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Characterization of three-stage rutting development of asphalt mixtures

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HIGHLIGHTS

- The mold edges physically induced a significant confinement stress in mixtures.
- A higher primary rutting rate indicated a lower F_N and a faster failure rate.
- A practical linear model could relate the primary transition and F_N values of mixtures.
- The proposed three stage rutting model showed better fitting than Francken model.
- The primary transition point and c-value could be used for mixture characterization.

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ABSTRACT

The three stage rutting behavior of several asphalt mixtures was investigated. Confinement, moisture, stress and temperature significantly affected rutting. Absence of a physically induced confinement stress by the metallic sides the wheel tracking testing mold had the highest influence on rutting, followed by temperature, moisture and lastly stress. A higher primary rutting rate indicated a lower flow number (F_N) and a faster failure rate. A linear model could relate the transition point between the primary stage and the mixtures' flow numbers. It was independent of the testing conditions, methods and types of mixtures. A new three stage model was proposed and could simulate the rutting development of mixtures better than the Francken model. The F_N of mixtures under different conditions of testing could also be related to parameter 'c' of the new model using a similar power law equation. The primary rutting rate, the primary transition point and parameter 'c' of the new model could be used in mixture characterization.

1. Introduction

Permanent deformation of hot mix asphalt (HMA) is one of the most critical distresses that affect the serviceability of asphalt pavements [1,2], and is caused by the accumulation of unrecovered deformations that occurs especially in summer under the repeated application of vehicle loads [3–5]. Other factors reported to cause rutting include temperature, moisture, loading speed, wheel wandering and mixture shear strength [6–9]. Rutting development could be divided into three phases: the primary phase in which the strain rate rapidly decreases with loading cycles; the secondary phase in which the strain rate is almost constant; and the tertiary phase in which the strain rate rapidly increases with loading cycles [4,5,10,11]. Much effort was put in developing rutting development models in the last three decades. These proposed models included empirical or semi-mechanistic models, mechanistic-empirical models and fully mechanistic models [12]. Among these models, those which could simulate three stage rutting included Huurman model, Francken model, Zhang et al. model, Ye et al. model, Zhao-Zhang model, Zeng et al. model, Zhang-Pei-Zhang model and Ghazi-Imad model [1,4,13–18].

Three-stage models enable accurate simulation of rutting development and the identification of the transitional points of the rutting phases. The primary, secondary and tertiary stages of rutting development in asphalt mixtures could related to densification, shear flow and shear failure of the mixtures respectively. According to literature, the primary stage is caused by the initial densification or compaction. The secondary stage is characterized by a relatively constant strain rate, and it could be related to the shear flow of mixtures, while the tertiary flow could be related to the shear failure of the mixtures [14]. In practice, most asphalt pavements are rehabilitated prior to reaching the tertiary rutting stage so as to minimize the structural damage, and to avoid unsafe

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trafficking conditions [19]. The number of cycles at which tertiary rutting begins (often reffered to as the flow number) and the strain rate of the secondary stage have been populary used as indicators for screening mixtures. Three stage models' parameters with high coefficients of correlation to rutting development could make predictions of rutting and mixture characterisation easier to be determined analytically [19–23].

Testing methods commonly used for rutting investigation include: wheel tracking testing, static loading testing and uniaxial repeated loading testing [24,25]. The correlations between the wheel tracking and uniaxial repeated loading testing results have been reported to be good, and suitable shift factors could be developed to translate the rutting results of uniaxial dynamic tests to wheel tracking results. These tests can differentiate the effect of temperature, stress and loading speed on rutting development, and their results have been shown to be well correlated to field performance [26]. However, the stress state experienced by mixtures under wheel tracking testing better simulates the stress in the field, compared to the simple compressive stress of uniaxial repeated loading testing. Static testing does not simulate the dynamic loading effect due to moving traffic, and thus is rarely used in rutting investigation studies.

In this study, wheel tracking testing and uniaxial repeated loading testing were used for investigating the three stage rutting development of various asphalt mixtures. The effects of stress, temperature, confinement and moisture damage on rutting development of asphalt mixtures were analysed. Correlations between the primary, secondary and tertially slopes were determined, as well as the relationships between the primary and secondary transition points. Based on Francken model, a simplified three-stage model with fewer parameters was proposed. The high correlation coefficients between the parameters of the new model, secondary slopes and the flow number indicated that they could be used for mixture performance optimisation.

