Study on the Rut Change Law of Multi-Asphalt Pavement Structure of Heavy-Duty Highway

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Abstract. In order to explore the rut change law of multi-asphalt pavement structure of heavy-duty highway, the influence of actual traffic axle load on pavement design life is studied by analyzing the measured traffic axle load of heavy-duty highway and comparing the difference between actual and designed axle load. The ruts of different pavement structures and different lanes were compared to study the rut distribution law of four asphalt pavement structures of heavy-duty highway, and evaluate the rut performance of four asphalt pavement. It can be obtained that the traffic volume predicted at the time of design is much lower than the actual traffic volume. Compared with the cumulative action times of the equivalent designed axle load with the original design life of 15 years, the measured axle load spectrum is expected to reach the designed service life in the 6.2 year; The rut of the four asphalt pavement structures is less than 10mm, and the rut condition of S1 is basically the same as that of S3 and S4. The average rut of S2 is slightly larger than that of the other three pavement structures because it is located at the light controlled intersection, and S4 has the smallest rut. As a fully flexible asphalt pavement structure, S3 has the same rutting resistance as S1 and S4.

Keywords: highway, asphalt pavement, fully flexible, axle load spectrum, Rut.

1 Introduction

With the increasing traffic volume, the durability and safety of pavement structures are of increasing concern, especially on heavy-duty highways, where the effect of wheel loads on pavement performance becomes particularly important. Pavement rutting (also known as rutting settlement), as a common pavement deformation, has a direct impact on driving comfort, driving safety and the service life of the pavement[1-4]. With the increase of wheel loading, the plastic permanent deformation in asphalt mixture layer is also intensified, which not only leads to the decline of pavement function, but also may lead to the phenomenon of water slipping in rainy days, which may lead to the occurrence of traffic accidents in serious cases[5-7]. Therefore, reasonable rutting control is essential to ensure the long-term stability of the pavement. The current design specification sets the maximum allowable rutting deformation limit to ensure that the

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pavement function is not affected by excessive rutting, and when the rutting exceeds the limit, it needs to be repaired in a timely manner in order to restore the performance of the pavement and prolong its service life[8-9].

In past studies, rutting behaviour has been extensively explored by means of real engineering projects, test roads and accelerated loading devices. Nevertheless, the analysis of rutting behaviour of different pavement structures under the same conditions is complicated by the fact that the formation and development of rutting patterns are influenced by complex factors due to the large variation in traffic axle loads on real roads. Although full-scale experiments or laboratory simulations can provide some insights into the study, the revelation of the long-term evolution of rutting deformation remains limited as the experimental environments are usually too simplified to fully reproduce the actual natural and traffic conditions. Therefore, the aim of this study is to assess the effect of actual traffic loads on rutting deformation by comparing the actual axle loads with the design axle loads, with a view to providing a more scientific basis for future pavement design and maintenance.

2 Project Overview

In this project, four different test sections of asphalt pavement structures were installed on a mountainous heavy-traffic motorway with a total length of 2 km and a length of 500 m for each structure (see Figure 1). The motorway was constructed to a standard of six lanes in both directions, belonging to the II5a natural region, with a design speed of 80 km/h, and mainly serving heavy traffic. The four types of asphalt pavement structures include: semi-rigid base asphalt pavement structure (S1) with 4 cm SMA-13 asphalt concrete on the surface, 6 cm AC-20 asphalt concrete in the middle layer, 8 cm AC-25 asphalt concrete in the lower layer, 36 cm cement-stabilised crushed stone on the base layer, and 20 cm lime-stabilised soil on the sub-base layer, which is the mainstream pavement structure in China at present; a full-flexible structure plus an anti-fatigue layer (S2), in which high modulus asphalt HMAC-20 is used in the middle layer and a 10 cm FAC-13 anti-fatigue layer is directly laid on the road bed; fully flexible structure with graded gravel (S3), in which HMAC-20 asphalt concrete is also used in the middle layer and graded gravel is laid on the road bed; and composite base layer (S4), which is a combination of a large-size permeable asphalt gravel base (LSPM-25) and semi-rigid base layer.) and semi-rigid subgrade, are widely used pavement structures on highways in Shandong Province.S2 and S3 represent the future direction of asphalt pavements in China, while S1 is the current mainstream structure and S4 is typical of regional applications. Through a comparative study of these four structures, this project aims to assess the performance of different pavement structures and their adaptability under heavy traffic conditions[10].

