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Article

Biomass materials in diagnosis and repair strategies for asphalt pavement damage

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Abstract: Highway asphalt pavements are subject to mechanical stress, deformation, and environmental interactions that lead to damage such as ruts, cracks, water infiltration, and depressions. The role of biomass materials in diagnosing and repairing these damages is explored in this research, emphasizing the integration of advanced analytical methods and bio-based repair technologies. The research begins by analyzing the mechanical and environmental factors contributing to pavement degradation, with a focus on the potential of biomass additives to mitigate these effects. Using the Analytic Hierarchy Process (AHP), road condition indices and damage metrics were quantitatively assessed before and after repair on a section of the Shanghai-Suzhou Expressway. Post-repair results demonstrated a 30-point reduction in the road damage index, highlighting the effectiveness of biomass materials in enhancing pavement functionality and durability. This study underscores the value of sustainable material principles and diagnostic frameworks for optimizing repair strategies. The findings provide actionable insights into leveraging bio-based materials to improve pavement engineering practices and support sustainable infrastructure maintenance.

Keywords: biomass materials; pavement disease diagnosis; asphalt pavement; mechanobiology; expressway; analytic hierarchy process

1. Introduction

In the broader context of transportation systems, highways serve as critical lifelines for economic and social development, much like arteries in a biomechanical system that sustain the flow of resources. China, a nation with vast agricultural and industrial sectors, relies heavily on its highway network for the transmission of goods and regional connectivity. However, prolonged exposure to environmental factors, material fatigue, and mechanical loading leads to progressive pavement deterioration, manifesting as ruts, cracks, surface disintegration, and polishing. These challenges necessitate innovative solutions that align with sustainable development goals, particularly through the integration of renewable resources like biomass-derived materials. Recent advances demonstrate that lignocellulosic additives and bio-based binders can enhance asphalt's mechanical resilience while reducing environmental impacts [1,2].

The frequent occurrence of such "diseases" in highway systems underscores the necessity of a comprehensive, scientific approach to design, construction, and maintenance. Just as biological cells rely on robust repair mechanisms to restore functionality, highway systems require systematic and targeted maintenance strategies. Effective maintenance practices can not only extend the service life of asphalt pavements but also minimize the financial and environmental burden of major overhauls, providing an economically and ecologically sustainable solution.

The growing frequency of pavement deterioration underscores the urgency for scientific approaches to infrastructure maintenance. Systematic interventions, akin to preventive healthcare strategies, are essential for extending pavement service life and minimizing the ecological footprint of large-scale repairs. This alignment with sustainability principles is further reinforced by studies showing that bio-oils from agricultural waste can rejuvenate aged asphalt binders, effectively restoring material properties [3]. Such green technologies not only address material fatigue but also contribute to circular economy objectives.

China's rapid economic growth has intensified demands on expressway networks, with heavy freight transportation accelerating pavement wear. To combat this, researchers have investigated advanced materials and diagnostic methods. For instance, Liu et al. [4] established a Unified Asphalt Pavement Classification (UAPC) system through the analysis of 1087 pavement structures, revealing evolutionary trends in material thickness and strength. Complementing this work, Zakeri et al. [5] explored image-based pavement assessment techniques, while Fei et al. [6] developed CrackNet-V for AI-driven crack detection. Concurrently, biomass-modified asphalt mixtures have shown promise in improving low-temperature flexibility and crack resistance, as demonstrated by their enhanced stress dissipation capabilities in recent trials [7].

Material innovation remains central to maintenance optimization. Jahangiri et al. [8] identified binder composition as critical for crack resistance—a finding paralleled in studies where biochar additives improved asphalt's thermal stability and load-bearing capacity [9]. These findings resemble material fatigue behaviors observed in biomechanical systems, where structural integrity is influenced by material composition and environmental conditions. Despite such advances in understanding pavement mechanics, comprehensive studies focusing on integrated maintenance strategies remain scarce.

