Research on the Applicability of Pavement Maintenance Measures and Technologies for Expressways under Multi-Stage Maintenance Conditions

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Abstract. After more than 30 years of rapid development in expressway construction in China, by the end of 2023, the total mileage of national expressways in operation had reached 183,000 kilometers. However, a large number of existing expressways are facing issues of structural aging or over-aged service, with more than 30% of expressways having exceeded their designed service life. To maintain excellent service levels and extend their useful life, multiple pavement maintenance projects need to be carried out. Based on 12 years of continuous pavement technical condition detection data, as well as basic data such as construction and maintenance history and traffic volume, from the expressway network of a northern province in China, this study analyzed the implementation effects and applicable conditions of expressway pavement maintenance measures under multi-stage maintenance interventions. The research results indicate that the direct overlay measure is suitable for heavy-duty pavements with good structural strength. The impact of road conditions and traffic volume on the service life of pavements that adopt milling and overlay measures is relatively small. This study provides scientific basis and technical support for the pavement maintenance of highways in long-term service.

Keywords: Expressway, Pavement maintenance, Multi-stage maintenance, Maintenance measures, Maintenance countermeasure set.

1 Introduction

Since the completion and opening of the first 147-kilometer expressway in China in 1988, the country has experienced a rapid development period in highway construction spanning 30 years. As of the end of 2023, the total mileage of completed and opened expressways nationwide has reached 183,000 kilometers. In recent years, with the development of socio-economic conditions, some expressways have undergone reconstruction and expansion projects due to insufficient traffic capacity and severe structural damage, entering a new service life cycle. However, a large number of existing

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_76

highways are still confronted with the issues of structural aging or overservice. According to statistics, by the end of 2024, more than 30% of highways in China have exceeded their designed service life, leading to inevitable deterioration in both pavement performance and structural performance. Therefore, it has become an important task to adopt targeted maintenance measures for different pavements reasonably and effectively [1,2,3].

According to the "Specifications for Design of Highway Asphalt Pavement Maintenance" (JTG 5421-2018) [4], the design service life for structural rehabilitation projects of pavements is 10 to 15 years, the expected service life for functional rehabilitation projects is 5 to 8 years, and the expected service life for preventive maintenance projects is 2 to 5 years. However, in the process of multiple pavement maintenance and management of highways, issues such as poor implementation effects of maintenance measures and excessively short service lives often arise, resulting in severe waste of resources. The main reasons for this include: unreasonable design of maintenance schemes, poor construction quality of maintenance projects, and unscientific maintenance management [5].

This study focuses on highways that have been in long-term service, where the pavement structure has undergone multi-stage maintenance interventions, leading to complex and diverse service behaviors [6,7]. By conducting long-term tracking and observation of the implementation conditions and effects of various pavement maintenance measures, and combining analysis of influencing factors such as the full life-cycle construction and maintenance history, traffic volume, road age, and pavement structure type, this study proposes the applicable conditions for highway pavement maintenance measures under multi-stage maintenance interventions. Furthermore, it establishes a set of pavement maintenance countermeasures with superior performance [8,9,10].

2 Typical Maintenance Strategies

2.1 Typical Structures and Development Trends

This study is based on the pavement maintenance management work of an expressway network (exceeding 3,000 km) in a northern province of China. It continuously collected pavement technical condition inspection data, as well as basic data such as construction and maintenance history and traffic volume, for nearly 12 years (from 2012 to 2023), to conduct research on the long-term performance tracking of pavements and the applicability of maintenance measures.

Summarizing the history of highway construction in China, it is found that the thickness of asphalt concrete layers in newly constructed pavements has gradually increased. In the 1980s and 1990s, a three-layer pavement structure with a total thickness of 15cm was commonly used. After 2010, asphalt concrete pavement structures with a thickness of over 20cm became widespread. Regarding the base layer structure of pavements, China has been promoting the use of semi-rigid base layers, with cement-stabilized crushed stone and lime-fly ash stabilized crushed stone as the main material types. Especially after 2010, both the base layer and subbase layer structures have adopted cement-stabilized crushed stone materials. Typical pavement structures and development trends are shown in Fig.1 below.

