–70 °C, every 5 °C increase in the temperature of an asphalt mixture doubles its deformation [50], [51]. To test the effect of the temperature on the rutting resistance of asphalt mixture, a temperature range of 40–70 °C, with a 5 °C interval, was initially chosen. Additionally, interpolation was performed at temperatures close to the softening point of asphalt binder to explore the combined effect of temperature and the softening point of the asphalt binder. Therefore, a total of seven temperatures were chosen for the rutting test based on the softening point of asphalt binder, as shown in Table 8. The rutting test was conducted on three identical specimens with the same typical AC-13 and modified AC-13 dense gradation at each test temperature listed in Table 8.

5.1.5. Traffic loading

Overloading on asphalt pavements has a significant impact on their ability to resist high-temperature rutting, and it is a characteristic that distinguishes Chinese asphalt pavements from those in other countries [23, 25, [52]. When vehicles are overloaded, the weight on each axle increases significantly, which leads to higher wheel pressure, and this change in wheel pressure directly affects the pressure distribution of the wheel load on the road. To investigate how different wheel pressures and overloads affect the rutting resistance of asphalt pavement, three test loads were used in the current study: 78 kg, 88 kg, and 102 kg, which correspond to wheel pressures of 0.7 MPa, 0.8 MPa, and 0.9 MPa, respectively, as shown in Table 9. Three identical specimens with each test load were then fabricated for rutting test.

5.1.6. Compaction degree

Insufficient compaction is a major contributing factor to asphalt pavement rutting [18]. Factors such as rolling method, compaction work, rolling temperature, gradation type, and segregation degree of asphalt mixture all affect the degree of compaction, making it difficult to achieve identical compaction levels in the rutting plate test. To address this issue, 30 standard rutting plate specimens of AC-13 were produced in the current study with dimensions of 300 mm × 300 mm × 50 mm, using adjusted compaction load and rolling time as per the specification [41]. After 24 h, the rutting plates were removed from the mould, and their void ratios and compaction degrees were calculated by measuring their bulk density. 16 specimens with compaction levels ranging from 95% to 100% were selected for rutting tests, as shown in Table 10. The rutting test was performed after the rutting plates were left to dry naturally at room temperature.

5.2. Wheel tracking test

The rutting resistance of asphalt mixtures can be evaluated through various tests, and in this study, the WTT was used following the specification [3,23,41]. For each test group, three square slabs with dimensions 300 mm × 300 mm× 50 mm were fabricated at a mixing temperature of 155 ± 5 ℃ and a compaction temperature of 145 ± 5 ℃. The specimens and moulds were submerged in water at 60 ± 1 °C for 8 h and then subjected to a tire pressure of 0.7 ± 0.05 MPa from a static solid rubber tire with an outer-diameter of 200 mm and a width of 50 mm. The loading wheel travelled 230 ± 10 mm with a speed of 42 ± 1 cycles/min for 60 min. The relationship between the RD and the loading time was successively obtained. The dynamic stability (DS) was calculated using the RDs at loading time of 45 min (RD_{45}) and 60 min (RD_{60}) according to Eq.(2).

$$DS = \frac{15 \times 42}{RD_{60} - RD_{45}} \tag{2}$$

Table 7
Rutting plate thickness of each $L/NMAS$.

$L/NMAS$	2.5	3	4	5
Thickness of rutting plate/cm	3.3	4.0	5.3	6.6

Table 8
Test temperature of each asphalt mixture type.

Item	Softening point/°C		Test temperature							
	T_{800}	$T_{R\&B}$	40	45	48	52	55	58	60	70
AC-13	48.6	47.6	√	√	√	√	√	/	√	/
SBS modified AC-13	56.4	58.3	/	√	/	√	√	√	√	√

Table 9
Test load and corresponding wheel pressure.

Test load/kg	78	88	102
Wheel pressure/MPa	0.7	0.8	0.9

Table 10
Compaction degree of each rutting plate.