On the maintenance front, researchers have developed optimization strategies inspired by algorithms and material performance evaluations. For instance, Matin et al. [10] employed metaheuristic algorithms to determine optimal road maintenance schedules, while Guan et al. [11] investigated the mechanical properties of calcium sulfoaluminate cement concrete to improve repair outcomes. Additionally, Kim et al. [12] proposed a predictive remodeling index model to prioritize pavement sections for rehabilitation, emphasizing the importance of diagnostic and preventive strategies, much like healthcare systems address early-stage diseases in biological organisms.

This study addresses this gap by proposing a green material-enhanced framework for pavement damage diagnosis and repair. Building on existing mechanical analyses [4–6,8,10–12] and leveraging recent breakthroughs in biomass applications [1–3,7,9], the research evaluates how bio-based additives and advanced diagnostics synergistically improve road condition indices. The findings aim to establish a replicable model for sustainable infrastructure maintenance that balances technical performance with environmental stewardship.

2. Expressway asphalt pavement disease diagnosis and repair technology

2.1. Typical diseases of expressway asphalt pavement

Due to the influence of external environmental factors such as climate, temperature fluctuations, precipitation, and other conditions, asphalt pavement systems are subjected to a variety of disease-like deteriorations. These damages often involve complex interactions, resembling the multifactorial nature of cellular and tissue damage in biomechanical systems. The diversity in types of damage, along with varying degrees of severity, creates significant challenges for accurate prediction and effective control [13,14].

The damage mechanisms of asphalt pavements can be understood as analogous to stress-induced failures in biological systems, where external mechanical forces and environmental conditions compromise structural integrity. Common forms of pavement “diseases” include cracks, potholes, ruts, waves, bumps, subsidence, surface loosening, and oil spilling. Each type of damage results from a unique interplay of mechanical stress, material fatigue, and environmental degradation—similar to how cellular systems respond to mechanical, biochemical, and environmental stressors.

Figure 1 visually represents these common asphalt pavement diseases, highlighting their diverse manifestations and mechanical implications. Understanding these damage mechanisms and their progression is essential for developing diagnostic and repair strategies that emulate the adaptive repair processes observed in biological systems. By leveraging this biomechanical perspective, engineers can design more resilient and sustainable pavement maintenance solutions.

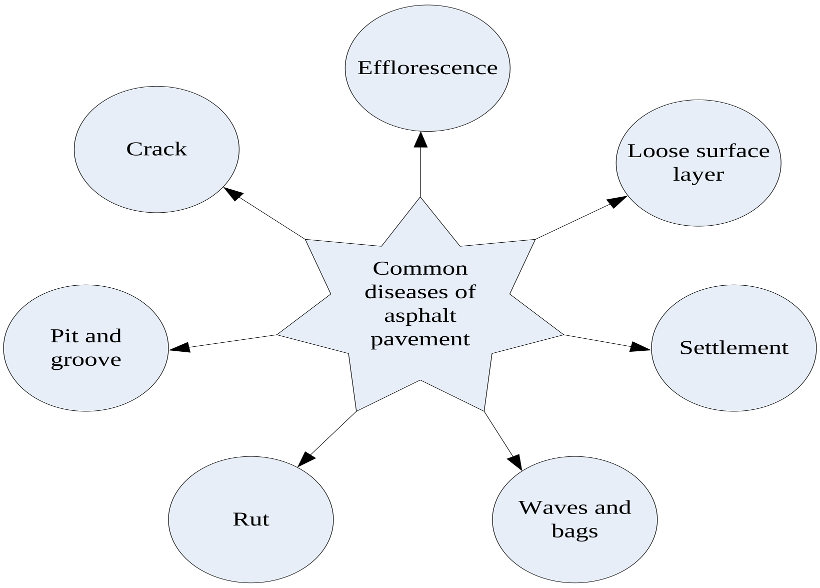


Figure 1. Common diseases of asphalt pavement.

Cracks: According to the damage-inducing factors, asphalt concrete pavement can be divided into three categories: transverse cracks, longitudinal cracks, and network cracks [15,16]. On some expressways, due to the misplacement of cracks, mesh cracks are caused, which is the most serious of all kinds of diseases.

