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Calibration and validation of a rutting model based on shear stress to strength ratio for asphalt pavements

Won Jae Kim, Van Phuc Le, Hyun Jong Lee *, Huy Thien Phan

Department of Civil and Environmental Engineering, Sejong University, South Korea

HIGHLIGHTS

- A rutting model in power law form was proposed.
- The model considers shear stress to strength ratio.
- Predictive equations for cohesion (c) and internal friction angle (ϕ) were developed.
- A rutting model was calibrated and validated using field rutting data.
- The model accurately estimate rut depths under varying load and environmental conditions.

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ABSTRACT

In this study, a rutting model in power law form was proposed considering the shear stress to strength ratio which can be calculated in terms of cohesion (c) and internal friction angle (ϕ) for different asphalt mixtures. Predictive equations for c and ϕ were first developed from laboratory testing at a reference temperature of 50 °C using multiple regression analyses considering asphalt binder, aggregate and volumetric properties of different asphalt mixes. The predictive c and ϕ equations were found to have correlation coefficients of 0.87 and 0.86 respectively. The rutting model considers the number of load cycles (N), shear strength ratio, temperature and load duration as main parameters of the permanent strain wherein the coefficients were determined using tri-axial compressive strength and repeated load permanent deformation testing. It was calibrated using field rutting data from twenty-six Westrack pavement sections. Moreover, the rutting model was validated using field performance data obtained from Korean national highways' long term pavement performance database. It was found from the validation that the model can accurately estimate rut depths under varying load and environmental conditions in the fields.

1. Introduction

Permanent deformation is one of the major distresses occurring in asphalt concrete (AC) pavements. It typically manifests as rutting that appear as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides. The rutting is highly dependent on the pavement structure, traffic and environment conditions. Since the rutting is a load-associated distress, the accurate prediction of rutting behavior of asphalt mixes plays an important role for asphalt pavement design and analysis. Therefore, a lot of research efforts have been made to develop rutting models that can accurately describe the rutting behavior of asphalt mixes.

Most of the available rutting models in the literature are empirical or mechanistic-empirical with limited fundamental material characterization. Thus, poor correlations with actual field performance are common results [1]. Recently more advanced rutting models [2–7] based on mechanics such as viscoelasticity, viscoelasticity and continuum damage approaches have been introduced. In general, these advanced models require much more sophisticated constitutive models for AC behavior that can describe its degradation response (e.g., the consequent permanent deformation, cracking, and other damages). As a result, the mechanistic models are rarely used in real practice in asphalt pavement design and analysis.

Permanent strain models [8–11] and permanent to resilient strain ratio models [12–16] are most well-known mechanistic empirical AC rutting models. Basic permanent strain models relate the permanent vertical strain to the number of load cycles and the extended version of the models explicitly consider the effects of temperature, induced stress level, and other parameters. Unlike the permanent strain models, the permanent to resilient strain ratio models consider the elastic response of pavement structure

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* Corresponding author at: Department of Civil and Environmental Engineering, Sejong University, 98 Gunja-dong, Gwangjin-gu, Seoul 143-747, South Korea.

E-mail address: hlee@sejong.ac.kr (H.J. Lee).

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through the resilient strain. Since the resilient strain governed by the stiffness of the pavement materials, stress level, layer thicknesses, temperature and others, all these effects are indirectly considered in the models.

Most of the permanent to resilient strain ratio models [13–16] do not explicitly consider the stress level and material parameters in the models because the resilient strain mostly takes care of those two effects. Although these models [13–16] are relatively simple to use, Archilla et al. [17] found that the AC dynamic modulus, which was one of the main material properties for calculating the resilient strain, was not a good parameter for describing the rutting behavior of asphalt mixes. Besides, these models are based on unconfined conditions, thus, they need an adjustment factor to consider the confinement effects in the models such as NCHRP 1-37A modeling approach.

Permanent deformation of AC layer is the result of a complex combination of densification and shear flow. The shear flow is a more dominant contributor to the permanent deformation occurred in the AC layer [18]. Therefore, some researchers [19,20] have tried to incorporate shear properties in the rutting models. One of the major significance of these models compared to the existing rutting models mentioned above is that a fundamental engineering property, shear strength, was incorporated into the models to represent the rutting resistance of the materials.

These two studies [19,20] gave great insights of the application of shear properties to the rutting prediction of asphalt mixes. However, it is limited since rutting tests were performed using wheel tracking machines which is incapable of providing an accurate simulation of field stress states. Moreover, the quantity of tests data is limited and field validation was not conducted.