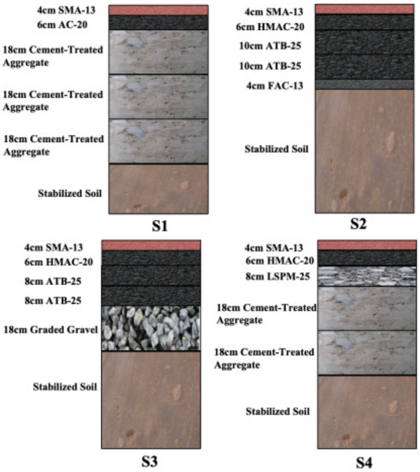


Fig. 1. Experimental Observation Section of Asphalt Pavement Structure

3 Traffic Volume and Axle Load

In this study, data collection of traffic volume and axle loads in the project-dependent test observation section was first carried out. For this purpose, the research team independently developed a load information collection system (see Fig. 2), which is capable of detecting in real time the traffic volume, vehicle type, axle load spectrum and other information of all lanes in both directions of the test observation section. Through this system, all kinds of traffic parameters can be accurately collected, thus providing data support for subsequent analyses[11]. Through the detection of the system, the basic traffic parameters were obtained and the daily traffic volume data and various types of traffic coefficients of the section were listed as shown in Table 1.

Table 1 demonstrates the main traffic parameters, of which the AADT (Average Annual Daily Traffic) is 8089 vehicles per day, the AADTT (Average Annual Daily Heavy Vehicle Traffic) is 6619 vehicles per day, the directional coefficient is 51.43% and the lane coefficient is 48.75%. These basic traffic parameters reflect the traffic flow situation of the test section and provide key data support for subsequent pavement performance assessment. Using these data, the impact of different types of vehicle loads on the pavement structure and performance can be more accurately analysed to further optimise the pavement design and maintenance strategy.

Fig. 2. Load information acquisition system

Table 1. Basic traffic parameters

AADT (Vehicles/day)	AADTT (Vehicles/day)	Directional Coefficient (%)	Lane Coefficient (%)
8089	6619	51.43	48.75

The annual average daily traffic (AADT) for this experimental section was 8,089 vehicles/day, covering all vehicle types from Class 1 to Class 11. The annual average daily heavy vehicle traffic (AADTT) for heavy vehicles (including large buses and trucks, Class 2 to Class 11) is 6619 vehicles/day, which accounts for 81.2% of the total traffic. The vehicle type distribution factors are shown in Figure 3. The total proportion of Class 3, Class 6 and Class 9 vehicles reaches 93.51%, which is much higher than other vehicle types, indicating that these three types of vehicles dominate the experimental section and are the most common vehicle types on the road section.

By analysing the axle load spectra of Class 3, Class 6 and Class 9 vehicles on the road section, it was found that the overloading problem was particularly serious, especially for Class 9 vehicles, whose overloading rate was as high as 25.26%. The overall overloading rate of the road section was 17.5 per cent, indicating that overloading was prevalent in the road section, which seriously affected the durability of the pavement structure. Compared with the design values, the measured traffic parameters (including the annual average daily traffic volume and the cumulative traffic volume of buses and trucks) significantly exceeded the original design expectations, which adversely affected the actual service life of the pavement structure[12].

