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Research Article

Development of a Full-Depth Wheel Tracking Test for Asphalt Pavement Structure: Methods and Performance Evaluation

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The rutting performance of asphalt pavement structure relies on the high temperature properties of asphalt mixture as well as the pavement structure and thickness. In order to investigate the influence of the structure and thickness, a full-depth wheel tracking test is developed in this research by improving the conventional wheel tracking test apparatus. The newly proposed test method is capable of varying its load speed and load size, controlling its specimen temperature gradient, and simulating the support conditions of actual asphalt pavement. The full-depth wheel tracking test based rutting performance evaluation of different asphalt pavement structures indicates that it is not reasonable to explain the rutting performance of asphalt pavement structure from the point of view of single-layer asphalt mixture rutting performance. The developed full-depth wheel tracking test can be used to distinguish rutting performance of different asphalt pavement structures, and two of five typical asphalt pavement structures commonly used in Shanxi Province were suggested for use in practical engineering.

1. Introduction

The Transport and Road Research Laboratory (UK) (TRRL) wheel tracking test is easy to operate and easy to understand, and the test results agree well with field test [1–3]. Owing to these advantages, the TRRL wheel tracking test is widely used throughout the world. Existing researches mainly concentrated on three aspects of the wheel tracking test: (1) test temperature selection; (2) correlation between field test results and laboratory test results; and (3) correlation between TRRL wheel tracking test results and results from other high temperature performance evaluating methods [4–6]. However, these areas of focus have been limited to research into the rutting performance of a single-layer asphalt mixture and characterization of the high temperature stability of the material but fail to consider the influence of the layer structure and thickness on the rutting performance of asphalt pavement, which is mainly due to the limitations of existing rutting evaluating apparatus.

In recent years, there have been some research reports on double-layer and full-thickness rutting tests [7–10]. Li et al. [11] conducted a full-depth rutting test under pressure values of 0.7, 0.9, and 1.1 MPa and temperatures of 60, 65, and 70°C to investigate the influences of overload and extraordinarily high temperature on dynamic stability. Wu et al. [12] and Shi et al. [13] investigated the influence of temperature, load, and thickness by performing a full-depth rutting test, and results had shown that the order and degree of influence of the three aforementioned factors are as follows: load > temperature > thickness. Guan et al. [14, 15] employed a variable-speed variable-load variable thickness wheel tracking apparatus to perform a full-depth rutting test on asphalt mixture material and pavement structure, fitted the relationship formula of dynamic stability under these conditions, and discussed the full-depth asphalt pavement rutting control standard. As the full-depth rutting is a new concept, many problems still need to be explored, including the precision of the temperature gradient control system which remains to be improved. Moreover, the modulus of the steel mold used as the lower support plate is much higher than the actual pavement, which leads to the stress distribution in the full-depth track board being significantly different from the actual pavement.

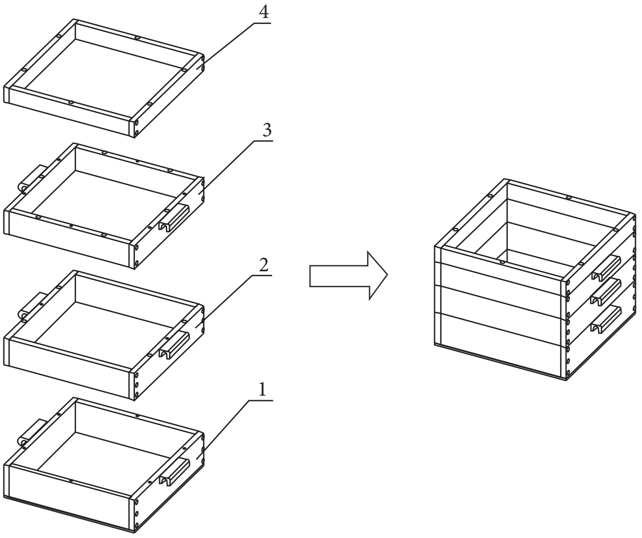

Figure 1: Schematic diagram of the developed full-depth wheel tracking test mold.