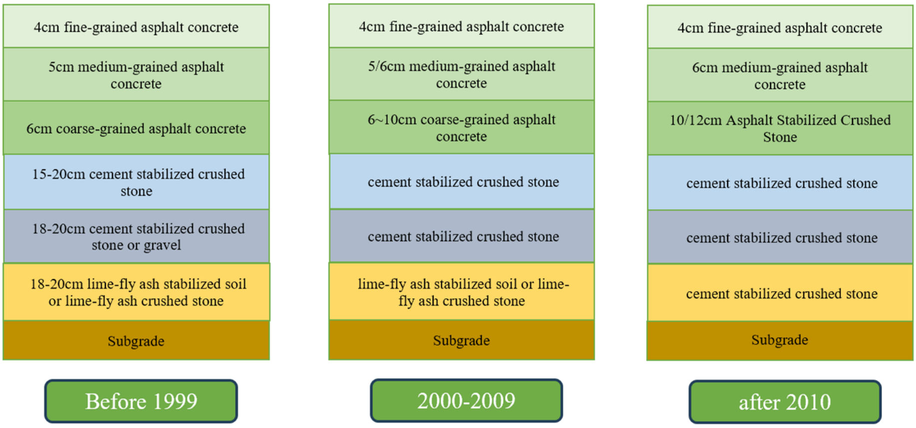


Fig. 1. Pavement Structure Types and Development Trends of Expressways in Typical Provinces of China

2.2 Typical Maintenance Strategies

(1) Direct Overlay and Structural Reinforcement

During the operation and maintenance process within the life cycle, the first two maintenance measures primarily focused on overlaying, increasing the total thickness of the asphalt surface layer to enhance structural bearing capacity and service life. However, due to limitations in pavement elevation and requirements for optimizing structural combinations, after a certain degree of pavement thickening, the maintenance measures shifted to milling and overlaying as the primary approach [11,12]. According to statistics, the average thickness of the asphalt layer on highways currently in service in a certain northern province's expressway network has reached 21.33cm. Additionally, for routes that opened to traffic before 2000 (with a current asphalt layer thickness of 23.69 cm and an original asphalt layer thickness of 15.82 cm), the average increase in asphalt layer thickness is 49.75%. For routes that opened between 2000 and 2010 (with a current asphalt layer thickness of 20.92 cm and an original asphalt layer thickness of 17.16 cm), the average increase is 21.91%. For routes that opened after 2010 (with a current asphalt layer thickness of 21.78 cm and an original asphalt layer thickness of 21.71 cm), the average increase is only 0.32%.

(2) Typical Maintenance Measures

A summary of the implementation of highway pavement maintenance projects across the province over the past 12 years reveals that the overlay of 4cm fine-grained asphalt concrete (4cm AC-13) is the most typical functional rehabilitation measure. It accounts for 32.70% of the total mileage of all corrective maintenance projects implemented (the total mileage of corrective maintenance measures is 5490.466km, with 4cm AC-13 accounting for 1795.334km). The 1cm MS-3 micro-surfacing (with 369.616km of 1cm MS-3 micro-surfacing and a total pre-maintenance mileage of 866.034km) is the most typical preventative maintenance measure, accounting for 42.68% of the mileage of all preventative maintenance projects implemented.

(3) Typical Maintenance Cycle

After reviewing the implementation timings of pavement maintenance projects across the province's highway network and compiling statistics on the typical pavement maintenance cycles of current highways, it was found that for newly constructed highways, the first pavement maintenance project is generally carried out approximately 5 to 10 years after completion. The higher the traffic volume grade, the shorter the service life of the pavement structure. The timing for the second pavement maintenance project typically falls within 4 to 6 years after the first maintenance project, with traffic volume having a less significant impact on the timing of the second maintenance.