No.	Bulk density/ (g·cm^{-3})	void volume/%	Compaction degree/%
1	2.452	8.7	95.0
2	2.462	8.3	95.4
3	2.465	8.2	95.5
4	2.465	8.2	95.5
5	2.486	7.4	96.3
6	2.486	7.4	96.3
7	2.488	7.3	96.4
8	2.498	6.9	96.8
9	2.506	6.7	97.1
10	2.532	5.7	98.1
11	2.540	5.4	98.4
12	2.553	4.9	98.9
13	2.555	4.8	99.0
14	2.568	4.4	99.5
15	2.568	4.4	99.5
16	2.581	3.9	100.0

6. Results and discussions

6.1. *Effect of aggregate gradation*

Fig. 4 shows that asphalt mixtures containing MCA have lower RD values at 60 min under WTT than those containing LCA, indicating superior rutting resistance. The dynamic stability of MCA specimens is also far higher than that of LCA specimens,

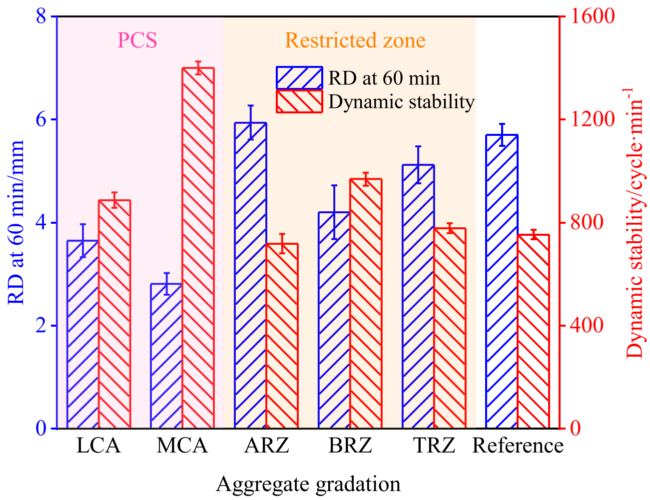

Fig. 4. WTT results for AC-13 with different aggregate gradations.

supporting this finding. Asphalt mixtures are viscoelastic-plastic materials that accumulate permanent deformation due to the repeated shear forces caused by traffic loads. These loads are resisted by the bonding force of asphalt (c) and the internal frictional force (φ) acting on aggregate contacts, as expressed in Eq.(3). Studies have shown that the aggregate interlock accounts for 60% of the high-temperature rutting resistance of asphalt mixtures, while the asphalt cohesion accounts for 40% [45,53, 54]. MCA has more coarse aggregates within the 2.36–4.75 mm sieve size range, which interlock to form the skeleton of the mixture and provide greater rutting resistance due to increased particle-to-particle contact points. Thus, the use of MCA results in superior rutting resistance compared to LCA.

$$\tau = c + \sigma \tan\varphi \quad (3)$$

where τ = shear strength of HMA; and σ = normal stress subjected on HMA.

In terms of the restricted zone, Fig. 4 depicts that asphalt mixtures with BRZ gradation have the lowest RD values at 60 min under WTT, indicating the best rutting resistance, followed by TRZ and ARZ. The dynamic stability of BRZ specimens is also superior to that of the other two gradations. The restricted zone is intended to produce a maximum density gradation with increased contacts and reduced air void space in the mineral aggregate [48]. Asphalt mixtures with gradations below the restricted zone have more coarse aggregates, which form the skeleton of the mixture and improve its rutting resistance. In contrast, mixtures with gradations through or above the restricted zone have excessive natural sand and are more susceptible to rutting.

In summary, compared to asphalt mixtures designed using the restricted zone or the reference group gradation, MCA designed using the PCS method provides the greatest contribution to rutting resistance. MCA gradation corresponds to the coarsest gradation, resulting in sufficient particle-to-particle contact points between coarse aggregates that can effectively slow the development of permanent deformation. In contrast, AC-13, a conventional dense asphalt mixture designed by the Taylor formula, is prone to rutting damage due to the lack of an interlocked aggregate skeleton. In practice, SMA, a well-known gap-graded asphalt mixture, is a better replacement for conventional dense asphalt mixtures since its stone-on-stone contact provides a stable aggregate skeleton matrix against rutting.