Therefore, this research aimed at improving the existing full-depth wheel tracking test method. In this paper, a full-depth wheel tracking test apparatus was first developed by improving the temperature gradient control system and the lower support plate constraints to better simulate the actual stress state of the asphalt pavement. Then, the newly developed apparatus was used to evaluate the overall rutting performance of the typical asphalt pavement structure in Shanxi Province, China.

2. Development of Full-Depth Wheel Tracking Test Apparatus Considering Temperature Gradient

Comparing to the existing full-depth wheel tracking test apparatus [14, 15], this research designed new test dies and temperature gradient control system and improved the loading system.

2.1. Mold Design of Full-Depth Wheel Tracking Test Apparatus. According to the thickness survey of the asphalt pavement structures, the headroom of the wheel tracking test apparatus was set as 30 cm.

The full-depth wheel tracking test mold, as shown in Figure 1, included the bottom plate and the side mold. The first-layer side mold was installed on the bottom plate to form a container to hold the asphalt mixture, based on which the first-layer specimen can be compacted in accordance with the standard method. Then, the second-layer side mold was installed above the first-layer side mold and the first-layer asphalt mixture specimen together with the second-layer side mold formed another container to hold the asphalt mixture. Additional specimens were compacted using the standard method.

The number of layers and the height of each layer were determined according to the specific conditions of the simulated pavement structures. The height of each side mold was between 4 and 10 cm, and if the thickness of a single layer was greater than 10 cm, it must be layered compacted as the molding machine cannot guarantee the compactness of the single layer higher than 10 cm.

2.2. Temperature Gradient Control System

2.2.1. Development of Temperature Gradient Control System. In this research, the temperature gradient control system was developed according to Guan et al. [15] by controlling the temperature of the top and bottom surfaces of the rutting test piece and keeping the temperature stable, while at the same time ensuring that the test piece was not exposed to heat exchange from the environment. Thus, after a long period of internal heat conduction, the temperature gradient can form in the interior part of the rutting test piece. By changing the temperature of the top and bottom surfaces of the test specimen, the desired test temperature field gradient can be obtained.

However, there are some defects in the temperature gradient control system reported by Guan et al. [15]. Firstly, the water in the sink is in an open environment and the environment chamber temperature and circulating water bath temperature will influence each other. Secondly, as the test mold is placed on the steel support, it is difficult to ensure uniform supporting. Thirdly, the height of the circulating water in the sink is greater than that at the bottom surface of the test specimen, which means the test specimen contacts water not only at the bottom surface and the same temperature of the circulating water is maintained at the bottom of the range (3 or 5 mm). This is contrary to the original intention of controlling the bottom surface temperature of the test specimen and may lead to significant difference between the temperature distribution of the test specimen and actual road surfaces. Moreover, the sheathing paper is easy to tear or damage during the rolling and forming process, which may affect the effectiveness of the heat insulation and complicate the specimen molding process. Lastly, the sheathing paper is designed for one-time use and is wasted unnecessarily.

Therefore, this research improved the temperature gradient control system reported by Guan et al. [15] by developing a new mold that can realize the constant temperature control of the specimen bottom surface, which will be introduced in detail in the following part. The temperature of the specimen top surface was controlled by controlling the environmental chamber temperature. The thermal insulating layer was installed around the test mold to prevent heat conduction and heat exchange between the test piece and the environmental box.

2.2.2. Mold Design for Maintaining Constant Temperature of the Specimen Bottom. At the bottom of the test mold, a temperature control bottom mold was set, and a sealing cover plate was arranged above it. Then, the side plate was arranged on the upper side. The temperature control bottom mold was connected to the incubator, by which the temperature of the circulating water in it was controlled. The circulating water