3 Implementation Effect of Maintenance Measures

3.1 Service Life of Maintenance Measures

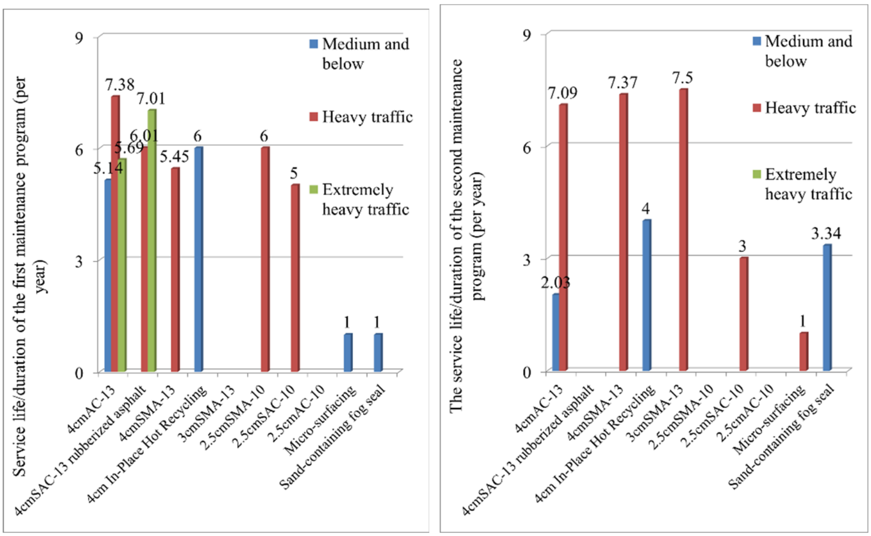
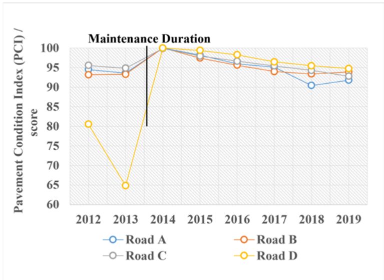


Fig. 2. Service life of highway maintenance measures

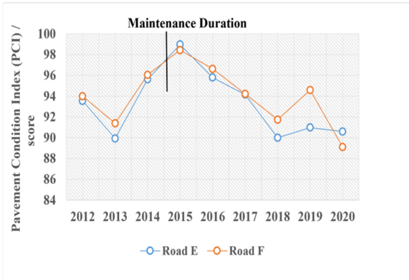
After statistical analysis of highway maintenance measures across the province, the main maintenance measures were found to be as shown in Figure 2. By tracking the implementation effects of various pavement maintenance projects following the completion and opening of highways, it has been found that the service life of a 4cm AC-13 overlay is approximately 4.84 years, with traffic volume having a insignificant impact on it; a 4cm SMA-13 overlay is mainly used on heavily trafficked road segments and has a service life of about 6.27 years, with an average service life that is 1.43 years longer than that of the 4cm AC-13 overlay; the implementation effect of in-place hot recycling is similar to that of the 4cm AC-13 overlay and is mainly used on road segments with moderate or lower traffic volumes; a 2.5cm SMA-10 thin overlay has good performance when used on heavily trafficked road segments, with an average service life of 6 years; the service life of micro-surfacing is approximately 1 year; sand fog seal is mainly applied to road segments with moderate or lower traffic volumes, with an average service life of about 2.17 years.