6.2. Effect of asphalt content

In Fig. 5, it can be seen that as the asphalt content in the mixture rises, the RD values at 60 min under WTT first decrease and then rapidly increase, reaching the lowest value at an OAC of 4.9% for AC-13% and 5.0% for SBS modified AC-13 mixtures. The dynamic stability of the mixture also increases at first and then decreases sharply with increasing asphalt content, reaching a peak value at the same OAC for both mixtures. This is because both insufficient and excessive asphalt are potentially detrimental to the rutting resistance of asphalt mixtures [17, 54, [55]. As mentioned in Eq.(3), the cohesion of asphalt binders and the internal friction between aggregates determine the shear strength of the mixture. Insufficient asphalt binder results in poor bonding properties between aggregates, while excessive asphalt binder results in more free asphalt and lubrication between aggregates, making the mixture softer and reducing its stability. It is acceptable to have asphalt content ranging from OAC-0.5 to OAC for sufficient high-temperature stability. However, when the asphalt content exceeds 5.9%, the dynamic stability of the mixture does not meet the standard requirement of $DS \geq 600 cycle \bullet \mathrm{min}^{-1}$ [43]. Increasing or decreasing the asphalt content by 0.5% above or below the OAC has different effects on dynamic stability for AC-13 and SBS modified AC-13 mixtures, with SBS modified mixtures showing greater stability overall. SBS modified mixtures are more recommended in highly rutted areas.

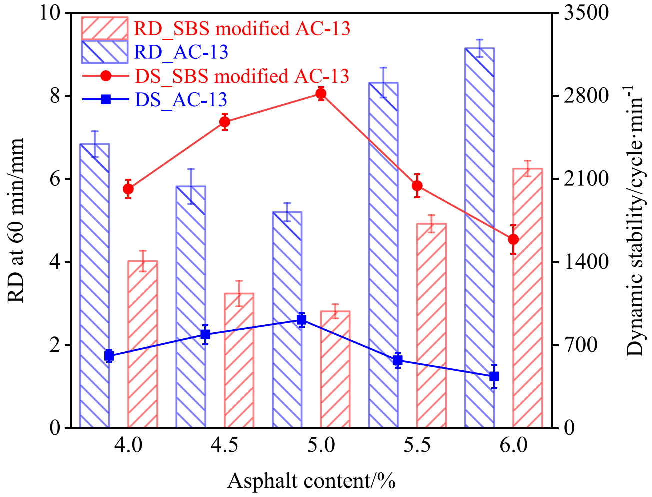

Fig. 5. WTT results for AC-13 and SBS modified AC-13 with different asphalt contents. Note: RD_SBS modified AC-13 = RD at 60 min under WTT for SBS modified AC-13; RD_AC-13 = RD at 60 min under WTT for AC-13; DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

6.3. Effect of layer thickness

Fig. 6 shows that as the thickness of the asphalt mixture layer increases, the RD at 60 min under WTT increases for both AC-13 and SBS modified AC-13, indicating a decrease in the high-temperature stability of asphalt mixtures. The dynamic stability of the specimens also decreases as the layer thickness increases, supporting this trend. The reason for this is that as the mixture layer thickens, the temperature gradient and aggregate segregation make it difficult to ensure proper compaction, resulting in a mixture with insufficient aggregate interlock to withstand repeated traffic loading, leading to viscos and plastic deformation.

To investigate the effect of layer thickness on the rutting resistance of asphalt mixtures, Fig. 7 shows the relationship between the dynamic stability of AC-13 and SBS modified AC-13 mixtures with their $L/NMAS$ ratio, which was statistically fitted. The R^2 values were found to be 0.98998 and 0.99578 for AC-13 and SBS modified AC-13, respectively, indicating a good fit. As the $L/NMAS$ ratio increases, the dynamic stability of both mixtures decreases in the shape of a concave curve, with the peak point occurring at a $L/NMAS$ ratio of approximately 2.75. This observation supports the recommendation in the specification [43] that the layer thickness of the mixture should be 2.5–3 times its NMAS.

