Application of Dynamic Stability Criterion in Evaluating Field Rutting of Asphalt Pavements Using the Wheel Tracking Test

Huy Thien Phan[1]; Van Phuc Le, Ph.D.[2]; and Hyun Jong Lee, Ph.D.[3]

Abstract: In this study, the application of the dynamic stability (DS) criterion to evaluate rutting of asphalt pavements using the wheel tracking test is presented considering field pavement conditions. A simplified model estimating the rut depth of asphalt pavements was first developed considering the DS, the number of load cycles (N), the maximum shear stress ($\tau_{\max}$), and load duration (t). To develop the model, indirect tensile (IDT) and uniaxial compressive strength (UCS) tests were conducted to measure cohesion (c) and internal friction angle (ϕ) of three asphalt mixtures. In addition, seven types of asphalt mixtures were evaluated to determine their DS using the wheel tracking test. To determine the average maximum shear stress, a predictive regression equation was established through the KENLAYER program with various combinations of asphalt concrete (AC) modulus, subbase and subgrade resilient moduli, and layer thicknesses. Based on the rutting performance of six pavement sections from the WesTrack test, the rutting model was validated and applied to different AC layer scenarios. It was found that the proposed model is accurate in estimating the rut depth of AC layers under varying load and environmental field conditions. Application of the DS criterion in evaluating rut depth for asphalt concrete is proposed using the developed rutting model. **DOI: 10.1061/JPEODX.0000375.** *© 2022 American Society of Civil Engineers.*

Author keywords: Rut depth; Shear stress; Shear strength; Asphalt pavement; Wheel tracking test; Dynamic stability (DS).

Introduction

Rutting is one of the major distresses in asphalt pavements and is mainly because of the shear flow of asphalt mixture that causes premature failure of the pavement. Thus, characterizing the rutting resistance of an asphalt mixture is an important process in mix design to prevent premature rutting failure.

For the characterization of rutting resistance of asphalt mixes, various laboratory tests such as wheel tracking (WT), flow number (FN), triaxial repetitive loading, simple shear, and uniaxial creep and recovery have been established and are currently used (Walubita et al. 2018, 2019a, 2020; Zhang et al. 2013). The WT test has been widely used because the test method is relatively simple and easy to perform. As of the present, there are many different types of WT test devices available such as the Hamburg wheel tracking (HWT) device, French pavement rutting tester, Georgia loaded wheel tester, and Japan WT device. These devices are somewhat similar in concept with slight differences in design and mechanism. The similarities and differences of these devices are well summarized in the study of Hao and Hachiya (2004).

HWT tests are widely used in the United States in evaluating rutting resistance. There are some researchers using the HWT test to estimate the pavement rut depth under field conditions. Based on field projects for 51 hot mix asphalt (HMA) and warm mix asphalt (WMA) pavements, it was found that the HWT rut depth alone is not sufficient to predict the field rutting performance (Zhang et al. 2017). On the other hand, the Texas flexible pavements and overlays database for three HMA mixes (ranging from fine to coarse graded) and five in-service highways were used to correlate and validate the HWT laboratory test data to field rutting performance of in-service highways (Walubita et al. 2019b, 2020). These study results showed that the laboratory HWT test correlated well with the actual measured field performance data. Moreover, a field rut depth predictive model was developed based on the HWT rut depth (Zhang et al. 2021). The study results showed that the HWT rut depth magnitudes were closer to field rut depth. However, the HWT standard test in the United States is typically conducted in a wet condition and inadequate results in dry conditions have been reported (Chaturabong and Bahia 2017). Although the WT test is promising for the characterization of rutting resistance of asphalt mixes, only a limited amount of research efforts has been made.

Dynamic stability (DS), representing the inverse slope of a rutting curve obtained from the WT test, has been used as a criterion to characterize the rutting resistance of asphalt mixes. The DS is computed from the measured rut depth between 45 and 60 min in the WT test. The minimum DS values in the Japanese standards are classified based on traffic volume (Hao and Hachiya 2004), while in Korea the minimum values are specified based on asphalt mix types (Kim et al. 2004). The current DS criterion is empirically established based on field experiences. In the wheel tracking test, slab specimens with dimensions of 300 × 300 × 50 mm subjected to a single tire loading are used to measure the rut depth. Because of this, the confining pressure that exists in the real condition may not be simulated. As a result, it is not easy to correlate the DS value with rutting performance in the field.

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Therefore, the main objective of this study was to develop a rutting prediction model that can predict field rut depth using the laboratory WT test result. To accomplish this objective, WT tests for various asphalt mixes were conducted. A WT rutting model was first developed using the WT test data and then correlated with a field rutting prediction model proposed by Kim et al. (2017). Through analytical studies regarding the WT test conditions and structural behavior of asphalt pavement, a simplified rutting model was proposed to predict the field rut depth based on the DS values obtained from the WT test. The model was validated with WesTrack testing data (TRB 2005). Finally, a new concept to establish a new DS criterion using the rutting model was proposed.

Experimental Program

Materials and Specimen Preparation

In this study, laboratory tests were conducted on seven different types of asphalt mixes as presented in Table 1. Aggregate gradations used for the mixes are presented in Fig. 1. As seen in the figure, three dense gradations (coarse, fine-plus, and fine) and a stone mastic asphalt (SMA) gradation were used. In addition, two types of binders, conventional binder (PG 64-22) and modified binder (PG 76-22), were used. The HMA samples were lab compacted by means of the Superpave gyratory compactor to a target $7\% \pm 1\%$ air voids. The volumetric properties of the mixes are also provided in Table 1.

For each mixture, slab specimens ($300 \times 300 \times 50$ mm) were prepared to be tested in the WT device. They were compacted at prefixed volumetric properties in a roller compaction machine in which the air void contents were determined before testing.