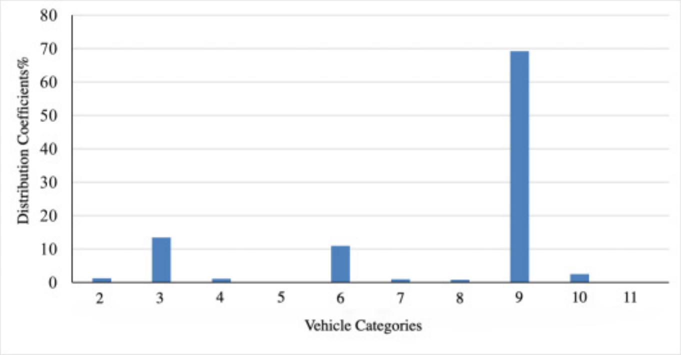


Fig. 3. Model Distribution Coefficients

Based on the measured axle load data, the cumulative number of equivalent design axle loads experienced by the road section far exceeded the design values, resulting in the accumulation of permanent deformations, fatigue cracks and compressive strains. Specifically, the pavement's design anticipated service life (15 years) under actual traffic loading has been significantly shortened and is expected to reach the design equivalent axle load criterion in 6.2 years. This means that rutting and pavement damage will occur earlier than expected, further indicating that the pavement structure of this road section has a major overloading problem.

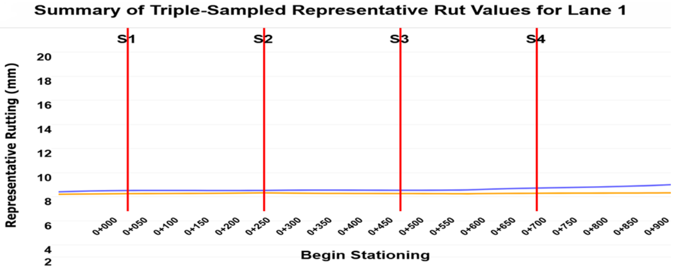
These results highlight the importance of the impact of traffic loading on the pavement structure, especially in heavy traffic sections. The overloading situation not only accelerates the deformation of the pavement, but also poses a threat to the long-term stability and service life of the pavement. Therefore, reasonable control of traffic loading and effective traffic management and pavement maintenance measures have become the key to ensure the long-term safe use of pavements.

4 Rut

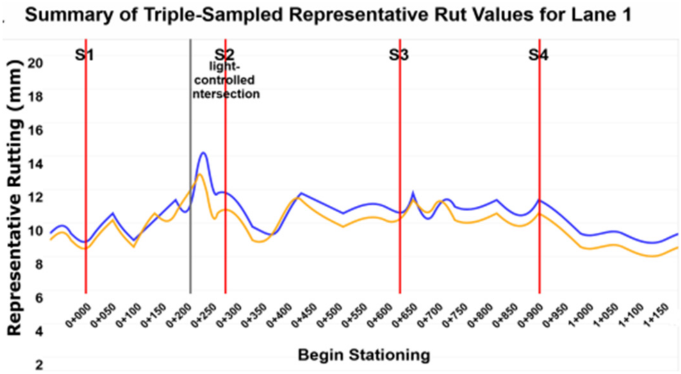
In this paper, two rutting tests were conducted on each of the four asphalt pavement structures in the test observation section, with the test time chosen to be conducted in July, which is the highest temperature time of the year. The tests were conducted before and one year after the opening of the road section to assess the changes in rutting performance of the pavement structures at different points in time. During the rutting tests, several tests were conducted on each of the three lanes of the road section, specifically on the three lanes of the test half, with each lane being tested three times respectively[13]. For each test, a representative 10-metre rut was selected for measurement (see Figures 4 to 6), and the average representative rut depth of the three test results was calculated (see Figures 7 to 9).

In the tests, Lane 1 was the outermost travelling lane, which is usually a concentrated area for heavy vehicles; Lane 2 was the middle lane, and Lane 3 was the innermost overtaking lane, where vehicles are usually more dispersed and travelling loads are lighter. In particular, it should be noted that a traffic signal-controlled intersection was set up in Section S2, and the pavement in this section was subjected to more severe traffic conditions during the test, including braking, stopping and starting operations, which made the pavement in Section S2 subjected to more concentrated heavy loads and repetitive impacts, and thus its rutting performance was more obvious and severe compared with other pavement structures[14].

