Analysis of the Discriminability of High-Temperature Performance Indices of Modified Asphalt Mixtures

Mengjun Gu

Abstract Different indices have various capabilities to evaluate the high-temperature performance of modified asphalt mixtures. This study aims at investigate the discriminability of high-temperature performance indices. The values of five indices were determined from wheel tracking test, Marshall test and uniaxial penetration test, including dynamic stability (DS), comprehensive stability index (CSI), maximum rutting depth (RD), Marshall stability (MS), and uniaxial penetration strength (UPS). The discriminability of five indices was further examined by entropy weight method and CRITIC method, respectively. The results show that DS, MS and UPS are not appropriate to evaluate the high-temperature performance of modified asphalt mixtures, but CSI and RD show preferable distinguishing ability to evaluate the high-temperature performance. As a consequence, RD is recommended to be employed as secondary index to supplement the CSI in wheel tracking test. The findings of this study will contribute to the optimization of evaluation on high-temperature performance of modified asphalt mixtures.

Keywords Road engineering · Modified asphalt mixture · Discriminability · Entropy weight method · CRITIC method

1 Introduction

The high-temperature performance of asphalt mixtures is of great significance to the service of asphalt pavement, which directly determines whether it will occur serious bleeding, slippage, rutting and other distresses. To prevent adverse rutting distress, many types of additives were utilized to prepare modified asphalt mixtures, including SBS, rubber powder, polyethylene, etc. [1]. Obviously, those modified asphalt mixtures have remarkable and excellent high-temperature performances, whereas their evaluation methods remain to be enhanced because existing laboratory tests show high discreteness, poor uniformity, and low accuracy [2].

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Engineering practice has proved that the asphalt mixtures meeting the dynamic stability requirements in the specification could also occur severe rutting distress in the actual pavement [3]. The contradiction often occurs when the dynamic stability is large but the actual rutting depth is large. The possible reason for this is that the conditions of wheel tracking test cannot completely consider actual temperature, speed, and loads of the pavement. It is also believed that the wheel tracking test can only distinguish the rutting resistance of asphalt mixtures with relative small stiffness, but cannot successfully evaluate the rutting resistance of mixtures with high modulus [4].

In order to overcome the issues mentioned above, many researches attempt to upgrade the existing indices to improve their performance. Peng et al. [5] proposed a new concept of rutting coefficient WRI based on the limitation of dynamic stability, which considers cumulative deformation and maximum deformation, thus improved the evaluation efficiency of anti-rutting indices. Du and Dai [6] held the view that the dynamic stability only incorporated the growth rate of shear flow deformation in the stable consolidation period, but ignored the deformation in transition period. So comprehensive stability index (CSI) was developed to evaluate the rutting resistance of asphalt mixtures. Zhou et al. [7] found that the maximum rutting depth performed well correlation with the creep slope of asphalt mixtures, so it is recommended to employ the maximum rutting depth as supplementary evaluation index in wheel tracking test.

It is concluded that these findings aim at establishing new indices or simply validating their performance, but rarely compared their discriminative ability on high-temperature performance, in particular modified asphalt mixtures. In order to enhance the discriminability of high-temperature indices with higher preciseness, the DS, CSI, RD, MS and UPS of different modified asphalt mixtures were obtained by conducting wheel tracking test, Marshall test, and uniaxial penetration test. Further discriminability study on those five indices were compared by entropy weight method and CRITIC method. The outcomes of this study can offer recommendations on electing indices for evaluating high-temperature performance of modified asphalt mixtures.

2 Materials and Experimental Program

2.1 Test Materials

The PR PLAST.S (hereinafter referred to as PR) anti-rutting additive produced by a French company was used to modify asphalt mixtures, which presented as black solid particles with a particle size of about 4 mm. Relying on its inter-locking, reinforcement and cementation effects, the high-temperature performance of asphalt mixture can be greatly improved by directly mixing PR into asphalt mixture. Total 10 types of asphalt mixtures were designed in accordance with *Technical Specification*