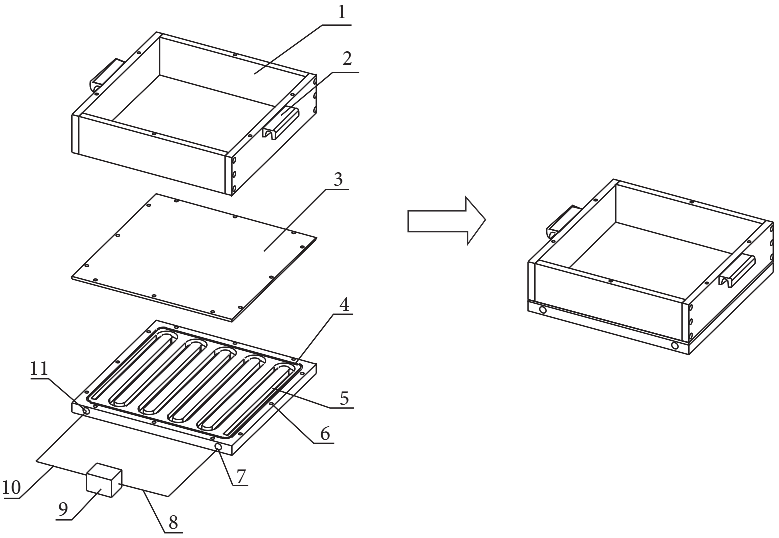

Figure 2: Schematic diagram of test mold for specimen bottom constant temperature controlling; 1: side plate; 2: handle; 3: sealing cover plate; 4: sealing ring; 5: constant temperature water channel; 6: fixed hole; 7: outlet; 8: outlet pipe; 9: thermostat; 10: water inlet pipe; and 11: water inlet.

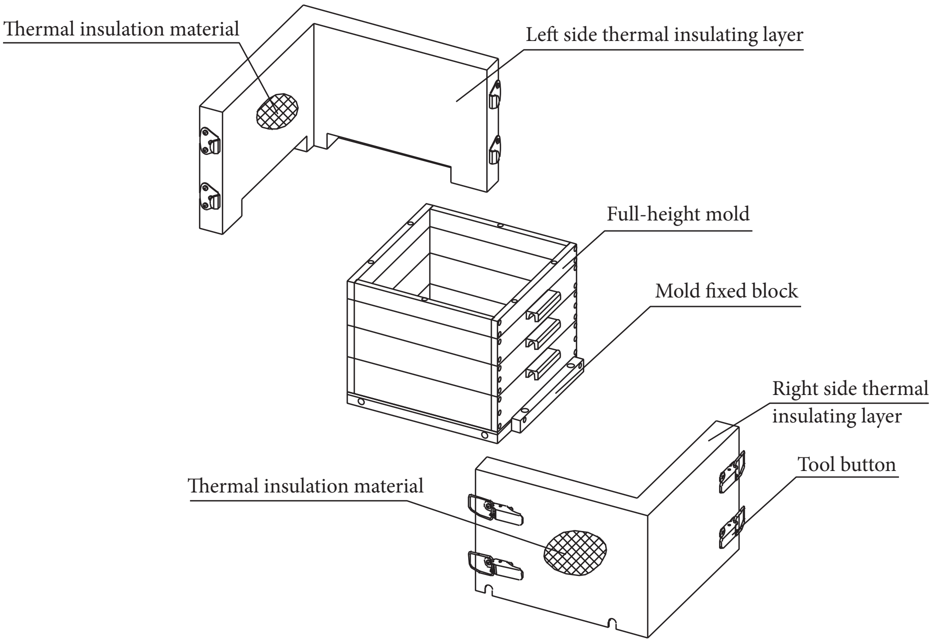

Figure 3: Schematic diagram of the left and right side thermal insulating layers and the full-height test mold.

transfers heat to the sealing cover plate and thus the specimen bottom temperature is controlled. More details about the mold are shown in Figure 2.

2.2.3. Thermal Insulating Layer Design for Specimen Temperature Gradient Control. As shown in Figures 3 and 4, the thermal insulating layer was composed of two parts, the left side thermal insulating layer and the right side thermal insulating layer. The left and right side thermal insulating layers were made up of same material and surround the test mold, connected by tool button. The thickness of the thermal insulating layer was 3 cm. The thermal insulating layers comprised two layers of inner and outer structures. The outer shell was made of 1.5-mm thick Q235 ordinary carbon structural steel, which mainly supports the thermal insulating layer. The internal thermal insulating layer was made up of aluminum silicate considering its excellent heat preservation and thermal insulation properties.

2.3. Full-Depth Wheel Tracking Test Loading System. The loading system of the existing wheel tracking test apparatus was improved to be capable of varying its load speed and load

Table 1: Aggregate gradation of different mixtures.