3.2 Laws of Performance Change Over Time

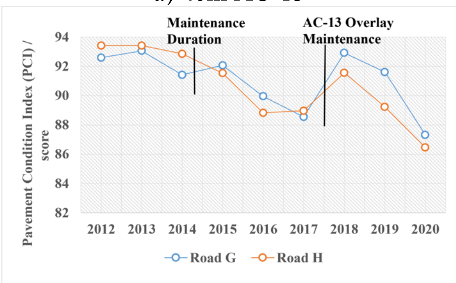
Track the changes in pavement technical condition indicators before and after the implementation of various pavement maintenance measures on representative road segments, and summarize the optimal maintenance timing and maintenance schemes with the best application effects, as shown in Figure 3.



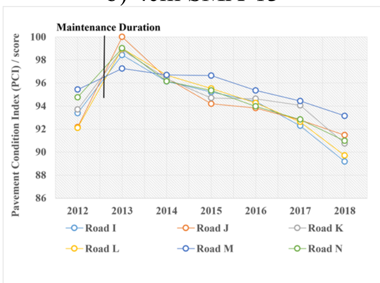
a) 4cm AC-13



b) 4cm SMA-13



c) Micro-surfacing



d) 4cm SAC-13 rubberized asphalt

Fig. 3. Laws of Performance Change Over Time

As shown in the above graph, after applying the 4cm AC-13 maintenance measure, the PCI index decreases slowly. The decay rate of the PCI index for road segments that were in poor and good condition before maintenance is relatively similar, indicating that 4cm AC-13 maintenance can be performed when the PCI index is around 60 and the road condition is poor, in order to improve economic benefits. For road segments that were in good condition before maintenance, the PCI index does not decay significantly after applying 4cm SMA-13 maintenance, and the road condition can be maintained at a high level for several years. After applying micro-surfacing maintenance measures, there is no significant improvement in the PCI index, indicating that the effect of micro-surfacing maintenance is not obvious when the road condition is already high. However, after applying 4cm AC-13 overlay maintenance, the PCI index increases significantly but then drops rapidly. After applying 4cm SAC-13 rubber asphalt concrete maintenance on road segments that were in good condition, the PCI index returns to its pre-maintenance level after approximately four years.

4 Collection of Maintenance Strategies

Through the aforementioned research, the project team has concluded that the commonly used maintenance measures for highways are milling and repaving, as well as direct overlay. The service life of these maintenance measures is related to both the road condition before maintenance and the traffic volume. When the maintenance measure involves milling and repaving, the impact of road condition and traffic volume on the service life of the pavement is relatively minor. However, in the case of direct overlay, different traffic volume levels have a significant influence on the service life of the pavement.

For pavements that adopt direct overlay measures, when the road condition is poor, pavements subjected to heavy traffic have a longer service life compared to those subjected to light traffic. The analysis indicates that this is because both traffic levels have pavements with the same Pavement Condition Index (PCI) grade. However, pavements with heavy traffic continuously endure larger loads, while those with light traffic experience less pressure. This demonstrates that pavements with heavy traffic have better structural strength. By directly overlaying an additional layer of asphalt concrete on this basis, the strength of the original structural layer can be increased, thereby extending the service life of the pavement. Conversely, pavements with light traffic have relatively poorer structural strength, and adopting the direct overlay maintenance method does not produce a significant positive impact on the pavement structure.

For pavements that adopt milling and repaving measures, when the road condition is poor, pavements subjected to heavy traffic have a shorter service life compared to those subjected to light traffic. This indicates that the milling and repaving method can enhance the pavement's structural strength to a certain extent at its root. After repaving the structural layer, the service life of the pavement basically has a negative correlation with traffic loading. In addition, for both maintenance methods, the service life is generally positively correlated with the road condition before maintenance.