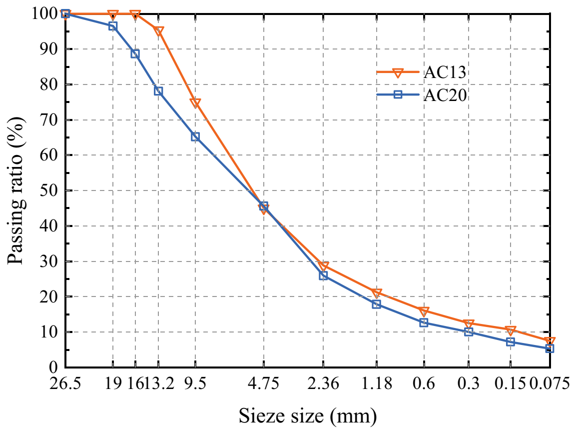

Fig. 1 Gradation curve of asphalt mixtures

Table 1 Volume parameters of asphalt mixtures

Mixture	VFA/%	VMA/%	VV/%	VA/%	Theory maximum relative density/g cm^{-3}	Bulk relative density/g cm^{-3}
AC13	75.0	16.4	4.1	12.3	2.639	2.531
AC20	71.6	14.8	4.2	10.6	2.573	2.465

for Construction of Highway Asphalt Pavements (*JTG F40-2004*), including AC13, 0.2% PR-AC13, 0.4% PR-AC13, 0.6% PR-AC13, 0.8% PR-AC13, AC20, 0.2% PR-AC20, 0.4% PR-AC20, 0.6% PR-AC20, 0.8% PR-AC20. The gradations of AC13 and AC20 were shown in Fig. 1. SK-70# asphalt, limestone mineral powder, and aggregates were used to prepare PR-AC13 mixtures and PR-AC20 mixtures with different content of PR modifiers. The PR content refers to the mass ratio of modifiers to asphalt mixtures. The optimal asphalt contents of AC13 and AC20 were 4.7% and 4.1%, which were determined via Marshall method. The volume parameters of asphalt mixtures were shown in Table 1.

2.2 Experiments

The wheel tracking test was generally used to evaluate the high-temperature stability of the asphalt mixture for its simplicity and good relationship with real pavement. Wheel tracking test has the relatively comprehensive process of consolidation, shearing, and flow deformation, thus the above mixtures were examined by wheel tracking test under 0.7 MPa wheel-pressure and 60 °C. Finally, dynamic stability (DS) was determined.

In addition, another index comprehensive stability index (CSI) was proposed to consider the transition and stable phase of consolidation, showing good relationships with other indices [6, 8, 9]. CSI was described as:

$$CSI = \frac{(t_2 - t_1)NC_1C_2}{d_1(d_2 - d_1)} \tag{1}$$

where N is the rolling speed of wheels; C_1 and C_2 are coefficients related to machine type and specimen. d_1, d_2 are deformations corresponding to time t_1, t_2, respectively.

Relative to DS, d_1 is brought into the calculation of CIS again, thus the transition and stable stage during consolidation deformation is taken into account. On the other hand, the maximum rutting depth (RD) was also selected as an evaluation index. Marshall stability (MS) was also taken to evaluate high-temperature of asphalt mixtures.

The uniaxial penetration test was conducted by universal testing machine to evaluate the high-temperature stability of the asphalt mixtures under 60 °C. The uniaxial penetration strength was accordingly determined as below.

$$\sigma_p = P/A \tag{2}$$

$$UPS = k\sigma_p \tag{3}$$

where σ_p denotes penetration stress, MPa; UPS denotes the uniaxial penetration strength; P denotes the maximum penetration load, N; A is the cross-sectional area of indenter, mm^2; and k denotes strength coefficient.

Based on the experiments above, the indices DS, CSI, RD, MS, and UPS were selected as indices to evaluate the high-temperature stability of modified asphalt mixtures. Moreover, in order to verify the consistency of different indices that characterize the high-temperature properties of mixtures, the Pearson Correlation Coefficient was further calculated to indicate the correlation of five indices.

3 Analysis of High-Temperature Performance of Mixtures

Figure 2a–e are the results of different types of asphalt mixtures, and five indices are compared in the bar chart, including DS, CSI, RD, MS, and UPS. Relative to AC13 and AC20 mixtures, the incorporation of PR modifier causes five high-temperature performance indices of asphalt mixtures to increase with varying degrees. The high-temperature stability of 10 types of mixtures generally improves with the increase of PR content. It is notable that the high content (0.8%) of the PR modifier results in a considerable increase in both DS and CSI, as well as remarkable decrease in maximum rutting depth. Whereas the MSs of 10 types of asphalt mixtures varied slightly, even for higher content of PR modifier. Thus it implies that the PR modifier shows different synergistic effects on five indices, thus the applicability of five indices is expected to be verified regarding high-temperature stability of asphalt mixtures.