6.4. Effect of temperature

Fig. 8 indicates that as the test temperature rises, the RD at 60 min under WTT first increases gradually, next steeply, and finally slowly for both AC-13 and SBS modified AC-13 asphalt mixtures. The temperature at which the abrupt increase in RD occurs is close to the softening point of the respective asphalt binders. These findings suggest that the softening point of asphalt binders has a significant impact on the high-temperature stability of asphalt mixtures. Similarly, the dynamic stability of specimens first decreases slowly, then sharply, and finally gently with increasing test temperature. The temperature at which the dynamic stability drops sharply corresponds to the softening point of the asphalt mixtures. To investigate the combined effect of softening point and temperature on the rutting resistance of asphalt mixtures, the dynamic stability-temperature line in Fig. 8 is divided into three segments based on temperature zones below, near, and above the softening point (BSP, NSP, and ASP). The slope of dynamic stability, which represents the decrease in dynamic stability for each℃ increase is calculated and plotted in Fig. 9.

Fig. 9 depicts that the sensitivity of the asphalt mixture to temperature changes, i.e., the rate of decrease in dynamic stability, is the highest near the softening point of the respective asphalt binder, followed by that below and above the softening point. The most sensitive temperature zone for the rutting resistance of the asphalt mixture to temperature changes is around 3 °C near the softening point of the asphalt binder. The observation is reasonable because the rutting resistance of the asphalt mixture is influenced by two factors, the internal friction force between aggregates and the cohesion of asphalt binders. The variation in aggregate interlock is neglectable within the test temperature range. However, as the temperature rises, asphalt cohesion decreases, leading to a reduction in the rutting potential of the mixture. When the test temperature is below the softening point of the asphalt, the reduction of cohesion is relatively low, resulting in a relatively low reduction of dynamic stability of the asphalt mixture. When the test temperature reaches the softening point of the asphalt, the cohesion of asphalt decreases sharply, reducing its contribution to the rutting resistance of asphalt mixtures. After the test temperature exceeds the softening point of the asphalt, the mixture's rutting resistance is primarily provided by the interlocked aggregates, with little contribution from asphalt cohesion. As a result, although the asphalt cohesion is continuously decreasing, the rate of decrease in dynamic stability is minimal. Another reason for the decrease in rutting resistance of the mixture is that as the viscosity of the asphalt decreases, its lubricating ability increases, continuously decreasing the aggregate interlock.

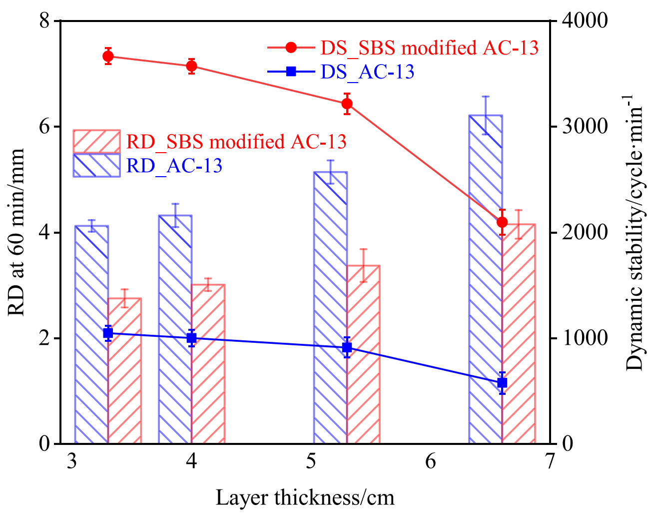

Fig. 6. WTT results for AC-13 and SBS modified AC-13 with different layer thicknesses. Note: RD_SBS modified AC-13 = RD at 60 min under WTT for SBS modified AC-13; RD_AC-13 = RD at 60 min under WTT for AC-13; DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