Through these rutting tests, the study can further reveal the long-term performance of different asphalt pavement structures under high temperature and heavy traffic conditions, especially the rutting evolution trend after a certain service life. These test data provide an important basis for analysing the durability and performance of different pavement structures, and at the same time provide a scientific reference for the design, construction and maintenance of similar road sections in the future.

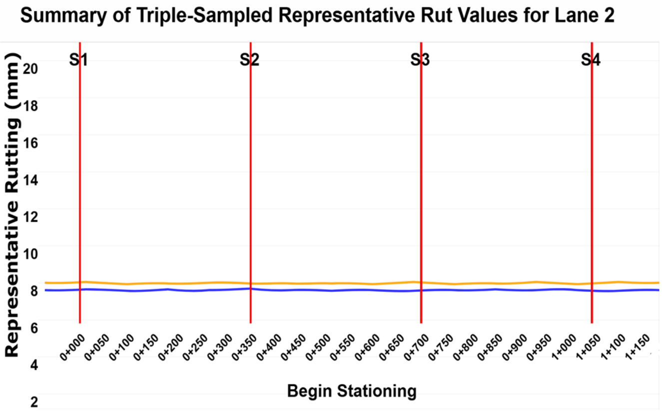


(a) Before opening to traffic



(b) After opening to traffic

Fig. 4. Representative values of 3 rutting tests in lane 1



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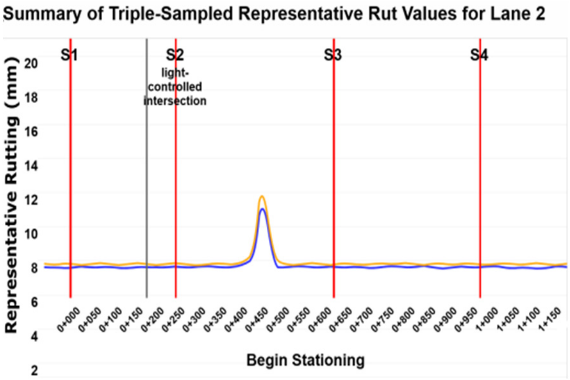
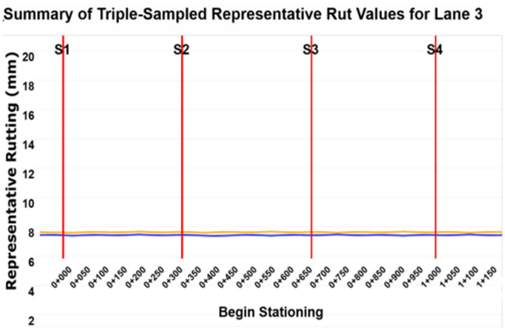


(b) After opening to traffic

Fig. 5. Representative values of lane 2 rutting detection for 3 times



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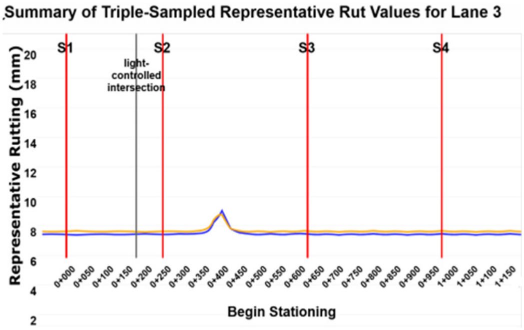

(b) After opening to traffic

Fig. 6. Representative values of 3 rutting tests in lane 3

As shown in Figures 4 to 6, when conducting three parallel rutting tests on the same lane, a certain degree of variability is observed among the three measurements. The variability in the three parallel tests conducted prior to the opening of the road is relatively minor, whereas the variability in the three parallel tests conducted after the opening of the road is significantly more pronounced. Among them, the variability in the three parallel tests for Lane 1 after the road opening is the most conspicuous.

