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Multi-stress loading effect on rutting performance of asphalt mixtures based on wheel tracking testing

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HIGHLIGHTS

- Temperature was a more significant rutting factor than the loading sequence.
- Lighter stresses applied after an overloading stress caused the least damage.
- Initial application of lighter stresses minimised the damage rate due to overloading stresses.
- Rutting became solely dependent on the secondary rutting rates after the initial loading phases.
- A multi-stress rutting indicator was proposed and could be used for mixture performance optimization.

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ABSTRACT

Wheel tracking testing on AC-20 limestone asphalt mixtures was carried out to determine the effect of multi-stress loading on rutting development. Rutting rates increased with the application of higher levels of stress, however, they reduced with the subsequent application of lower stresses. The primary densification rates were highest in the first loading phase, after which rutting development became solely dependent on the secondary rutting rates. 50 °C was the shift temperature for rutting development, below which rutting rates increased linearly, but the increase became exponential at higher temperatures. Heavier loads applied first caused accelerated damage, but their effect was minimised when lighter stresses were applied beforehand. A rutting index based on a new multi-stress analytical model was proposed, and could be used to evaluate the rutting performance of mixtures under more realistic loadings.
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1. Introduction

Rutting is one of the major load induced distresses which leads to a reduction of the long-term performance of flexible pavements. It is recognized to be associated with various factors such as temperature and traffic volume. The rate of creep of asphalt mixtures is initially high, but then reduces as the material hardens till when its plastic compliance reaches a horizontal asymptote, a point where a mixture is considered too stiff and brittle, and from which further loading increases the rate of propagation, coalescence, and re-bonding of micro cracks, that result in the advent of the tertiary stage of creep [1]. Several researchers consider designing asphalt mixtures against rutting as a significant step towards mitigating potential safety problems, and ensuring a long pavement service life. Indoor testing, field investigation and mechanical analysis of the rutting behaviour of pavement structures having one or two or three asphalt layers, revealed that each asphalt layer significantly contributes to rutting development.

Most highways in China consist of either two or three asphalt layers with an incompressible rigid or semi-rigid base. As a result, asphalt layers were determined to contribute more than 90% of the total rutting. Studies done on Jing-Zhu and Heng-da highways in China which contained various two and three asphalt layers, revealed that for a three asphalt layer, most rutting occurred in the middle layer, followed by the top and lastly in the bottom layer. However for a two asphalt layer, most rutting occurred in the bottom layer [2–4]. Asphalt layers which are highly susceptible to rutting should be designed and constructed carefully.

Witczak et al. recommended three test methods for rutting characterisation: The repeated load permanent deformation test, static creep permanent deformation test and the dynamic modulus test [5]. In addition, loaded wheel testers (LWTs) such as asphalt pavement analyzers (APA), hamburg wheel tracking devices (HWTD) and flat rubber wheeled loaded wheel testers (FLWT)

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were considered suitable devices for rutting investigation, because of their ability to induce a stress state in test specimens roughly similar to that in actual pavements. LWTs were shown to have rutting results highly correlated with actual field performance [6,7]. Most rutting investigation studies based on the above testing methods considered single-stress repeated testing approach (SS-RLT). However, asphalt pavements in the field are subjected to repeated loads of various magnitudes from moving traffic, implying that realistic investigations of rutting should consider a multi-stress repeated testing approach (MS-RLT). Furthermore, under SS-RLT, characterization of asphalt mixtures under different stress conditions requires preparation and testing of several specimens, which makes the testing process tedious and costly [8].

MS-RLT considers a single specimen subjected to a series of cyclic loadings of different magnitudes in a single test [9]. It offers much more meaningful information regarding the rutting resistance of asphalt mixtures, since it can simulate a wide axle load spectrum expected in the field. Jiang et al. observed that MS-RLT was more efficient than the traditional dynamic creep test [10]. In this study, AC-20 limestone mixtures that are commonly used for the middle layer of three-layer pavements in China were selected. FLWT wheel tracking device was used to investigate the effect of multi-stress loading on rutting development. The contact pressure between the rubber tire and specimen surface was varied during testing to obtain a multi-stress loading effect, which also imposed varying confinement stresses in mixtures. A multi-stress rutting model with a high correlation coefficient was proposed, together with a rutting index that could be used to evaluate the high temperature performance of asphalt mixtures.