Table 1. Mix types and properties used in laboratory tests

Mix type	Binder grade	Asphalt content (%)	Air void (%)	VMA (%)	VFA (%)
A	PG 64-22	5.0	6.1	15.51	60.67
B	PG 76-22	5.0	5.7	16.53	65.52
C	PG 64-22	6.5	3.4	20.61	83.50
D	PG 64-22	5.3	8.2	14.41	43.06
E	PG 64-22	5.7	7.9	14.02	43.66
F	PG 64-22	6.6	6.5	14.89	56.34
G	PG 64-22	5.9	7.5	17.69	57.61

Note: A, B, F, and G are 19-mm coarse gradation; C is 13-mm SMA; D is 13-mm fine gradation; E is 13-mm fine-plus gradation; VMA = voids in mineral aggregate; and VFA = voids filled with asphalt.

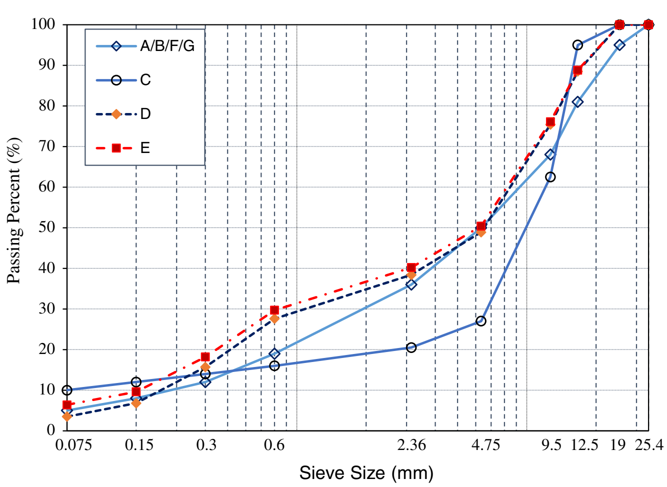

Fig. 1. Aggregate gradations.

Instead of the triaxial compression strength (TCS) test, Christensen and Bonaquist (2002) proposed an alternative method in determining shear properties c and ϕ using the indirect tensile (IDT) and uniaxial compressive strength (UCS) tests. This alternative method was verified by Li et al. (2011). For simplicity, the IDT and UCS tests were adapted in this study to measure shear properties.

A Superpave gyratory compactor was used to make cylindrical specimens with a diameter of 150 mm and a height of 175 mm. The gyratory-compacted specimens were then cored and sawn to obtain the UCS testing specimens with a diameter of 100 mm and height of 150 mm. Similarly, the compacted specimens were also cut to obtain the required 50-mm-thick specimens for IDT testing.

Testing Methods

In this study, three different types of laboratory tests including WT, UCS, and IDT were conducted. A WT machine (Berlin) with an environmental chamber and a tracking wheel with a diameter of 200 mm and width of 50 mm was used. The test was performed at a loading pressure of 689 kPa and loading speed of 42 passes/min under a temperature condition of 60°C (Walubita et al. 2020). The slab specimens ($300 \times 300 \times 50$ mm) were used to measure the rut depth in the WT test. The WT tests were stopped after 60 min.

For the UCS and IDT tests, a constant displacement rate of 50 mm/min was applied to the specimens at a temperature condition of 60°C using a servo-hydraulic testing system. The peak compressive loads were measured to calculate the compressive or indirect tensile strength of the specimens.

Test Results

Christensen and Bonaquist (2002) proposed a simple method in determining cohesion and friction angle based on the IDT and UCS test data using the following equations:

$$\tan\alpha = \frac{|\sigma_{\mathrm{UCS}}| - 4|\sigma_{\mathrm{IDT}}|}{|\sigma_{\mathrm{UCS}}| - 2|\sigma_{\mathrm{IDT}}|} \tag{1}$$

$$\phi = \sin^{-1}(\tan\alpha) \tag{2}$$

$$c = \left(\frac{2 - \tan\alpha}{\cos\phi}\right)\sigma_{\mathrm{IDT}} \tag{3}$$

where $\tan\alpha$ = slope parameter; σ_{IDT} = indirect tensile strength; and σ_{UCS} = uniaxial compressive strength.

In the WT test, the DS is computed from the measured rut depth between 45 and 60 min under dry conditions at a reference temperature of 60°C as follows (Kim et al. 2004):

$$\mathrm{DS} = \frac{42 \times 15}{d_{60} - d_{45}} \tag{4}$$

where DS = dynamic stability under dry conditions at a reference temperature of 60°C (cycles/mm); d_{60} = rut depth at 60 min under dry conditions at a reference temperature of 60°C (mm); and d_{45} = rut depth at 45 min under dry conditions at a reference temperature of 60°C (mm).

The cohesion (c) and friction angle (ϕ) values for all the asphalt mixes were calculated using Eqs. (1)–(3) using the uniaxial compressive and indirect tensile strength data. Also, DS values were

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Table 2. Test results at 60°C

Mix type	σ_{UCS} (kPa)	σ_{IDT} (kPa)	c (kPa)	ϕ (degrees)	d_{45} Rut depth at 45 min, (mm)	Rut depth at 60 min, d_{60} (mm)	Dynamic stability (cycles/mm)
A	776.7	77.0	145.8	48.8	3.25	3.77	1,222
B	1,210.2	147.6	265.4	42.6	1.41	1.57	4,048
C	467.9	49.1	91.6	47.3	7.45	8.41	664
D	—	—	—	—	3.81	4.14	1,955
E	—	—	—	—	11.01	12.60	398
F	—	—	—	—	16.78	18.39	392
G	—	—	—	—	5.47	6.11	979

computed using Eq. (4) using the WT test data. All the test results are summarized in Table 2.