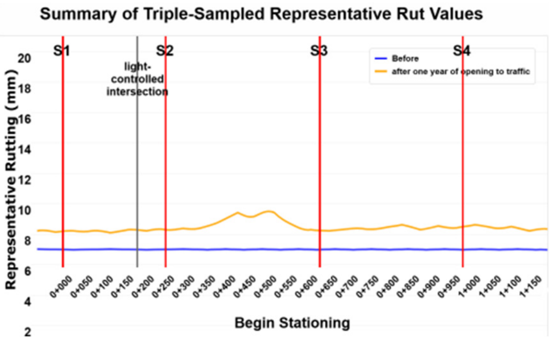

Fig. 7. Average representative value of lane 1 rut

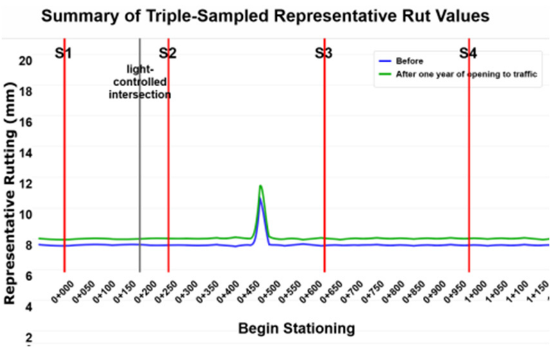

Fig. 8. Average representative value of lane 2 ruts

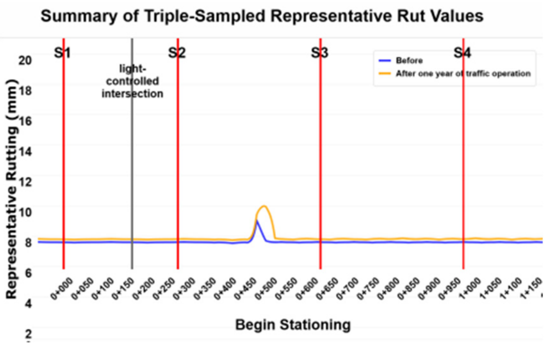

Fig. 9. Average representative value of 3 ruts in lane

Rutting measurements for each lane were compared before and after one year of traffic operation as shown in Figures 7 through 9. In general, rutting increased in all lanes, but the extent of the increase varied by lane and pavement configuration. For S1, the most significant increase in rutting was observed in Lane 1, which has the most heavy vehicles. The average rut depths for Lane 1, Lane 2 and Lane 3 are 5.9 mm, 4.47 mm and 3.6 mm respectively. Compared with the pre-opening period, the rutting depth of Lane 1 increased significantly by 2.51 mm, with a maximum rutting depth of 9.29 mm, especially near signalised intersections. For S2, rutting increased in all lanes, with lane 1 having the highest average rut depth of 8.78 mm and a maximum of 14.14 mm. Rutting depth increased by 5.57 mm in lane 1 and 2.11 mm in lane 2, with significant increases in both lanes near signalised intersections.

For S3, rutting increased in lane 1 with average rut depths of 5.72 mm, 4.26 mm and 4.00 mm for lane 1, lane 2 and lane 3 respectively. The maximum rut depth in S3 in Lane 1 was 8.77 mm, an increase of 2.39 mm in Lane 1 compared to the pre-opening period. In contrast, the rutting in Lanes 2 and 3 has changed very little. For S4, there was little change in rutting for all three lanes, with average rut depths of 4.78 mm, 4.19 mm and 3.78 mm for Lane 1, Lane 2 and Lane 3 respectively. The maximum rutting depth of 7.30 mm was observed in Lane 2. Compared to the pre-opening period, rutting in Lane 1 has increased by 1.25 mm, while Lane 2 and Lane 3 show the smallest change of less than 1 mm. Overall, the most significant increase in rutting was seen in S2, particularly in lanes 1 and 2, whilst the smallest change was seen in S4[15].