Gradation type	Passing (%)												
	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13C	100	100	100	100	97.3	75.4	45.6	27.1	20.3	14.2	10.7	8.2	5.1
SMA-13	100	100	100	100	94.6	64.0	24.7	20.4	16.0	14.2	13.3	12.5	9.8
AC-20C	100	100	92.3	82.9	69.6	58.2	39.9	27.3	18.7	13.7	10.9	6.9	4.7
ATB-25	100	95	70	58	52	42	30	23.5	17.5	13	9.5	6.5	4

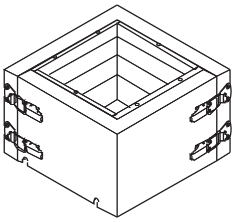

Figure 4: Schematic diagram of the integrated thermal insulating layers and the test mold.

size. A frequency converter was added to the actuating device of the standard wheel tracking test apparatus to enable the test wheel to vary its load speed within the range of 10 to 50 times per minute (one path). The contact pressure of the test wheel was adjustable between 0.5 and 1.4 MPa in step of 0.1 MPa by changing the weight of the loading plate.

2.4. Evaluation Index of Full-Depth Wheel Tracking Test. The dynamic stability index was still used as the evaluation index of the full-depth wheel tracking test. The dynamic stability was obtained by collecting the rutting depth data at 45 and 60 minutes and calculated as

$$\mathrm{DS} = (t_2 - t_1) \times N \times C_1 \times C_2 \times (d_2 - d_1), \qquad (1)$$

where DS is the dynamic stability of the asphalt mixture, d_1 is the deformation corresponding to time t_1, d_2 is the deformation corresponding to time t_2, C_1 is the correction factor of the test machine type, and C_2 is the specimen coefficient (for the laboratory prepared specimen with a width of 300 mm; C_2 equals 1).

3. Evaluation of Rutting Performance of Asphalt Pavement Structures

3.1. Asphalt Mixture Design and Rutting Performance Evaluation

3.1.1. Asphalt Mixture Design. In this research, six asphalt mixtures commonly used in Shanxi Province, China, were selected to compose the full-depth asphalt pavement structure. The top surface layer asphalt mixtures included the styrene-butadiene -styrene- (SBS-) modified asphalt mixture AC-13C and stone matrix asphalt mixture SMA-13. The bottom surface layer asphalt mixtures included SBS-modified asphalt mixture AC-20C, asphalt mixture AC-20C with 3‰ antirutting cracking agent, and asphalt mixture AC-20C with 4‰ antirutting cracking agent. The upper base course was comprised of the asphalt treated base ATB-25. The proportions of the mixes were determined using the Marshall method.

The aggregate gradations were shown in Table 1, which were determined according to the Chinese "Technical Specification for Construction of Highway Asphalt Pavements" (JTG F40-2004).

The material properties of different mixtures were shown in Table 2.

3.1.2. Wheel Tracking Test of Asphalt Mixtures. The wheel tracking tests of asphalt mixtures were carried out according to the TRRL procedures at a temperature of 60°C, a load pressure of 0.7 MPa, and a walking speed of 21 cycles/min (the thickness of the track plate is 50 mm), using the dynamic stability evaluation index, and the test results were shown in Table 3.

It could be found that the dynamic stability of all the six asphalt mixtures meets the requirements of Chinese "Technical Specification for Construction of Highway Asphalt Pavements" (JTG F40-2004). However, in engineering practices, the pavements paved with the above mixtures still exhibit serious rutting damage. The failure of the asphalt mixture dynamic stability index in controlling pavement rutting is attributed to its inability to account for the structure characteristic of the asphalt pavement. Instead of single-layer specific asphalt mixture, the asphalt pavement is a combination of multilayers with different materials. It is essential and more reasonable to evaluate the rutting performance from the view point of full-depth pavement structure.

3.2. Performance Evaluation of Full-Depth Wheel Tracking Test under Flexible Foundation. The asphalt layers of typical composite asphalt pavement structure in Shanxi Province, China (see Table 4), were selected to conduct the full-depth wheel tracking test by improving the constraining position of the bearing layer under the track board. A 5 cm height mold was added under the track board mold to contain a natural rubber block measuring 30 cm × 30 cm × 5 cm, which was bonded to the asphalt mixture track board using epoxy adhesive. The temperature control conditions reported by Yi [16] were adopted here, and the controlled temperature of environmental chamber was 60°C and the temperature of circulation bath was 45.7°C. The specimens were kept for 10 hours in the environmental box before the wheel tracking test was carried out. Then, the full-depth wheel tracking test was

Table 2: Material properties of different mixture.