Development of a New Procedure to Estimate Field Rut Depth Using WT Test Data

From a previous study (Kim et al. 2017), an asphalt pavement rutting model was proposed considering the number of load cycles N, shear stress to strength ratio τ/τ_f temperature T, and load duration t. Because the shear strength in the rutting model was determined in terms of cohesion (c) and internal friction angle (ϕ) of asphalt mixes, prediction equations for c and ϕ were established through a series of multiple-regression analyses using laboratory test data. The prediction equations considered asphalt binder contents and stiffness, aggregate gradations, and volumetric properties of various asphalt mixes at a reference temperature of 50°C. The rutting model was first calibrated using WesTrack testing data obtained from 26 different pavement sections and was further validated using field rutting performance data obtained from eight different locations in Korea. The final rutting model proposed by Kim et al. (2017) is as follows:

$$\varepsilon_p = 10^{-14.3486}(N)^{0.29425}\left(\frac{\tau}{\tau_f}\right)_{\text{ref}}^{2.7844}(T)^{6.79174}(t)^{0.44878} \tag{5}$$

$$\left(\frac{\tau}{\tau_f}\right)_{\text{ref}} = \frac{\tau_{\max}(\tan\phi_{\text{ref}}\ \sin\phi_{\text{ref}} + \cos\phi_{\text{ref}} - \tan\phi_{\text{ref}})}{c_{\text{ref}} + \sigma_3\ \tan\phi_{\text{ref}}} \tag{6}$$

where ε_p = cumulative permanent strain; N = number of load cycles; τ = shear stress (kPa); τ_f = shear strength (kPa); $T = (9/5)\times T_c + 32$, where T_c is pavement temperature (°C); t = loading time (s), which is affected by vehicle speed, tire contact area, and effective depth in asphalt layers (ARA Inc., ERES Consultants Division 2004); $\tau_{\max}$ = maximum shear stress under the given loading condition (kPa); σ_3 = actual minor principal stress under the given loading condition (kPa); c_{ref} = cohesion at reference temperature of 50°C (kPa); and ϕ_{ref} = friction angle at reference temperature of 50°C (degrees).

The authors' original rutting models presented in Eqs. (5) and (6) were developed at a reference temperature of 50°C. Because the WT test is typically performed at a temperature of 60°C, the rutting models were revised using the test data obtained from previous research (Kim et al. 2017) as follows:

$$\varepsilon_p = 10^{-16.289}(N)^{0.294}\left(\frac{\tau}{\tau_f}\right)_{60}^{2.208}(T)^{7.119}(t)^{0.456} \tag{7}$$

$$\left(\frac{\tau}{\tau_f}\right)_{60} = \frac{\tau_{\max}(\tan\phi_{60}\ \sin\phi_{60} + \cos\phi_{60} - \tan\phi_{60})}{c_{60} + \sigma_3\ \tan\phi_{60}} \tag{8}$$

where c_{60} = cohesion at reference temperature of 60°C (kPa); and ϕ_{60} = friction angle at reference temperature of 60°C (degrees).

To predict the WT rut depth, a WT rutting prediction model was established following the form of the field rutting model in Eq. (7). Because the temperature and loading speed in the WT are constant, Eq. (7) can be simplified as follows:

$$\varepsilon_{p-\text{WT}} = k_0(N_{\text{WT}})^{k_1}\left(\frac{\tau}{\tau_f}\right)_{\text{WT}}^{k_2} \tag{9}$$

where $\varepsilon_{p\text{-WT}}$ = rut depth in WT test; N_{WT} = number of load cycles in WT test; and k_i = model coefficients

$$\left(\frac{\tau}{\tau_f}\right)_{\text{WT}} = \frac{\tau_{\max}^{\text{WT}}(\tan\phi_{60}\ \sin\phi_{60} + \cos\phi_{60} - \tan\phi_{60})}{c_{60} + \sigma_3^{\text{WT}}\ \tan\phi_{60}} \tag{10}$$

where $\tau_{\max}^{\text{WT}}$ = maximum shear stress under the given loading condition in WT test; and σ_3^{WT} = minor principal stress under the given loading condition in the WT test.

To predict the rut depth in the WT slabs using Eqs. (9) and (10), the maximum shear stress ($\tau_{\max}^{\text{WT}}$) and the minor principal stress (σ_3^{WT}) must be known. Finite-element (FEM) analysis was conducted to investigate the stress developed in the WT slabs for various asphalt mixes with different stiffness as shown in Fig. 2. The asphalt concrete (AC) dynamic modulus values were assumed to be in the range of 100–1,000 MPa at 60°C. It was observed from the FEM analysis results that the maximum shear stresses were developed along the vertical depth at the loading edge. The average maximum shear stress and the minor principal stress below the edge of the tracking wheel were found to have constant values (101.5 kPa for the average maximum shear stress and 29.4 kPa for the minor principal stress). Because the WT test has a single asphalt layer, the internal stresses are independent of the modulus. Based on this observation, Eq. (10) can be expressed as follows:

$$\left(\frac{\tau}{\tau_f}\right)_{\text{WT}} = \frac{101.5(\tan\phi_{60}\ \sin\phi_{60} + \cos\phi_{60} - \tan\phi_{60})}{c_{60} + 29.4\ \tan\phi_{60}} \tag{11}$$

To determine the coefficients of the WT rutting model (i.e., k_0, k_1, and k_2) in Eq. (9), WT tests for three different types of asphalt mixtures (A, B, and C) in Table 2 were conducted. The c and ϕ values of each mixture were determined based on the IDT and UCS test results. Eq. (11) was used to calculate the shear stress to

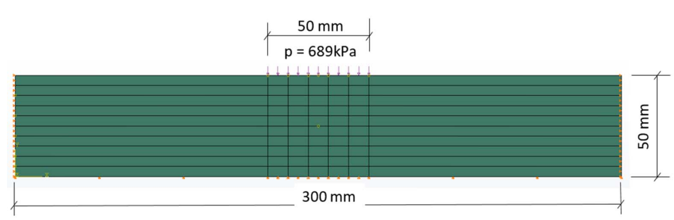

Fig. 2. Mess of elastic FEM model for WT test condition.