2. Experimental details

AC-13 and AC-20 asphalt mixtures were used in this study. They are commonly used in the construction of asphalt pavements in China. The raw materials contained in AC-13 mixtures were basalt aggregates, limestone mineral filler and the SBS modified asphalt, while AC-20 mixtures contained limestone aggregates, limestone mineral filler and the SBS modified asphalt. The SBS modified bitumen had a penetration of 85 dmm at 25 °C, softening point of 52 °C, ductility of 52.1 cm at 5 °C and a viscosity of 644.5 cP at 135 °C. The properties of the aggregates and mineral filler are shown in Table 1 and were measured according to JTG E42-2005 standard [27]. Table 2 listed the combined aggregate gradation of the AC-13 and AC-20 asphalt mixtures as well as the optimum asphalt content. It should be noted that all the tests on different conditions at least four times testing were conducted to make sure the repeatable of the results.

Table 2
Composition of the AC-13 and AC-20 asphalt mixtures.

Sieve size (mm)	Passing Percent (%)	
	AC-13	AC-20
26.5	–	100
19	–	95
16	100	83
13.2	95	72
9.5	76.5	61
4.75	53	40.5
2.36	37	30
1.18	26.5	22.5
0.6	19	16
0.3	13.5	11
0.15	10	8.5
0.075	6	5
Aggregates	Basalt	Limestone
Filler	Limestone	
Asphalt binder	SBS modified asphalt	
Asphalt content	4.7%	4.4%
Voids in mineral aggregate (VMA)	13.4%	12.2%
Voids filled with asphalt (VFA)	77.7%	70.8%

The wheel tracking test (WTT) method was used to evaluate the rutting resistance of asphalt mixtures. It has been widely used for rutting characterization [28,29]. Square slab specimens of size 300 mm × 300 mm × 50 mm were prepared according to Chinese specification JTG E20-2011 [30]. The target air voids for mixtures designed at the optimum asphalt content was 4 ± 0.5%. It has been reported that at lower temperatures and stresses, asphalt mixtures took a longer loading time for them to fail in shear [18]. Therefore, AC-13 and AC-20 asphalt mixture specimens were prepared and tested at two high temperatures of 60 °C and 70 °C, and two stresses of 0.7 MPa and 0.9 MPa.

The gyratory compaction is considered to be one of the best methods of laboratory compaction for asphalt mixtures [29]. For that reason, a gyratory compactor (T401, Troxler, USA) with a compaction pressure of 625 kPa and set at a compaction angle of 1.25° was used to prepare specimens for uniaxial repeated loading testing. The designed specimen size for this testing was 100 mm diameter × 100 mm height after coring and trimming. Immersion rutting testing was applied to AC-20 asphalt mixtures so as to investigate the effect of moisture damage on rutting development. Two stresses (0.7 MPa and 0.9 MPa) and two temperatures (60 °C and 70 °C) were selected.

It should be noted that the square slab specimens used for wheel tracking testing (WWT) were compacted in a steel mold 300 mm × 300 mm × 50 mm. This steel mold contributed to the total confinement stress experienced by the mixtures. It was supposed that should one or both sides of the molds be removed (sides

Table 1
Properties of aggregates and mineral filler.

Property		Measured value			Specifications
		Basalt	Limestone	Limestone filler	
Los Angeles abrasion (%)		7.8	22.1		<30.0
Crushed stone value (%)		12.0	21.5		<30.0
Flakiness and elongation (%)		12.5	17.0		<18.0
Water absorption (%)		0.363	0.360		<3.0
Course aggregate specific gravity (g/cm^3)		2.961	2.703		>2.6
Fine aggregate specific gravity (g/cm^3)		2.872	2.688		>2.6
Mineral filler's specific gravity (g/cm^3)				2.703	>2.5
Percent passing (%)	0.6 mm			100	100
	0.15 mm			93	90–100
	0.075 mm			85.9	80–100