A rutting model of asphalt mixes was established based on the shear stress to strength ratio in the authors' previous researches [21,22]. In the works, triaxial compressive strength (TCS) and repeated load permanent deformation (RLPD) tests on the three types of asphalt mixes with various volumetric properties were performed at multiple load levels and temperatures to correlate shear properties to rutting performance. The model coefficients were independent of mix types and loading magnitudes. The model could successfully predict the permanent deformation of various mixes all the way up to the tertiary flow with a high level of prediction accuracy. The model was also calibrated using accelerated performance testing (APT) data.

Although the authors' original rutting model [22] showed some advantages compared to the existing mechanistic-empirical rutting models, one of the major weakness is that the model needs more tests efforts to characterize shear properties of asphalt mixes. In addition, the model requires calibration and validation with various rutting performance data obtained from fields.

Therefore, the main objectives of this study are to develop prediction equations for shear properties of asphalt mixes and to calibrate and validate the rutting model. To accomplish these objectives, additional laboratory tests were first conducted to measure shear properties of various asphalt mixes with different volumetric properties and testing conditions. The prediction equations for cohesion and friction angle were developed using the tests data and the rutting model form was revised. Finally, the rutting model was calibrated with WesTrack data [23] and validated with field performance data obtained in Korea.

2. Review of previous model

In the authors' previous research [21,22], a rutting model based on shear stress to strength ratio was developed using the TCS and RLPD tests results conducted on three types of asphalt mixes (i.e., two dense-graded mixes of maximum aggregate size of 19 mm with PG64-22 and PG76-22 asphalt binders, respectively and Stone Mastic Asphalt (SMA) with PG64-22 asphalt binder) under three different combinations of deviatoric stresses and confining pressures, and three temperature conditions. Additionally, the effects of loading frequencies were evaluated at four load durations (i.e., 0.1, 0.2, 0.4, and 0.8 s). In the previous studies, RLPD test results revealed an excellent exponential correlation between shear stress to strength ratio $\frac{\tau}{\tau_f}$ and permanent strain ϵ_p under certain load repetitions [21]. From laboratory test data, a rutting model based on shear stress to strength ratio was proposed:

$$\varepsilon_p = 2.9895 \times 10^{-3} e^{6.2807\times10^{-6}N} e^{3.6723\frac{\tau}{\tau_f}N^{0.1032}} t^{0.4224} \tag{1}$$

such that

$R^2 = 0.946$,
root mean square error = 0.006, and
average error = 13.34%.

In Eq. (1), N and t are number of load cycles and load duration, respectively. The shear stress to strength ratio can be calculated as follows:

$$\frac{\tau}{\tau_f} = \frac{(\sigma_1 - \sigma_3)(\tan\phi \sin\phi + \cos\phi - \tan\phi)}{2(c + \sigma_3 \tan\phi)} \tag{2}$$

where

ε_p = permanent strain,
τ = shear stress (kPa),
τ_f = shear strength (kPa),
N = number of load cycles,
t = load duration of each cycles (second),
σ_1 = actual major principle stress under the given loading condition (kPa),
σ_3 = actual minor principle stress under the given loading condition (kPa),
c = cohesion (kPa), and
ϕ = friction angle (°).

In addition to the rutting model, the authors proposed the prediction equations for the cohesion and friction angle as follows:

$$c = \alpha_0 + \alpha_1 T + \alpha_2 AC + \alpha_3 AV \tag{3}$$

$$\phi = \beta_0 + \beta_1 T + \beta_2 AC + \beta_3 AV \tag{4}$$

where

AC = binder content (%),
AV = air-void content (%),
T = temperature (°C), and
α_i and β_i = regression coefficients are based on asphalt mixtures.

The prediction equations of the cohesion and friction angle in Eqs. (3) and (4), respectively, are not useful for practical purposes because material coefficients α_i and β_i change when asphalt mix properties change. Therefore, new prediction equations for the cohesion and friction angle were proposed in this study.

3. Experimental program

3.1. Materials and specimen preparation

As mentioned earlier, the TCS tests were conducted on three asphalt mixes to obtain shear properties in the previous study [21,22]. In this study, laboratory tests were performed on four additional types of asphalt mixes with various air voids and binder contents. Information on the seven mixes including the three mixes obtained from the previous study is provided in Table 1.