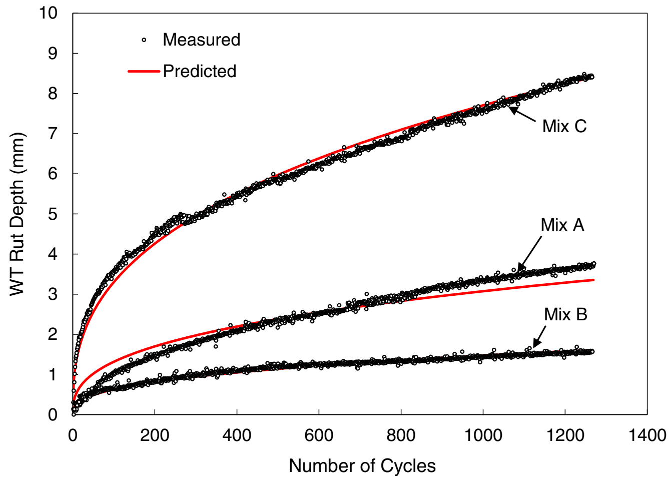

Fig. 3. Comparison of measured and predicted WT rut depth.

strength ratio value for each mixture. The permanent strain value for each mixture was estimated using Eq. (9) for a given number of load cycles.

By comparing the predicted and measured rut depths, a trial-and-error approach using SPSS software was conducted to determine the model coefficients in Eq. (9). As a result, the model coefficients k_0, k_1, and k_2 were found to be 0.148, 0.368, and 2.208, respectively. Fig. 3 compares the predicted and measured rut depths. It can be seen from the figure that the predicted rut depths generally fit well with the measured ones. The correlation coefficient is 0.99 and the average root-mean-square error (RMSE) is 1.3 mm.

Using the model coefficients obtained, the WT model in Eq. (9) can be expressed as follows:

$$\varepsilon_{p\text{-WT}} = 0.148(N_{\text{WT}})^{0.368}\left(\frac{\tau}{\tau_f}\right)^{2.208}_{\text{WT}} \quad (12)$$

The proposed rutting model in Eq. (12) cannot be directly used in estimating field rut depth because of the difference between the field and WT test conditions. Therefore, the WT model was correlated with field rutting model as follows:

$$\frac{\varepsilon_p}{\varepsilon_{p\text{-WT}}} = \frac{10^{-16.289}N^{0.294}(\frac{\tau}{\tau_f})^{2.208}\,T^{7.119}t^{0.456}}{0.148(N_{\text{WT}})^{0.368}\left(\frac{\tau}{\tau_f}\right)^{2.208}_{\text{WT}}} \quad (13)$$

Eq. (13) can be rearranged as follows:

$$\varepsilon_p = 10^{-15.459}\frac{N^{0.294}}{N_{\text{WT}}^{0.368}}K^{2.208}T^{7.119}t^{0.456}\frac{\text{RD}_{\text{WT}}}{50} \quad (14)$$

where ε_p = field cumulative permanent strain in asphalt pavement; RD_{WT} = rut depth in WT test (mm); and

$$K = \frac{(\frac{\tau}{\tau_f})}{(\frac{\tau}{\tau_f})_{\text{WT}}} \quad (15)$$

Substituting Eqs. (8) and (11) into Eq. (15) yields

$$K = \frac{\tau^{\max}(c_{60} + 29.4\ \tan\phi_{60})}{101.5 \times (c_{60} + \sigma_3\ \tan\phi_{60})} \quad (16a)$$

$$K_a = \frac{\tau^{\max}}{101.5} \times \alpha \quad (16b)$$

Table 3. Approximate coefficient for surface and binder course layer

Mixture	Cohesion c_{60} (kPa)	Friction angle ϕ_{60} (degrees)	Coefficient α for surface course	Coefficient α for binder course
AC-19C	200	54	0.923	1.124
AC-19M	472	37.3	0.927	1.018
SMA-13	254	42.4	0.893	1.048
Average	—	—	0.915	1.064

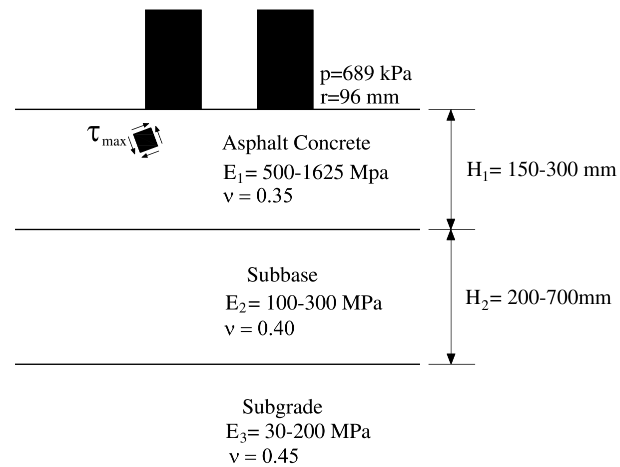

Fig. 4. Pavement geometry and input parameters for structural analysis.

where K_a = approximate equation of K [Eq. (16a)]; and α = approximate coefficient due to asphalt layers shown in Table 3.

As shown in Eqs. (14) and (16), stress conditions must be known first to predict the field rut depth from WT test data. For simplicity, a prediction equation for the average maximum shear stress was developed and proposed for each layer in this study. The prediction equation was developed through a multiple-regression analysis using a synthetic database obtained from a series of structural analyses conducted for 750 different pavement sections. Fig. 4 shows geometric information of the pavement, material properties, and loading conditions considered in the analysis. A multilayered elastic program KENLAYER was used to calculate the average maximum shear stress ($\tau_{\max}$) and corresponding the minor principal stress (σ_3). The average maximum shear stresses were developed for each AC layer below the edge of tire.

The average maximum shear stress models obtained from the regression analysis are as follows:

$$\tau_{\max-S} = 10^{8.4325}E_1^{0.845}E_2^{-0.691}E_3^{-0.093}H_1^{-3.496}H_2^{-0.110} + 213.43 \quad (17a)$$

$$\tau_{\max-B} = 10^{6.4855}E_1^{0.861}E_2^{-0.635}E_3^{-0.012}H_1^{-2.543}H_2^{-0.171} + 168.56 \quad (17b)$$

where $\tau_{\max\text{-}S}$ = average maximum shear stress for surface layer (kPa); $\tau_{\max\text{-}B}$ = average maximum shear stress for binder layer (kPa); E_1 = modulus of AC layer (MPa); E_2 = modulus of aggregate subbase (MPa); E_3 = modulus of subgrade (MPa); H_1 = thickness of AC layer (mm); and H_2 = thickness of aggregate subbase (mm).

