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Systematic comparison of two-stage analytical rutting models of asphalt mixtures

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HIGHLIGHTS

- The performance of 18 two-stage analytical models of rutting was investigated.
- An $R^2 > 95\%$ could not guarantee well simulated initial rutting values or accurate long term rutting predictions.
- Long term prediction based on early age rutting was the best indicator for selecting good models.
- Accurate long term predictions based on early age rutting required correction factors.
- The best model was considered as Theng-Lytton model and its related rutting index could well be used for mixture design.

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ABSTRACT

The performance of 18 analytical models was investigated based on statistical analysis of R^2, limiting deviation error, as well as their ability to predict long term rutting of AC-13 and AC-20 asphalt mixtures. An $R^2 > 95\%$ on fitting could not guarantee well simulated initial rutting values or accurate long term rutting predictions. However, a model showing a maximum of 200 initial cycles exceeding a deviation error of 20%, could guarantee rutting curve fittings with $R^2 > 95\%$. The ability to accurately predict long term rutting was considered the best indicator of good models. Among the 18 models, only Theng – Lytton, Paute – 1, Paute – 2 and Monismith – 1 models satisfied the limiting values of the proposed performance indicators. Nonetheless, these same models required correction factors to accurately predict long term rutting when fitted to early age rutting results. Theng-Lytton model was considered the most reliable model, and a related rutting index was developed which could well be used for mixture design and optimisation.

1. Introduction

Rutting is one of the major distresses that affect the serviceability of asphalt pavements [1–5]. It progressively develops with an increasing number of loading applications, and appears as longitudinal depressions along the wheel paths. Factors that have been reported to significantly affect rutting include: temperature, loading stress, loading speed, number of load repetitions, traffic wandering and the shear strength of asphalt mixtures [3–7]. The evolution of rutting could be divided into three stages: the primary rutting stage in which the rutting rate rapidly decreases with loading cycles; the secondary rutting stage in which the rutting rate could be considered steady, and the tertiary rutting stage in which the rutting rate rapidly increases with loading cycles [2,5]. The primary, secondary and tertiary stages of rutting are caused as a result of densification, shear deformation and shear failure respectively [5]. Several analytical models have been proposed in past studies to provide valuable information about the performance of asphalt mixtures such as its expected service life and its remaining service life.

Table 1 shows the various models of rutting that were proposed in past studies. They were fitted to field or experimental data and by interpolations or extrapolations, they could be used to predict rutting development. The disadvantage of these models was that every coupled combination of stress and temperature resulted in different values of its coefficients. The relationship between such values of the model coefficients and the applied stress levels or temperatures was reported to have relatively low values of R^2 [8,9]. This implied that such models could not accurately predict the effect of coupled factors on rutting development. Therefore,

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Table 1
Analytical models of rutting proposed in past studies.

No.	Model	Parameters	Reference
1	$\in_p = A.\exp\ (-(B/N)^C)$	A, B, C	Tseng and Lytton [9]
2	$\in_p = A + BN - C(\exp\ (-DN)).$	A, B, C, D	Cerni et al. [12]
3	$\varepsilon_p = A + BLogN$	A, B	Barksdale [14]
4	$Log\ \in_p = A + BlogN + C(logN)^2 + D(logN)^3$	A, B, C, D	Monismith and Mclean [15]
5	$Log\ \in_p = A + BlogN$	A, B	Brown and Snaith [16]
6	$\varepsilon_p = AN^B$	A, B	Monismith et al. [17], (Monismith-1)
7	$\in_p = AN^B + C(\exp(DN) - 1)$	A, B, C, D	Francken and Clauwaeat [18]
8	$\in_p = A + B(N^{0.5})$	A,B	Eisenmann and Hilmer [19]
9	$\in_p = \frac{A\sqrt{N}}{\sqrt{N}+B}$	A, B	Paute et al. [20], (Paute-1)
10	$\in_p = AN^B + C$	A, B, C	Paute et al. [20], (Paute-2)
11	$\in_p = A(1 - N/100)^{-B}$	A, B	Paute et al. [21], (Paute-3)
12	$\in_p = (AN + B)(1 - \exp(-CN))$	A, B, C	Wolff [22]
13	$\in_p = AN + \frac{BN}{\left[1+\left(\frac{B.N}{C}\right)^D\right]^{1/D}}$	A, B, C, D	Theyse [23], (Theyse-1)
14	$\in_p = AN + B(1 - \exp(-CN))$	A, B, C	Theyse [23], (Theyse-2)
15	$\varepsilon_p = AN^B + (CN + D)(1 - \exp(-EN))$		Perez and Gallego [24]
16	$\in_p = ALnN + B$	A, B	Ahari et al. [25] (Logarithmic model)
17	$\in_p = AN + B(N^{0.5})$	A,B	Modified Eisemann and Hilmer model
18	$\in_p = A + B(N^C + \exp(DN))$	A, B, C, D	JMW

rutting predictions could be improved by considering models that take into the effect of coupled factors.