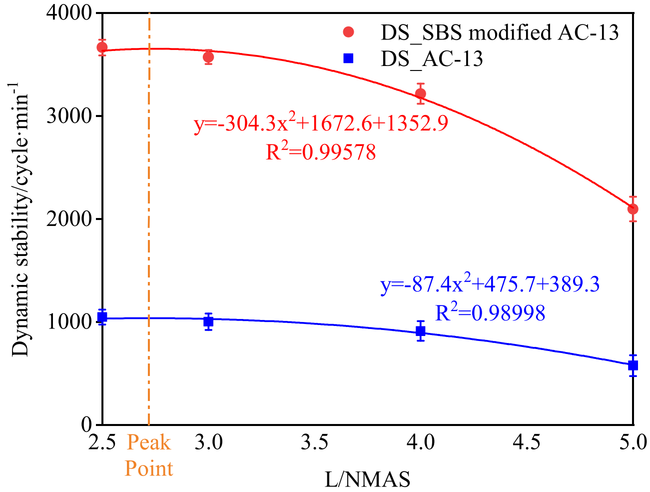

Fig. 7. WTT results for AC-13 and SBS modified AC-13 with different *L/NMAS* ratios. Note: DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

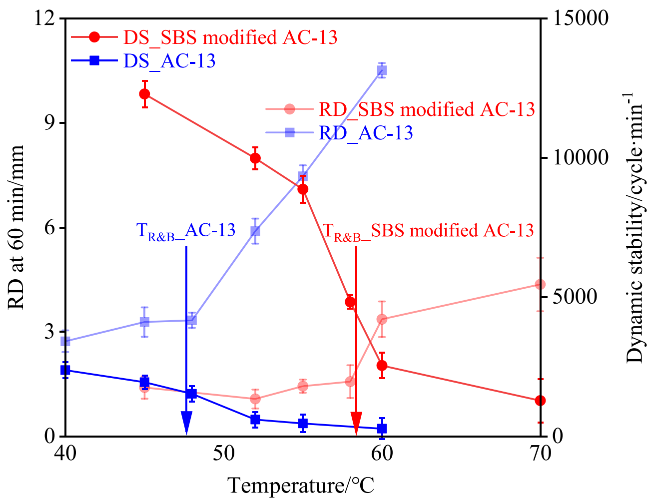

Fig. 8. WTT results for AC-13 and SBS modified AC-13 with different test temperatures. Note: RD_SBS modified AC-13 = RD at 60 min under WTT for SBS modified AC-13; RD_AC-13 = RD at 60 min under WTT for AC-13; DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

The above findings suggest that as the ambient temperature rises above the softening point of the asphalt binders, the mixture becomes more fluid and prone to rutting under repeated traffic loading. To improve the rutting resistance of asphalt mixtures, technical advancements in the softening point of asphalt binders, such as using SBS modified asphalt, are effective. When the actual temperature of the pavement exceeds the softening point of the asphalt, a temporary traffic closure is an effective way to prevent rutting. During the hot season, lightening the colour of the pavement and sprinkling water on it are also effective methods of lowering pavement temperatures.

6.5. Effect of traffic loading

According to Fig. 10, when traffic loading increases, so does the RD at 60 min for the specimens tested under WTT. When traffic loading increases from 78 Kg to 88 Kg (i.e., tire pressure is increased from 0.7 MPa to 0.8 MPa), the viscous and plastic deformation of both AC-13 and SBS modified AC-13 increases by 32.9% and 26.2%, respectively. When the load exceeds 80 Kg, the deformation rate of both mixtures changes from moderate to rapid. As the load is further increased to 102 Kg and the tire pressure is increased from 0.8 MPa to 0.9 MPa, the deformation of AC-13 and SBS modified AC-13 is increased by 52.9% and 46.3%, respectively. Additionally, the dynamic stability of the specimens decreases with increasing traffic loading, with AC-13 and SBS modified AC-13 showing reductions of 22.8% and 14.9%, respectively, as the load increases from 78 Kg to 88 Kg. Once the load reaches 80 Kg, the rate of decrease