Fig. 5 compares the average maximum shear stress values obtained from KENLAYER analysis and from the regression models in Eqs. (17a) and (17b). The correlation coefficients are 0.97 and

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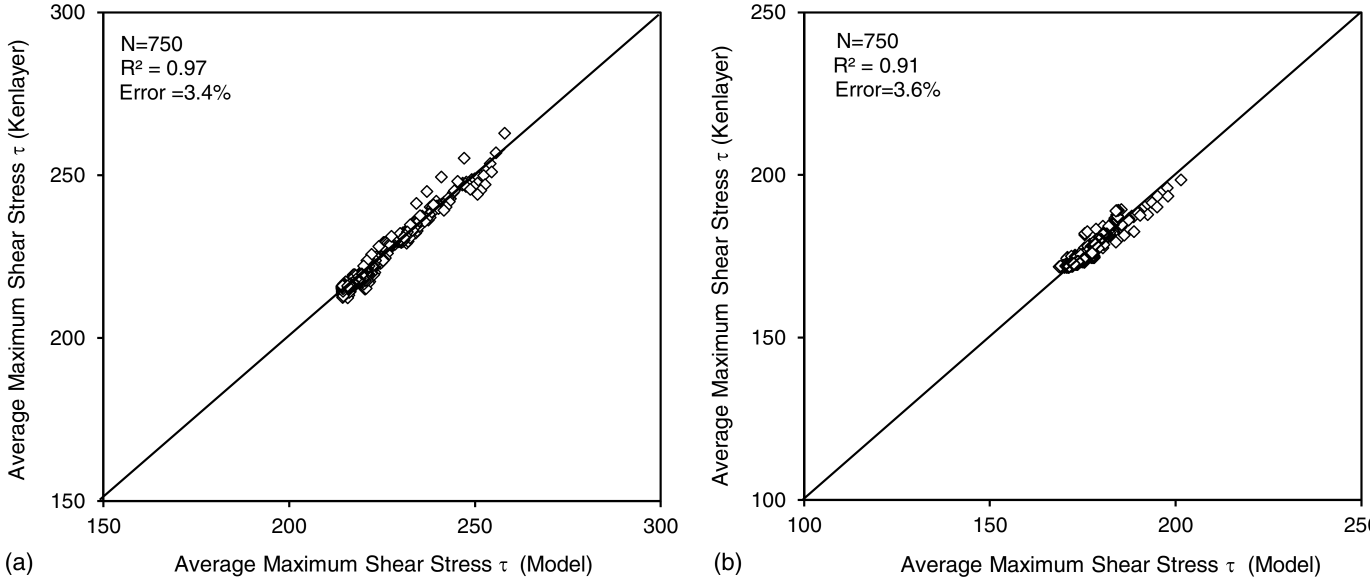

Fig. 5. Comparison of average maximum shear stress from KENLAYER analysis and from regression model corresponding to Eqs. (17*a*) and (17*b*): (a) surface course; and (b) binder course.

0.91 for surface layer and binder layer, respectively, verifying the accuracy of the regression model.

In addition to the average maximum shear stress, the corresponding average minor principal stress at the same point was investigated and found to be in the range of 36–116 kPa for the surface course and a range of 5–35.8 kPa for the binder course. In addition, the tan ϕ values in Eq. (16*a*) and the cohesion values were measured at 60°C for each mixture in Table 3. Using Eq. (16*a*), the coefficient α was computed for each layer. In this study, because α for each mixture is similar, the average coefficients α of 0.915 and 1.064 were used to analyze the surface and binder course, respectively.

Using Eq. (18), the rutting model in Eq. (14) can be further simplified as follows:

$$\varepsilon_p = 10^{-21.589}\left(\frac{RD_{WT}}{N_{WT}^{0.368}}\right)N^{0.294}(\alpha\tau_{max})^{2.208}T^{7.119}t^{0.456} \tag{18}$$

where τ_{max} = average maximum shear stress for each layer (kPa).

The major difference between the two rutting models presented in Eqs. (14) and (18) is that the rutting model in Eq. (18) does not need the shear properties of asphalt mixes for the prediction of rut depth. As a result, the field rut depth could be directly predicted from the laboratory WT test result.

Traditionally, as mentioned previously, DS has been used as an important parameter representing rutting resistance of asphalt mixes. Because the DS in Eq. (6) indicates the inverse slope of a rut depth curve in the WT test, the higher DS values represent better rutting resistance. Although the DS has been used in the asphalt mix specification in Asia to minimize rutting distress in asphalt pavements, the minimum DS requirements were empirically established based on field experience. Therefore, to establish the DS requirements more rationally and objectively, it is important to understand how the DS values are related to field rutting.

To establish the relationship between DS and field rut depth, the WT rut depth in Eq. (18) needs to be replaced with DS. To accomplish this, the relationship between DS and RD_{WT} was first established. The rut depths at 60 min and the DS values for the seven asphalt mixtures in Table 2 were compared as shown in Fig. 6.

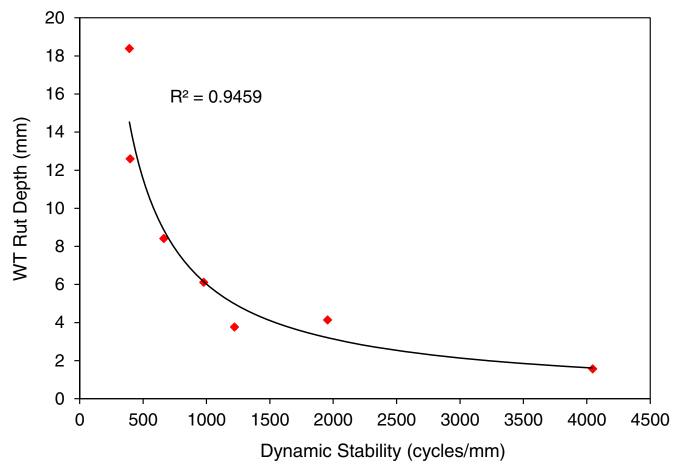

Fig. 6. Relationship between DS and WT rut depth at 60 min.