5 Analysis of Rutting in Different Asphalt Pavement Structures

In this study, the actual traffic axle loads on the test section were found to be significantly different from the predicted values, resulting in a reduction of the original design service life of 15 years to only 6.2 years and accelerating the occurrence of pavement distresses, especially the intensification of rutting. However, despite the traffic loads exceeding the design expectations, the four asphalt pavement structures performed well after two summer high-temperature periods, with the average depth of rutting not exceeding 10 mm (see Figure 10), indicating that these pavement structures have strong durability and resilience under high-temperature conditions.

By quantitatively analysing the three years of monitoring data, we developed a multiple regression model which had an R^2 value of 0.87, indicating that 87% of the rutting variance could be explained by the predictor variables. Statistical analyses showed that cumulative equivalent axle loads (ESALs) had the strongest correlation with rut depth (r=0.78, p<0.001), followed by pavement temperature (r=0.62, p<0.001). In terms of structural factors, the thickness of the high modulus asphalt layer showed a significant negative correlation with rut depth (r=-0.65, p<0.001), which indicated that thickening the high modulus asphalt layer could effectively reduce the occurrence of rutting.

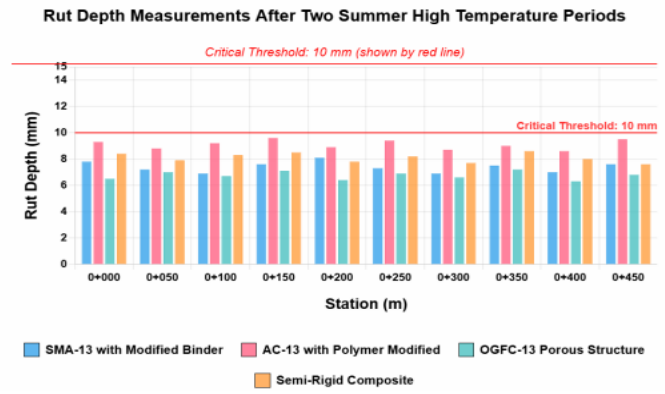

Fig. 10. Rut Depth Measurements After Two Summer High Temperature Periods

By quantitatively analysing the three years of monitoring data, we developed a multiple regression model that showed $R^2 = 0.87$, indicating that 87% of the rutting variance could be explained by the predictor variables. Statistical analysis showed that cumulative equivalent axle loads (ESALs) had the strongest correlation with rutting depth (r=0.78, p<0.001), and pavement temperature showed moderate correlation (r=0.62, p<0.001). Of the structural factors, high modulus asphalt layer thickness showed a significant negative correlation with rutting (r=-0.65, p<0.001). The S2 structure was

18. 7% more rutted than the other structures in the braking acceleration region at the intersection, but performed 15. 5% better than the repaired S1 at extreme temperature conditions (>45°C) (p<0.05) (Figure 11).

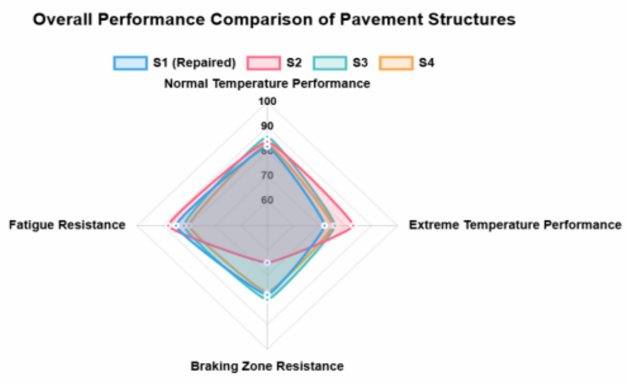

Fig. 11. Overall Performance Comparison of Pavement Structures

The S4 structure performed the best of all test sections, with a rut depth that was 12.4% ($p<0.01$) lower than the baseline S1 structure. This result indicates that the S4 structure has a significant advantage in terms of durability and rutting resistance. In contrast, the fully flexible S3 structure is comparable to the S1 structure in terms of rutting resistance, with a rutting difference of only 3.2% ($p=0.41$), but the S3 structure has a more stable performance under different loading conditions, with a coefficient of variation of 8.7% compared to 13.5% for the S1 structure(see Figure 10).