In summary, the direct overlay measure is suitable for heavy traffic pavements with good structural strength, as it can extend the overall service life of the pavement by increasing the strength of the newly overlaid layer. However, for light traffic pavements with poor structural strength, the effect of direct overlay is limited. The milling and repaving measure can enhance the pavement's structural strength at its root, but it requires reassessment of the damage degree of the original pavement and the design of the structural layer after repaving. For pavements with particularly heavy traffic loads, more frequent maintenance and repairs may be required. Additionally, starting maintenance when the road condition is good can extend the pavement's serviceable life. In practical applications, the selection of appropriate maintenance measures should be based on comprehensive considerations of factors such as the specific condition of the pavement, traffic loads, and maintenance budgets. Meanwhile, it is also necessary to strengthen the daily monitoring and maintenance of pavements, promptly identify and address potential issues to ensure the long-term safe use of pavements. More maintenance measures and their applicable conditions are shown in Table 1.

Table 1. Collection of Maintenance Strategies

NO.	Maintenance Measures		Applicable Conditions		
	Overlay Type	Overlay Thickness	Traffic Conditions	Service Life	Pavement Condition Index Requirements (PCI/RQI)
1	Sand fog seal	--	Moderate to low traffic volume	2 years	> 90 / > 85
2	Micro-surfacing	1~1.5cm	Heavy to below heavy traffic volume	2 years	> 85 / > 80
3	Ultra-thin Wearing Course	1.5~2.5cm	All levels of traffic volume	3~5 years	> 85 / > 80
4	Thin Overlay	2.5~3.5cm	All levels of traffic volume	3~5 years	> 80 / > 75
5	AC-13C	4~6cm	Heavy to below heavy traffic volume	4~5 years	> 80 / > 80
6	SMA-13	4~6cm	All levels of traffic volume but with a high proportion of heavy vehicles	4~6 years	--
7	Milling and Repaving	4~6cm	Heavy to below heavy traffic volume	4~6 years	> 70 / > 70
8	Direct Overlay	4+6cm	All levels of traffic volume but with a high proportion of heavy vehicles	5~8 years	> 80 / > 80
9	Milling and Repaving	4+6cm	All levels of traffic volume but with a high proportion of heavy vehicles	5~8 years	> 70 / > 70
10	Milling and Repaving	4+6+9cm	All levels of traffic volume but with a high proportion of heavy vehicles	5~8 years	> 60 / > 60

5 Conclusions

Most existing research has concentrated on the analysis of single maintenance measures or short-term maintenance effects, whereas this study conducted an in-depth exploration of the technical applicability of expressway pavement maintenance measures under multi-stage maintenance conditions, based on a 12-year tracking and analysis of pavement maintenance management data from an expressway network exceeding 3,000 kilometers in a northern province of China. By systematically collecting key data such as traffic volume, construction and maintenance history, and pavement technical condition, combined with long-term tracking observations of pavement performance, the study revealed the implementation effects and influencing factors of different maintenance measures under various conditions.

The study first summarized the typical characteristics and development trends of China's expressway pavement structure and maintenance strategies, clarifying the main measures for expressway pavement maintenance and their proportional distribution. Through in-depth analysis of the service life and performance variation patterns of typical maintenance measures, the study revealed the applicability of different maintenance measures under varying traffic volumes, pavement structure types, and maintenance timings. On this basis, the study proposed a set of maintenance countermeasures for expressway pavements under multi-stage maintenance conditions, providing theoretical support and technical guidance for scientifically formulating maintenance plans and optimizing the allocation of maintenance resources.

The findings of this study not only contribute to improving the level of expressway pavement maintenance management, extending pavement service life, and reducing maintenance costs, but also hold significant importance for promoting the sustainable development of expressway pavements in China. Despite the significant progress made in this study regarding the technical applicability of highway pavement maintenance measures under multi-stage maintenance conditions, there are still certain limitations. For instance, the data in this study mainly originate from the highway network of a certain province in northern China, which may not fully represent the maintenance situation of highways nationwide. In addition, since the implementation effects of maintenance measures are influenced by multiple factors, this study may not have fully considered all relevant factors when exploring the applicability of maintenance measures. Therefore, in future research, it is necessary to further expand the data sources and comprehensively consider more influencing factors to further improve the accuracy and universality of the research.

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