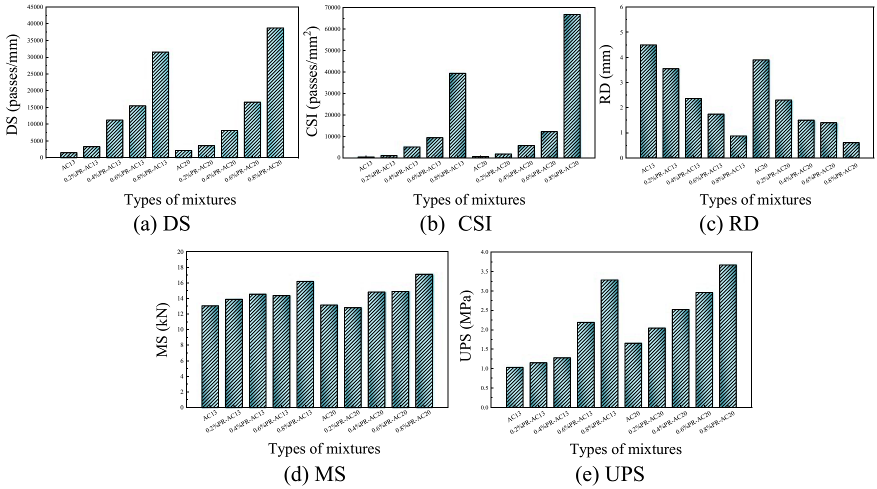

Fig. 2 Results of high-performance tests for different types of asphalt mixtures

The correlation between each index was evaluated with Pearson's Coefficient, as shown in Table 2. It is found that the DS, CIS, and MS have a strong correlation between each other, because their Pearson's Coefficients are greater than 0.9. However, this kind of result is not consistent with the above findings via bar charts. The poorest correlation occurs between CSI and RD, and the absolute value of their Pearson's Coefficient is 0.706, which means the comprehensive stability index (CSI) cannot completely reflect the deformation properties of modified asphalt mixtures under high-temperature conditions. It deduced that the introduction of d_2 adversely influenced the correlation between CSI and RD compared with DS.

Consequently, the results of the correlation analysis have several differences from the findings in the bar chart. So the discriminability of these indices remains to be examined through more advanced methods in need, thus determining the most appropriate index to evaluate high-temperature stability of modified asphalt mixtures.

Table 2 Pearson's coefficients between different indices

Pearson's coefficient	DS	CSI	RD	MS	UPS
DS	1	0.9554	− 0.8245	0.9495	0.8611
CSI	0.9554	1	− 0.706	0.9014	0.8184
RD	− 0.8245	− 0.706	1	− 0.8277	− 0.8957
MS	0.9495	0.9014	− 0.8277	1	0.8223
UPS	0.8611	0.8184	− 0.8957	0.8223	1

4 Determination of Discriminability

4.1 Calculation with Entropy Weight Method

The entropy weight method was widely used to distinguish the discriminability of indices for its simplicity and objectiveness. Entropy weight method was used to calculate the weight of each index.

An initial matrix composed of m evaluated objects and n indices $\boldsymbol{A} = (a_{\text{ij}})_{m\times n}$ was constituted, where a_{ij} was the value of the jth index of the ith evaluated object. And the column formed by RD belonged to the inverse index, so the elements in the column were processed with isotropization transformation. After that, the matrix $\boldsymbol{X} = (x_{\text{ij}})_{m\times n}$ was determined. Then the normalization of data was conducted to eliminate the influence of dimension, as given by:

$$\delta_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \tag{4}$$

Entropy value E_j and entropy weight W_j of index j were calculated as:

$$E_j = -\sum_{i=1}^{m} \delta_{ij} \ln \delta_{ij} / \ln m \tag{5}$$

$$W_j = 1 - E_j / \sum_{j=1}^{n} 1 - E_j \tag{6}$$

Finally, discriminability of index j is calculated in accordance with Eq. (8).

$$D_j = W_j \left(\max_{i=1}^{m} \delta_{ij} - \min_{i=1}^{m} \delta_{ij} \right) \tag{7}$$

4.2 Calculation with CRITIC Method

Entropy weight method simply considers the discrete degree of data without accounting their conflicts. Criteria importance though inter-criteria correlation (CRITIC) method is an objective method to determine the weight of indices based on the contrast intensity and conflicts between indices, which is applicable for the evaluation of multiple-index. Standard deviation was used to indicate the contrast intensity, as given by:

$$\sigma_j = \sqrt{\sum_{i=1}^{m} \left(\delta'_{ij} - \overline{\delta'}_j\right)/(m-1)} \tag{8}$$

The conflicts between indices were characterized based on their correlation, as given by:

$$f_j = \sum_{i=1}^{m} \left(1 - r_{ij}\right) \tag{9}$$

where r_{ij} was the correlation coefficient of index i and j, and Pearson's Coefficient was adopted.