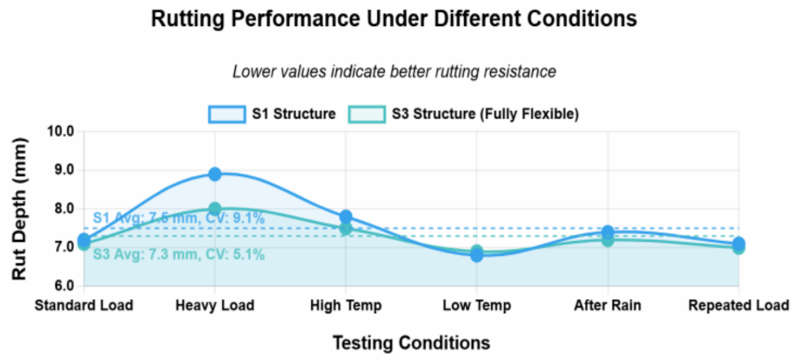

Fig. 12. Rutting Performance Under Different Conditions

This statistical result indicates that the S3 structure has better adaptability and consistency under variable traffic loading conditions. Further regression analyses showed that the rutting development rate followed a logarithmic non-linear pattern ($R^2 = 0.91$), a finding that provides a quantitative basis for selecting the optimal pavement structure based on specific traffic loads and environmental conditions. Through these analyses, this paper not only reveals the differences in the performance of different asphalt pavement structures under different conditions, but also provides scientific support for future pavement design and maintenance strategies. In particular, a rational selection of pavement structures based on changes in environmental factors such as traffic loads and temperatures will help to extend the service life of the pavement and improve the overall level of service of the road.

Overall, the S4 structure showed optimal durability and rutting resistance under a variety of conditions, especially when facing high traffic loads and extreme temperatures, and its superior design makes it the most suitable choice for long-term use. On the other hand, structures such as S2 and S3 showed their respective advantages and disadvantages under different traffic and environmental conditions, providing valuable data and experience for future pavement design and maintenance.

6 Conclusions

This study reveals a significant discrepancy between actual and predicted traffic loads on a heavily loaded motorway, with actual traffic loads far exceeding the initial design assumptions. Measured traffic data indicated that the pavement was originally designed to withstand 15 years of cumulative equivalent axle load application, but the actual conditions showed that this critical value was reached after only 6.2 years, much earlier than expected. This accelerated wear process highlights the importance of road load management, especially in environments with high intensity traffic flows and heavy vehicle traffic.

Despite the accelerated wear rate, the asphalt pavement structure still performed commendably in terms of rutting performance, with the average rutting depth remaining below 10mm throughout the section, even after two exceptionally hot summer months. However, structural differences between the different sections resulted in significant differences in rutting performance. Specifically, section S2 (located near the signalised intersection) experienced more severe rutting due to the concentration of high intensity heavy vehicles. In comparison, the rutting levels of Sections S3 and S4 are relatively similar, but Section S4 shows the least deterioration, indicating that the pavement in this section has been designed to be more robust or that there is an advantage in traffic load distribution that allows for better sharing of vehicle loads.

Although Segment S2 is the most severe in terms of rutting performance, this segment still outperforms the other structures in a number of ways, especially when considering the potential for repair and rehabilitation of other intersections, and the durability of this structure may provide some advantages for future maintenance. This difference in durability not only helps to assess the long-term performance of the segments, but also provides an important reference for future maintenance strategies. The case of S2 also suggests that more attention should be paid to traffic management and pavement design at special locations, such as intersections, during the design and construction phases in order to improve their load-bearing capacity and service life.

Overall, this study highlights the gap between traffic load predictions and actual conditions, suggesting that it is crucial to consider higher traffic loads and more adaptive pavement structure design in motorway design. Future pavement design and maintenance should flexibly adjust the design criteria and maintenance strategies of road structures based on actual traffic data and pavement performance to ensure the long-term safety and utilisation benefits of highways.

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