Mixture type	Asphalt-aggregate ratio (%)	Bulk volume relative density	Void volume (%)	Voids in Mineral Material,VMA (%)	Voids Filled with Asphalt, VFA (%)	Marshall Stability, MS (KN)	Flow value FL (mm)
SBS-modified asphalt mixture AC-13C	4.9	2.535	4	14.6	72.8	13.87	3.14
Stone matrix asphalt SMA-13	6.0	2.552	3.95	17.0	76.7	11.68	2.01
SBS-modified asphalt mixture AC-20C	4.2	2.418	4.02	12.9	68.8	17.36	2.568
3‰ antirutting cracking agent asphalt mixture AC-20C	4.5	2.440	4	13.8	71.2	13.8	3.2
4‰ antirutting cracking agent asphalt mixture AC-20C	4.5	2.440	4	13.8	71.2	13.8	3.2
Asphalt treated base ATB-25	3.6	2.456	4	12.1	61.6	23.7	3.5

Table 3: Wheel tracking test results of different asphalt mixtures.

Mixture type	Identifier	DS (cycles/mm)
SBS-modified asphalt mixture AC-13C	A1	8302
Stone matrix asphalt SMA-13	A2	9214
SBS-modified asphalt mixture AC-20C	B1	6664
3‰ antirutting cracking agent asphalt mixture AC-20C	B2	8953
4‰ antirutting cracking agent asphalt mixture AC-20C	B3	9579
Asphalt treated base ATB-25	C1	1901

Table 4: Results of full-thickness pavement rutting test.

Track board structure	Dynamic stability (cycles/mm)	Final deformation rutting depth (mm)
4 cm A1 + 6 cm B1 + 10 cm C1	4396	3.780
4 cm A1 + 6 cm B1 + 10 cm C1 + 5 cm block rubber	3818	4.549

conducted with a wheel load and wheel speed of 0.7 MPa and 21 cycles/min.

The test results of the above-described full-depth wheel tracking test with different boundary conditions are shown in Table 4.

Table 4 shows that the dynamic stability of the full-depth asphalt pavement structure is much lower than that of the single-layer asphalt mixture, and the rutting depth is greatly increased. Comparing to the SBS-modified asphalt mixture AC-13C and SBS-modified asphalt mixture AC-20C, the dynamic stability of the full-depth structure with improved constraint conditions reduces by 54% and 42%, respectively. The results further demonstrate the drawback of explaining the rutting performance of asphalt pavement structure from the point of view of single-layer asphalt mixture rutting performance. The full-depth structure dynamic stability can be used to optimize the asphalt pavement structure design.

The dynamic stability of the full-depth asphalt pavement structure with improved constraint conditions is slightly lower than that of the structural layer with the rigid constraint conditions, and the rutting depth increases slightly. The reason is that the rigid constraint conditions limit the permanent deformation of the full-depth asphalt mixture to a certain extent, thus leading to greater dynamic stability and smaller rutting depth. Considering the stress and strain distribution of the full-depth asphalt pavement structure with improved constraint condition are closer to actual pavement conditions under driving load than those without any improvement, the full-depth wheel tracking test with improved constraint condition is more suitable for the evaluation of the structure rutting performance.

3.3. Evaluation of Full-Depth Rutting Performance in Different Asphalt Pavement Structures.

Five different asphalt pavement structures typically used in Shanxi Province were evaluated in this study, as shown in Table 5. The full-depth wheel tracking tests were carried out with wheel load and wheel rolling speed of 0.7 MPa and 21 cycles/min. As mentioned above, the controlled temperature of environmental chamber was 60°C, and the temperature of circulation bath was 45.7°C.

Table 5: Test results for full-thickness rutting of different pavement structures.