As seen in the figure, the WT rut depth RD_{WT} is closely correlated with DS as follows:

$$RD_{WT} = 4030.5 \times DS^{-0.942} \tag{19}$$

Finally, using Eq. (19) and an N_{WT} value of rut depths at 60 min, Eq. (18) was modified as follows:

$$\varepsilon_p = 10^{-19.1242}DS^{-0.942}N^{0.294}(\alpha\tau_{max})^{2.208}T^{7.119}t^{0.456} \tag{20}$$

Validation

To validate the two rutting models proposed in Eqs. (14) and (20), independent field rutting performance data obtained from six different WesTrack pavement sections (TRB 2005) were used. All the pavement sections of WesTrack had the same thickness as shown in Fig. 7, but the properties of asphalt mixes were different as listed in Table 4. Only a single asphalt binder (PG 64-22) was used in the WesTrack testing. Because the WT test data for the original WesTrack mixes were not available, six asphalt mixes were

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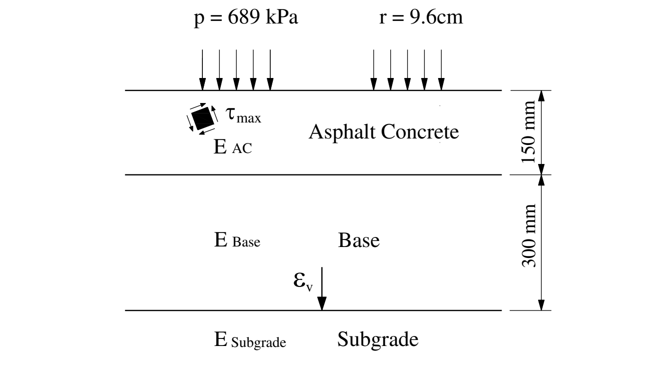

Fig. 7. WesTrack pavement section.

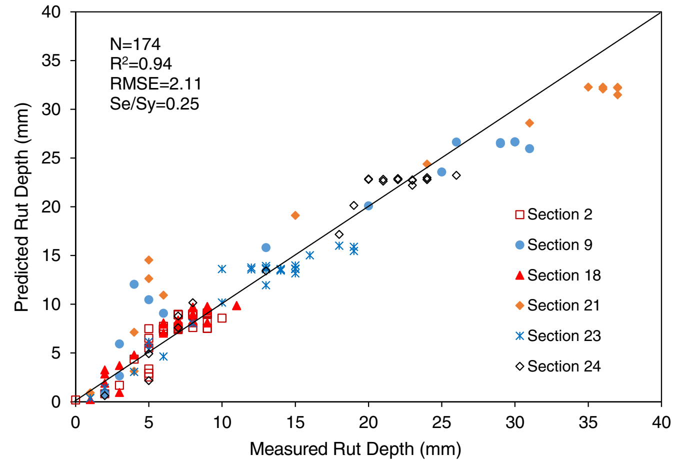

Fig. 8. Comparison of predicted and measured rut depth of WesTrack sections.

produced using a local aggregate and asphalt binder based on the mix properties presented in Table 4. The WT tests for the six mixes were conducted and the DS values were computed.

Because the measured AC modulus from the laboratory test may not be practical because of being time consuming and costly, the AC dynamic modulus was predicted based on the AC volumetric properties, gradation, specific temperature, and frequency using the Hirsch model (Christensen et al. 2003), which was validated in Le et al. (2016, 2017). The average maximum shear stress values were calculated using Eqs. (17*a*) and (17*b*). The resilient modulus of subbase and subgrade, pavement temperature, and vehicle speed provided in National Cooperative Highway Research Program (NCHRP) Report No. 455 (TRB 2005) were used in the calculation.

Following the same procedures used in Kim et al. (2017), rut depth values for the six WesTrack sections were calculated using the rutting model in Eq. (20) and were compared with the measured values in Fig. 8. As seen in the figure, the rutting model reasonably predicted the field rut depth.

Because the rutting model in Eq. (20) is a simplified version of the original rutting model in Eq. (14) based on the approximate solution of K value in Eq. (16*b*), some error could have been incurred in the rutting prediction. To evaluate the prediction accuracy of the rutting model in Eq. (20), the rut depth values for the same WesTrack sections were predicted from the original rutting model in Eq. (14). The c and ϕ values of the six asphalt mixes were estimated from the prediction equations proposed by Kim et al. (2017) using the mix properties provided in Table 4.

The predicted rut depths from the two rutting models are compared in Fig. 9. As seen in the figure, the correlation coefficient, R^2, is 0.998 and the RMSE is 0.27 mm. Thus, the simplified rutting model could predict field rut depth as accurately as the original rutting model. The simplified rutting model does not need shear properties of asphalt mixes that require additional UCS and IDT tests.

Rational Approach to Establish Dynamic Stability Criterion for Asphalt Mixes

As mentioned previously, the DS criteria were empirically established based on field experience. In Japan, the minimum DS value is specified based on traffic volume as listed in Table 5. As seen in this table, the minimum DS values are specified for four different traffic volume categories. However, field rutting is not only affected by traffic volume, but also by other factors such as AC thickness, vehicle speed, and pavement temperature. Therefore, these other factors must be considered in the DS criterion.

It can be seen in Table 6 that different binder grade and gradation produce different DS values. Therefore, the DS criterion of different mixture types can be applied for different design conditions considering AC thickness, vehicle speed, and traffic volume. Before applying these mixture types to asphalt pavement design, Eq. (20) was used to determine the DS criterion.