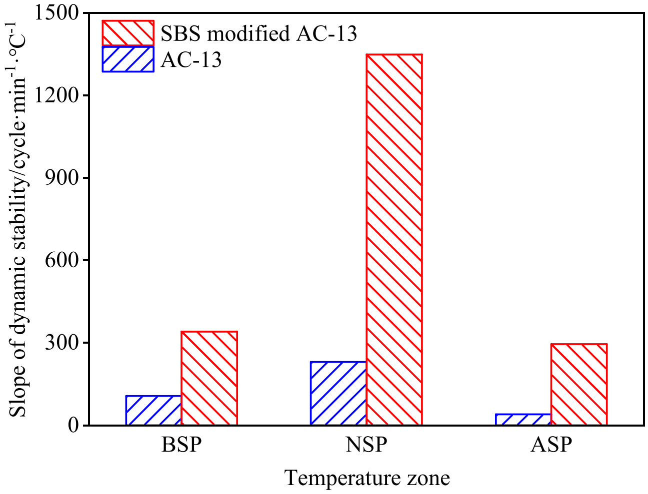

Fig. 9. Slopes of WTT results for AC-13 and SBS modified AC-13 with different test temperatures. Note: BSP, NSP and ASP = temperature zone below, near, and above softening point.

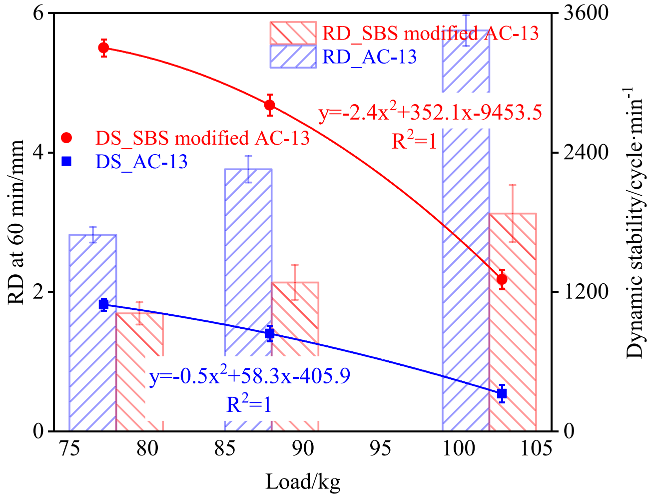

Fig. 10. WTT results for AC-13 and SBS modified AC-13 with different traffic loadings. Note: RD_SBS modified AC-13 = RD at 60 min under WTT for SBS modified AC-13; RD_AC-13 = RD at 60 min under WTT for AC-13; DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

in dynamic stability changes from gentle to steep for both mixtures. Furthermore, when the load is increased to 102 Kg, the dynamic stability of both mixtures does not meet the specification requirements DS≥ 600 cycle·min^{-1} and DS≥ 2000 cycle·min^{-1} for AC-13 and SBS modified AC-13, respectively, [43].

SBS modified AC-13 shows superior anti-rutting ability compared to AC-13 under the same conditions. Overloaded vehicles can jeopardize the high-temperature stability of asphalt mixtures. Reducing asphalt pavement rutting disease requires improved traffic management, cracking down on overloaded vehicles, and using technical means to limit tire pressure as much as possible.

6.6. Effect of compaction

Fig. 11 depicts a strong correlation between the RD and compaction degree of AC-13 and SBS modified AC-13 mixtures, with R^2 values of 0.98954 and 0.98003, respectively. The results indicate that as the compaction degree decreases, the RD at 60 min under WTT increases in a convex curve for both mixtures. The accumulation of viscous and plastic deformation is particularly rapid when the compaction degree is lower than 97%. A reduction in compaction by 2% points (from 97% to 95%) results in a significant increase in RD for both mixtures. Conversely, increasing the compaction degree improves the dynamic stability of the mixtures parabolically. The dynamic stability of the mixture at 100% compaction can be 1.5 times (AC-13) or 1.6 times (SBS modified AC-13) that at 98% compaction. It is essential to achieve the desired density and strength of the pavement through adequate compaction. The results