Furthermore, the relative significance of index j was described by information-carrying capacity C_j. The higher C_j means larger amount of information, which implied that the corresponding index had the higher significance, as described by:

$$C_j = \sigma_j \sum_{i=1}^{m} (1 - r_{ij}) = \sigma_j f_j \tag{10}$$

Thus, the objective weight of index j was determined by:

$$W_j = C_j / \sum_{i=1}^{m} C_j \tag{11}$$

4.3 Analysis of Discriminability

Tables 3 and 4 present the key results from the entropy weight method and CRITIC method, respectively. It clearly shows that the discriminability (D_j) determined by entropy weight method and CRITIC method is particularly different. For entropy weight method, the D_j of CSI is the greatest value among four indices, which is 0.2561. It implies the index CSI has a satisfactory ability to distinguish the high-temperature performance of modified asphalt mixtures. However, the D_j of CSI is close to 0, which means the good and poor performance of modified asphalt mixtures cannot be well separated. In addition, the sequence of discriminability of five indices in descending order is CSI > DS > RD > UPS > MS.

With regard to CRITIC method, the discriminability of five indices differs from that of entropy weight method. The sequence of discriminability of five indices in descending order is RD > CSI > DS > UPS > MS. In particular, the RD has the biggest D_j among five indices, even up to 0.6679. Consistent with the results determined by entropy weight, the MS still has poor ability to distinguish the high-temperature

Table 3 Results determined from entropy weight method

Items	DS	CSI	RD	MS	UPS
Entropy (E_j)	0.8257	0.6401	0.9146	0.9983	0.9645
Entropy weight (W_j)	0.2654	0.5479	0.1301	0.0026	0.0540
Discriminability (D_j)	0.0748	0.2561	0.0290	0	0.0065

Table 4 Results determined from CRITIC method

Items	DS	CSI	RD	MS	UPS
Information-carrying capacity (C_j)	0.0263	0.0542	0.0972	0.0037	0.0248
Entropy weight (W_j)	0.1275	0.2628	0.4713	0.018	0.1203
Discriminability (D_j)	0.0359	0.1228	0.6679	0.0005	0.0146

performance of modified asphalt mixtures due to extremely low D_j (approaching to 0). CSI has relative acceptable discriminability compared with DS, MS, and UPS, which reaches as high as 0.1228.

It was concluded that the D_j of RD remarkably varied when calculating by entropy weight method and CRITIC method. The major reason is attributed to the correlation between RD and other indices (especially for CSI) is rather poor, as examined in previous sections. The poor correlation causes large conflicts between indices, resulting in the increase of RD's significance on high-temperature performance. Nonetheless, RD is still an important index to reflect the deformation properties of modified asphalt mixtures under high-temperature.

It is notable that the CSI was always an acceptable index to evaluate the high temperature of modified asphalt mixtures, which is consistent with the findings obtained by Fang et al. [9]. The DS always shows weak performance on evaluating the high-temperature stability of modified asphalt mixtures even though it has been widely used for design and construction of asphalt pavement. The MS and UPS are not acceptable indices to evaluate the high-temperature stability due to their low discriminability. However, the RD can be employed as secondary index to supplement the CSI in wheel tracking test due to their good discriminability.

5 Conclusions

(1) High modifier content lead to a considerable increase in both DS and CSI of modified asphalt mixtures, but the MS varied slightly for 10 types of asphalt mixtures. Five indices have different variation trend for different modified asphalt mixtures.

(2) Five indices generally have relative strong correlation between each other except for CSI and RD, thus CSI cannot comply with the deformation properties of modified asphalt mixtures.

(3) The sequence of discriminability of five indices in descending order determined by CRITIC method is RD > CSI > DS > UPS > MS. And the sequence of discriminability of five indices in descending order obtained from entropy weight method is CSI > DS > RD > UPS > MS.
(4) DS, MS and UPS are poor in evaluating the high-temperature performance of modified asphalt mixtures. CSI is recommended to evaluate the high-temperature performance of modified asphalt mixtures. And RD is expected to be employed as secondary index to supplement the CSI in wheel tracking test.

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