The proposed analytical models contained either two, three or more model coefficients. Models with two or three coefficients could be considered to be simple formulated models. However, such models do not necessarily give high values of R^2. As an example, Paute-3 model has been reported to poorly predict the primary rutting stage [10]. Monismith – 1, Eisenmann – Hilmer and Paute – 2 models over predict the development of rutting when the applied stresses are below the permanent shakedown limit. Experimentally, materials such as asphalt mixtures and unbound granular materials (UGM) could attain a long-term steady state response when the applied stress is below the permanent shakedown limiting stress. This behavior was suggested to be as a result of a change in the response of a material due to compaction or change in the stress state or both [11]. Wolff rutting model also shows plastic shakedown behavior when its model coefficient 'A' is set as zero, and plastic creep when 'A' is set to be greater than zero.

The Brown-Snaith model could also accurately predict rutting when the stress level is below the plastic shakedown limiting stress. Its parameter 'A' represented an asymptote of rutting at large number of loading cycles usually above 100,000 cycles. Models that involved a large number of model coefficients such as Theyse-3 and Perez – Gallego models did not necessarily provide accurate predictions either, and their model coefficients rarely carried physical meaning. As an example, the coefficients of Theyse-3 and Perez – Gallego models could not be related to either the primary or secondary rutting stages of asphalt mixtures. Another limitation of the proposed analytical models was that apart from Monismith – Mclean, Francken – Clauwaeat and JMW models, all the other models were limited to modelling only the primary and secondary stages of deformation. Tseng – Lytton, Cerni et al., Barksdale, Monismith – Mclean, Brown – Snaith, Eisenmann – Hilmer, Paute-2, Paute-3, Ahari et al. and JMW models showed numerical instability as the rutting in mixtures approached zero.

Various models have been recommended for simulating the rutting development of asphalt mixtures, however limited information is available about their comparative performance under similar testing conditions. A performance comparison study could show the most reliable analytical models for predicting rutting, and conditions under they could be best applied. Cerni et al. [12] analysed the performance of five analytical models of UGMs and showed that Barksdale, Paute-3 and Monismith-1 models had R^2 values greater than 95%. They considered an $R^2 > 95\%$ as a reliability indicator for good rutting models. Majority of UGM rutting models including Monismith-1 and Francken – Clauwaeat models could also be used to simulate the rutting development behavior of asphalt mixtures [13].

The first objective of this study was to evaluate the performance of the proposed analytical models based on the following performance indicators: a limiting R^2 of 95% as proposed by Cerni et al. [12], a limiting deviation error in the predicted final rutting of 3.5%, a maximum of 200 initial cycles with a deviation error exceeding 20% per fitting, and an ability of the models to predict long term rutting based on early age rutting. Based on statistical analysis of the proposed indicators, the limitations of the proposed models and long term rutting predictions based on early age rutting were determined. The second objective was to determine the most reliable analytical models for predicting rutting development. A rutting index was determined based on the recommended most reliable model, and could be used for evaluating the high temperature stability of asphalt mixtures. The limiting values of this index for mixture design were determined. Fig. 1. shows the experimental program overview.

2. Experimental details

2.1. Raw materials

AC-13 basalt asphalt mixtures (BAMs) and AC-20 limestone asphalt mixtures (LAMs) were designed. Numbers 13 and 20 denoted the nominal maximum sizes of the aggregates as 13.2 mm and 19 mm respectively. AC-13 and AC-20 mixtures are commonly used in China for the construction of the wearing and intermediate asphalt courses respectively. Aggregates in AC-13 and AC-20 mixtures were prepared according to JTG E42-2005 standard [26] and Table 2 shows their properties. SBS modified asphalt was used for both AC-13 and AC-20 mixtures and had a penetration of 72.6 (units in 0.1 mm) at 25 °C, ductility larger than 100cm at 15 °C, softening point of 50 °C and a viscosity of 0.645 Pa.s at 135 °C. Table 3 shows the gradation of the aggregates, mixture design properties, as well as the volumetric properties of the mixtures. The optimum asphalt contents of AC-13 and AC-20