Structure combination	Upper layer	Middle layer	Bottom layer	DS_0 (cycles/mm)
1	A1	B1	C1	3818
2	A2	B1	C1	4472
3	A2	B2	C1	5903
4	A2	B3	C1	5931
5	A1	B2	C1	4890

Table 6: Two typical structures of asphalt pavements in a flat slope section of an expressway.

Structure type	Structure layers	Materials	Gradation type
Structure I	Upper layer	Stone matrix asphalt mixture	SMA-13
	Middle layer	Asphalt mixture with antirutting cracking agent	AC-20C (3‰ anticracking agent added)
	Bottom layer	Asphalt treated base	ATB-25
Structure II	Upper layer	SBS-modified fine-grained-type asphalt concrete	AC-13
	Middle layer	Asphalt mixture with antirutting cracking agent	AC-20C (3‰ anticracking agent added)
	Bottom layer	Asphalt treated base	ATB-25

The specimens were kept for 10 hours in the environmental box before the wheel tracking test was carried out and the test results of the full-depth wheel tracking test with different boundary conditions were shown in Table 5.

Conclusions can be drawn from Table 5 as follows:

(1) The difference between Combination 1 and Combination 2, as well as Combination 5 and Combination 3, is just the upper layer asphalt mixture. All other things being equal, the upper layer stone matrix asphalt (SMA) mixture can provide better rutting performance compared to SBS-modified fine-grained asphalt mixture. This is attributed to the skeleton dense structure of SMA mixture, in which the coarse aggregates form the skeleton structure and the fine aggregates fill the voids in the skeleton. The test results show that the rutting performance of the asphalt pavement structure can be improved by improving the upper layer asphalt mixture.

(2) The difference between Combination 1 and Combination 5 is just the middle layer asphalt mixture. And the difference among Combination 2, Combination 3, and Combination 4 is also the middle layer asphalt mixture. All other things being equal, adding an antirutting cracking agent to the middle layer asphalt mixture will achieve better overall rutting performance compared to using modified asphalt alone in the middle layer. Improving the rutting performance of the middle layer asphalt mixture has the most efficient effect on the overall rutting performance of asphalt pavement. Moreover, while adding approximately 3‰ of antirutting cracking agent to the middle layer asphalt mixture can result in good overall rutting performance, the resultant benefit of increasing the amount of antirutting cracking agent to 4‰ is limited.

(3) Comparison of Combination 2 and Combination 5 shows that the rutting performance of full-depth structure may be improved by reducing the upper layer while enhancing the middle layer asphalt mixture. Therefore, with the limitation of local materials, construction technologies, and economic conditions, the SBS-modified asphalt mixture AC-13C could be employed instead of stone matrix asphalt mixture SMA-13.

Based on the above analysis, and considering economic factors, two typical asphalt pavement structures were suggested as shown in Table 6. In practical engineering, the choice of which structure to use should be made according to the traffic situation, weather conditions, availability of local materials, and current expressway construction technologies.

4. Conclusions

This research focuses on the full-depth rutting performance of asphalt pavement structure. For this purpose, a conventional wheel tracking test apparatus based full-depth wheel tracking test was first developed, and a full-depth wheel tracking evaluation method was developed. The newly proposed test method is capable of varying its load speed and load size, controlling its specimen temperature gradient, and simulating the support conditions of actual asphalt pavement.

It is not reasonable to explain the rutting performance of asphalt pavement structure from the point of view of single-layer asphalt mixture rutting performance. The full-depth structure dynamic stability can be used to optimize the asphalt pavement structure design. Considering the stress and strain distribution of the full-depth asphalt pavement structure with improved constraint condition is closer are actual pavement conditions under driving load than those without any improvement, the full-depth wheel tracking test with improved constraint condition is more suitable for the evaluation of the structure rutting performance.

Improving the middle layer asphalt mixture rutting performance is the most efficient way to improve the overall rutting performance of asphalt pavement. Reducing rutting performance of the upper layer asphalt mixture and improving rutting performance of the middle layer asphalt mixture may enhance the rutting performance of pavement structure. Based on the full-depth rutting performance evaluation of five typical asphalt pavement structures, two typical asphalt pavement structures were suggested for use in practical engineering, and the choice of which structure to use should be made according to the traffic situation, weather conditions, availability of local materials, and current expressway construction technologies.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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