Dynamic Stability Criterion Based on AC Thickness and Traffic

To establish the DS criterion based on the AC thickness and traffic, three different AC thicknesses of 15, 20, and 30 cm were used to calculate the DS value. The subgrade modulus, subbase thickness, and subbase modulus were assumed to be 75 MPa, 30 cm, and 180 MPa, respectively. These values represent the common pavement thickness and stiffness characteristic of subbase layers widely used (Le et al. 2017). The vehicle speed used in this analysis is 60 km/h while maintaining a constant effective temperature of 30°C. The average maximum shear stress (τ_{max}) was calculated using Eqs. (17*a*) and (17*b*). Moreover, the reliability approach was

Table 4. Asphalt mix information used in WesTrack and WT test results

Section	Gradation	Asphalt content (%)	Air void (%)	VMA (%)	VFA (%)	c (kPa)	ϕ (degrees)	Dynamic stability (cycles/mm)
2	Fine	4.7	10.1	14.68	31.20	206.1	55.8	1,622
9	Fine-plus	6.7	4.1	16.30	74.85	157.0	52.7	337
18	Fine	5.9	4.6	12.83	64.15	201.4	53.2	1,595
21	Fine-plus	6.8	4.3	15.79	72.79	142.6	54.4	268
23	Coarse	5.8	5.1	11.63	56.14	172.0	53.9	753
24	Coarse	6.3	7.5	15.10	50.33	156.3	55.7	386

Note: VMA = voids in mineral aggregate; and VFA = voids filled with asphalt.

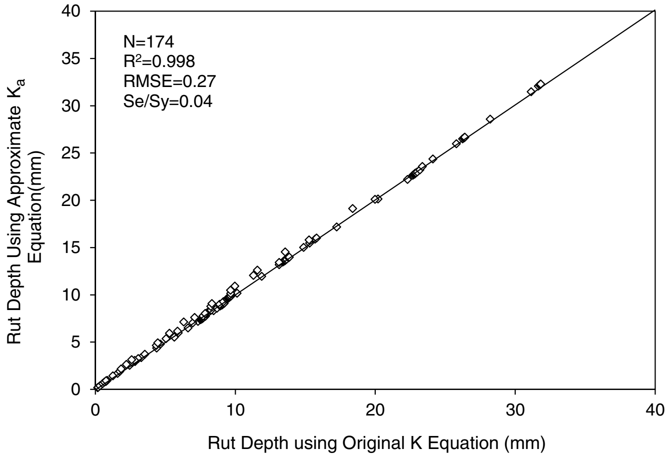

Fig. 9. Comparison of rut depths predicted from original and simplified rutting model.

Table 5. Dynamic stability standard proposed by the Japan Road Association

Traffic volume grade (cycles/mm)	Truck traffic volume, one way (volume/day)	Dynamic stability (cycles/mm) (min)
Low	Less than 1,500	800
Medium	1,500–3,000	1,000
Heavy	3,000–15,000	1,200
Very heavy	More than 15,000	3,000–5,000

Table 6. Dynamic stability test results

Mix type	Gradation	Binder	DS ranges (cycles/mm)
Hot mix asphalt	Dense	Conventional	1,634–2,747
Hot mix asphalt	Dense	Modified	5,727–7,203
Stone mastic asphalt	Gap	Modified	8,000–9,000

used to improve the analysis results. Using Eq. (20) with a rut depth criterion of 4 mm and reliability of 80%, which are the typical values used in Korea, the different DS criteria can be proposed based on AC thickness and traffic volume as shown in Fig. 10.

It can be seen clearly in Fig. 10 that different AC thicknesses and traffic volumes (low, intermediate, and high) provide different DS criterion values. Thus, it can be concluded that the DS criterion when related to field condition is highly dependent on the AC thickness and traffic volume.

Dynamic Stability Criterion Based on Vehicle Speed and Traffic

Three different vehicle speeds of 10 km/h (intersection), 60 km/h (normal road), and 100 km/h (highway) were used to calculate the DS criterion using a 20-cm-thick asphalt pavement (Le et al. 2017). Following the same procedure in establishing the DS criteria based on the AC thickness and traffic, the relationship between DS value and traffic volume with different vehicle speeds is presented in Fig. 11. As shown in the figure, the DS criterion is different because of different vehicle speeds and traffic volumes.

As shown in Fig. 11, low-traffic-volume roads require low DS values. Likewise, high-traffic-volume pavements require high DS values. As discussed in this study, DS values are normally associated with the mixture type. It can be seen from Table 6 that, depending on mixture type and binder grade, the DS criterion for different traffic volumes can be addressed. For example, an intersection (10 km/h) with a low traffic volume requires the DS minimal value of 1,823 cycles/mm for surface course and 1,157 cycles/mm for binder course based on Fig. 11. From Table 6, a dense-grade asphalt mixture with conventional binder is sufficient in providing rut resistance for this type of intersection. Meanwhile, from the same table, an intersection with higher traffic volume must be constructed using SMA mixtures with modified asphalt to address rutting resistance. Knowing the DS value of several mixtures can be helpful in determining the appropriate mixture to be used for different types of traffic volume. This study provided a new approach in using DS values in evaluating field rut performance by integrating DS performance of different AC mixtures and traffic volume. As a summary, using Eqs. (17*a*), (17*b*), and (20), the DS criterion using the wheel tracking test can be established considering the pavement structure, effective temperature, vehicle speed, and traffic volume. Hence, the DS criterion will have different values depending on the AC thickness, temperature, vehicle speed, and traffic volume. Even in the same design conditions, the DS criterion will be different between the surface layer and the subbase layer.