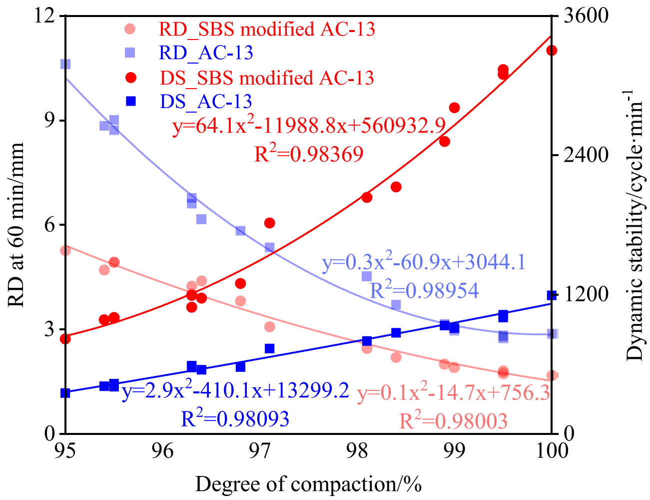

Fig. 11. WTT results for AC-13 and SBS modified AC-13 with different compaction degrees. Note: RD_SBS modified AC-13 = RD at 60 min under WTT for SBS modified AC-13; RD_AC-13 = RD at 60 min under WTT for AC-13; DS_SBS modified AC-13 = dynamic stability for SBS modified AC-13; and DS_AC-13 = dynamic stability for AC-13.

suggest that SBS modified AC-13 has better rutting resistance than AC-13 under the same conditions. The construction specification [43] mandates a laboratory compaction of no less than 97% for hot-mixed asphalt mixtures. However, because the mixture compaction during the laboratory WTT specified in the test procedure [41] is 100% ± 1%, predicting the high-temperature stability of asphalt pavement based on laboratory tests requires verification by field data to avoid overestimation of pavement performance and service life, and missing the best time for maintenance.

7. Conclusions

The study examined the impact of various factors on the high-temperature stability of asphalt mixtures, including internal factors like aggregate gradation, asphalt content, and layer thickness, external factors such as temperature and traffic loading, and human factors like compaction degree using WTT. Based on the findings and discussions on how these factors affect rutting, a meaningful conclusion and recommendation is made as follows:

- MCA designed using the PCS method contributes the most to the rutting resistance of the asphalt mixture due to its tightly interlocked aggregate skeleton formed by sufficient particle-to-particle contact points between coarse aggregates. SMA is a better replacement for conventional dense asphalt mixtures due to its stone-on-stone contact.
- Asphalt content ranging from OAC-0.5 to OAC is acceptable, and specific materials and mixture types should determine its upper threshold to avoid lubrication between aggregates SBS modified asphalt mixtures are recommended in highly rutted areas.
- The *L*/*NMAS* ratio should be 2.5–3 times the NMAS to ensure high-temperature stability of asphalt mixtures.
- Controlling the softening point of the selected asphalt to be higher than the highest possible pavement temperature, reducing pavement temperature, or temporarily closing traffic when the pavement temperature exceeds the asphalt softening point can enhance high-temperature stability.
- Overloaded vehicles jeopardize asphalt pavement stability. Traffic management, cracking down on overloaded vehicles, and limiting tire pressure can help reduce asphalt pavement rutting disease.
- Insufficient compaction degree is the primary cause of early rutting disease on asphalt pavements. Laboratory compaction of asphalt mixtures should be at least 97%. Predicting high-temperature stability of asphalt pavement based on laboratory tests necessitates verification by field data to avoid overestimating pavement performance and service life, and missing the best time for maintenance.

In the future, further research will be conducted to investigate the impact of various factors on the rutting resistance of asphalt mixtures, using multi-factor investigations that integrate orthogonal tests with statistical analysis to compare each factor's contribution. Additionally, it will be necessary to explore the relationship between laboratory test results and the performance of asphalt pavements in the field to improve the accuracy of performance predictions.

CRediT authorship contribution statement

The authors confirm contribution to this study as follows: **Yuanyuan Pan**: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Hui Guo**: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Wei Guan**: Software, Writing – review & editing. **Yongli Zhao**: Writing – review & editing.

Declaration of Competing Interest

No conflict of interest exits in the submission of this manuscript, and it is approved by all authors.

Data Availability

Data will be made available on request.

Acknowledgements

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