2. Materials and experimental program

Crushed limestone stones were used as the coarse and fine aggregates in AC-20 asphalt mixtures. The number '20' denoted the nominal maximum size of aggregates used as 20 mm. In order to minimise the variation of the combined aggregate gradation, coarse aggregates were especially sieved into five particle size ranges: 19–26.5 mm, 16–19 mm, 13.2–16 mm, 9.5–13.2 mm, and 4.75–9.5 mm. Six particle size ranges were sieved for the fine aggregates' portion and included: 2.36–4.75 mm, 1.18–2.36 mm, 0.6–1.18 mm, 0.3–0.6 mm, 0.15–0.3 mm, and 0.075–0.15 mm according to JTG E42-2005 standard [11]. Aggregate passing percentages at sieves of sizes 19, 16, 13.2, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.075 mm, were 95, 83, 72, 61, 40.5, 30, 22.5, 16, 11, 8.5 and 5% respectively. The used coarse aggregates had a specific gravity of 2.703 g/cm^3, Los Angeles abrasion of 22.1%, crushed stone value of 21.5% and a flakiness and elongation index of 17%. Limestone mineral powder was used as the filler. It contained 51.8% CaO, 3.49% SiO_2 and 1.29% Al_2O_3 as the main chemical compounds. Its passing percentages were as follows: 100%, 93% and 86% at the sieves of 0.6 mm, 0.15 mm and 0.075 mm respectively. SBS asphalt binder with a penetration of 72.6 (units in 0.1 mm) at 25 °C, penetration index of −0.36, ductility of 52.1 cm at 5 °C, softening point of 52 °C and viscosity of 0.645 Pa.s at 135 °C was used as the binder. According to specification JTG E42-2005, the mid-value of AC-20 aggregate gradation was designed for preparing mixtures [11]. The optimum asphalt content was determined as 4.4% based on Marshal design with specimens compacted with 75 blows per face.

A multi-stress repeated loading test (MS-RLT) based on FLWT wheel tracking device as according to JTG E20-2011 standard [12], was used to simulate the application of an actual wheel load on an asphalt pavement. FLWT test slabs of dimensions 300 mm (length) × 300 mm (width) × 50 mm (height) were compacted with a steel roller. They were conditioned for at least 5 h before the test. Detailed information about FLWT compaction could be found in [12]. During the rutting test, the contact pressure between the rubber tire and specimen surface was varied between 0.5 MPa, 0.7 MPa and 0.9 MPa stress levels so as to simulate the effect of multi-stress loading. The tire contact pressure was adjusted by applying relevant loads in form metal blocks to the wheel through a loading arm. Once the contact pressure was set, it was stable during the testing period. The allowable resting period between the applications of different stresses were 120 s. The applied stresses were believed to reflect loading levels for light, medium and heavy traffic in reality. They were applied in three different loading sequences (0.5-0.7-0.9 MPa; 0.7-0.9-0.5 MPa and 0.9-0.7-0.5 MPa), which were expected to offer meaningful information about the effect of a change in traffic loading on the performance of asphalt pavements. Loading stresses were applied over a wide range of temperature from 30 °C to 70 °C, which included all temperatures that were reported to significantly affect rutting in China [13]. FLWT was applied at a rate of 42 cycles/min and the evolution of rutting with loading cycles was measured with a linear variable differential transformer.

According to Jiang et al. multiple stresses should be conducted in the secondary stage of the creep curve. As a result, three loading phases with the first lasting 10,000 cycles, and the second and third phases of 5000 cycles each were considered. The number of loading cycles for each stage were selected long enough so that rutting would be in the secondary stage before other stresses in a similar sequence were applied. In addition, each stress per loading sequence was applied for more than 2520 cycles or 1 h of loading as recommended by JTG E20-2011, considering that Mo et al. had suggested that 1 h of testing was insufficient to explain the long term rutting behaviour of mixtures [14]. The multi-stress testing program for AC-20 limestone asphalt mixtures was shown in Table 1.

3. Experimental results and discussions

3.1. Multi-stress rutting results

Figs. 1 and 2 shows the effect of multi-stress repeated loading (MS-RLT) on the rutting development of AC-20 limestone mixtures. Three MS-RLT sequences were selected with each sequence designed with three different stress levels. Fig. 1A, B and C shows the three loading phases per sequence. The creep curves of each loading phase could be divided into two stages: the primary stage and the secondary stage. The strain rates decreased sharply in the primary stages but became almost constant in the secondary stages. With varying stress levels per MS-RLT sequence, the strain rates during the primary and secondary stages were found different.

Fig. 1A shows the rutting behaviour of mixtures that resulted from increasing stress levels in the 0.5-0.7-0.9 MPa loading sequence. Rutting increased with increasing stress levels and temperatures. Subsequent higher stresses caused higher rutting rates, which would minimise the service life of pavements in reality. A change of stress from 0.5 MPa to 0.7 MPa resulted in an increased secondary rutting rate of 1.9 times that caused by 0.5 MPa. Further increase of stress to 0.9 MPa resulted in an even higher rutting rate which was 1.5 times that of 0.7 MPa. These results were in agreement with Jiang et al. study that reported that higher stresses in a loading sequence accelerated shear failure in asphalt mixtures.

Fig. 1B shows the rutting behaviour of mixtures which resulted from decreasing stress levels in 0.9-0.7-0.5 MPa loading sequence. Rutting increased in the first loading phase for all temperature conditions, however under temperatures below 50 °C, rutting became stable as mixtures exhibited a long-term steady state response

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