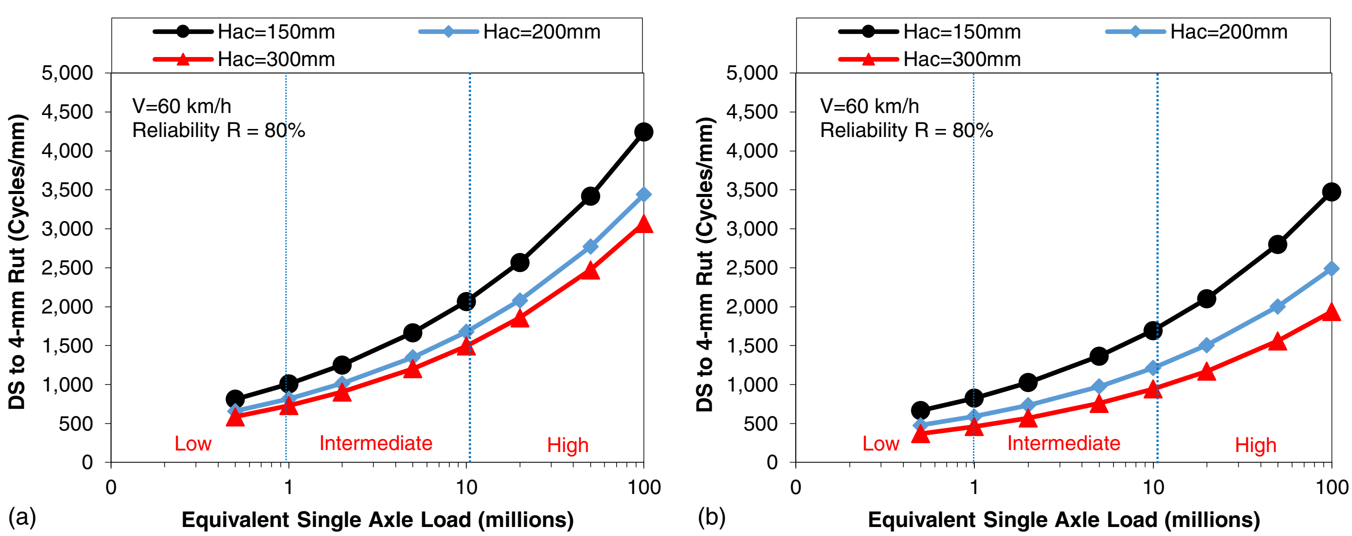

Fig. 10. DS criterion for AC rutting based on thickness and traffic: (a) surface course; and (b) binder course.

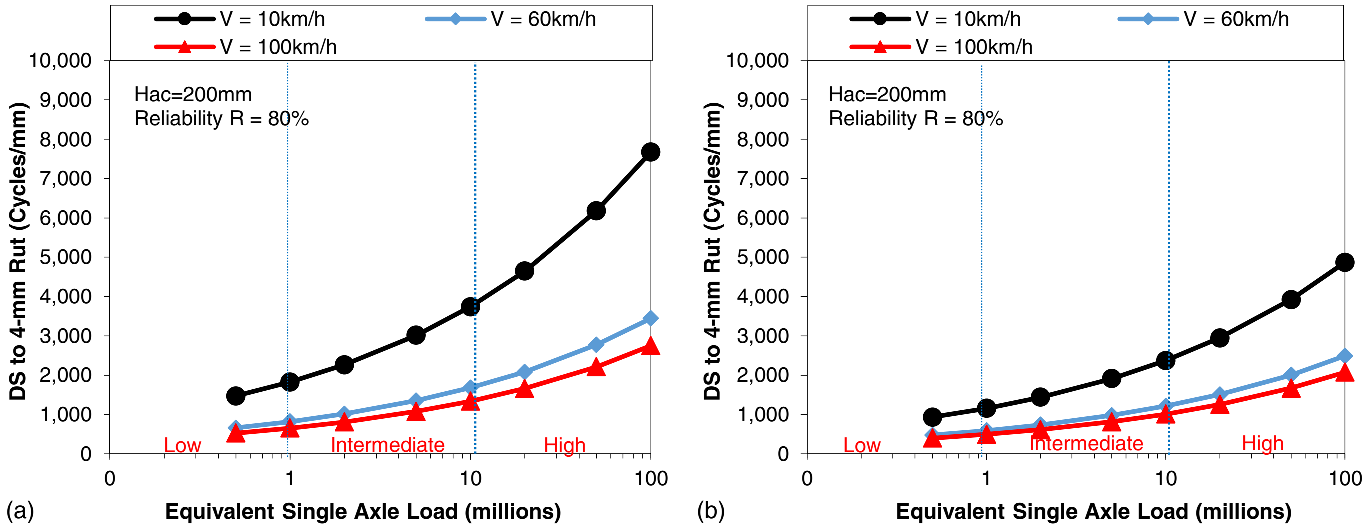

Fig. 11. DS criterion for AC rutting based on effective temperature and traffic: (a) surface course; and (b) binder course.

Based on current studies, the dynamic stability is a rutting parameter determined using the wheel tracking test in a laboratory setting only. This dynamic stability value is based on the slope of the last part of the wheel tracking test. Test results showed that mixtures with higher dynamic stability have higher rut resistance; hence, mixtures with lower DS have higher rutting.

However, in this study, this finding was not only shown but was further modified and improved. It was found that the dynamic stability of asphalt mixtures can be used in designing AC pavements considering several factors such as temperature, layer thickness, and traffic volume. Depending on the traffic and by setting rutting depth criteria, a design or target dynamic stability must be achieved during the mix design process. This dynamic stability criterion is based not only on wheel tracking performance but also in the field using the developed rutting model.

Conclusions

This study focused on the application of a new DS criterion in evaluating rutting in asphalt pavements using the wheel tracking test. The DS criterion of asphalt mixtures based on the mechanistic-empirical approach was proposed considering field conditions. Some of the important findings in this research are summarized as follows:

- A simple prediction model was developed and validated to estimate the rut depth in the field, which is a function of the DS, the number of load cycles (N), the average maximum shear stress ($\tau_{\max}$), and load duration. It was observed that the rutting model proposed in this study successfully predicted the field rut depth.
- The regression models were proposed to determine the average maximum shear stress for surface layer and binder layer considering AC modulus, subbase and subgrade resilient moduli, and layer thicknesses. The prediction equations have a correlation coefficient of 0.97 and 0.91 for surface layer and binder layer, respectively.
- Application of a new criterion for DS was proposed considering field pavement conditions such as AC thickness, effective temperature, vehicle speed, and traffic volume. In general, the DS criterion will have a different value depending on AC thickness, temperature, vehicle speed, and traffic volume. When pavements with the same design conditions are included, the DS criterion will be different between the surface layer and the subbase layer.
- The rutting model was developed using limited data; further studies are recommended to enhance the model using the same project with the DS test and must be validated for different binder grades.

Data Availability Statement

No data, models, or code were generated or used during the study.

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