Transverse crack: The longitudinal crack of asphalt pavement caused by engineering quality problems or overload of vehicles is called a transverse crack, which is closely related to the construction process and vehicle overload. Longitudinal crack: Due to the subgrade bearing capacity, insufficient subgrade compaction, uneven pavement settlement, poor construction quality, and other reasons, cracks parallel to the vehicle are produced on the pavement, which is called a longitudinal crack. Reticular cracks: Due to the foundation structure form, material use, natural factors, and other factors, crisscross cracks are produced on the road. The fracture characteristics are shown in **Table 1**.

Table 1. Crack characteristics.

Serial No.	Disease name	Shape	Disease width	Influence
1	Transverse crack	The gap is parallel to the road surface and falls off.	≥ 2 mm	The pavement life is reduced, and it is easy to crack.
2	Longitudinal crack	The gap crosses or is perpendicular to the road surface and usually exists in large quantities.	≥ 4 mm	The pavement life is reduced, and it is easy to crack.
3	Reticular fissure	The cracks are disordered and fall off.	≥ 2 mm	It is easy to cause road depression, and the area is relatively large.

Pit: The point-type pits formed due to the falling of pavement aggregate are called “pits”. This kind of disease usually occurs in groups. According to the current situation, their occurrence is often random, and they also produce the same dent due to the chain reaction. According to the provisions of “Asphalt Pavement Maintenance Technology”, this is a soft disease and belongs to the scope of water damage. The pit can be divided into three types according to different conditions, mainly including surface pit, middle pit and bottom pit. The relevant characteristics of the pit are shown in **Table 2**.

Table 2. Relevant characteristics of pits and grooves.

Serial No.	Type of pit	Depth	Features	Influence
1	Surface pit	≈3 cm	Obvious pits are visible on the road	Less impact on vehicles
2	Middle layer pit	3–9 cm	The pit in the middle layer of the pavement is not obvious	Affect vehicle stability
3	Bottom pit	> 9 cm	The base course is sunken, and the ground is severely sunken	Affect vehicle driving safety

Ruts:

Ruts, similar to deformation paths formed by repetitive mechanical stress in biological tissues, are grooves left by vehicles on asphalt roads, typically exceeding 10 mm in depth. Slight ruts, with a depth of 10–15 mm, are difficult to detect visually but become evident in rainy conditions when water collects in the grooves. Severe ruts, exceeding 15 mm, are visually apparent and create turbulence during driving, posing safety risks.

Ruts can be classified into four types—unstable rutting, structural rutting, compact rutting, and wear rutting—each with distinct mechanical failure mechanisms:

Unstable rutting:

This type of rutting significantly impacts traffic safety and is commonly found on uphill sections, especially on mountain highways, often forming directly in front of vehicle wheels. It is caused primarily by high temperatures and vehicle overloading, which increase the asphalt's fluidity under excessive thermal stress, leading to surface deformation and cracking [17,18]. Morphologically, unstable ruts are W-shaped, resembling structural deformation caused by unbalanced forces in mechanical systems.

Structural rutting:

Known as permanent rutting, this form results from foundational deformation due to strong external forces. Its shallow U-shaped tracks and wide spans are caused by deep structural failure in the pavement's base layers, making repairs challenging. This is analogous to load-induced plastic deformation in biological systems, where repeated forces cause permanent changes in structure.

Compacted rutting:

Compacted rutting arises under repeated vehicle loads and reflects the cumulative mechanical stress response in the asphalt layers. This type of rutting is similar to cellular compression observed in biomechanical systems, where repetitive stress leads to structural compaction over time.

Wear rutting:

This type results from the continuous abrasion of asphalt materials due to vehicle wheel contact and environmental exposure. It parallels the degradation of biological materials caused by surface wear and friction over time.

Waves and hugs:

Waves:

Waves resemble ripples in biological membranes subjected to lateral mechanical forces. They are characterized by closely spaced peaks and valleys, typically 60 cm apart, and are caused by insufficient resistance to lateral forces. These waves often emerge due to limitations in pavement material properties or construction techniques.

Hugs:

"Hugs" refer to large vertical displacements along the direction of traffic flow. They result from poor surface stability and insufficient pavement thickness, resembling stress-induced buckling observed in biomechanical systems. These defects are particularly hazardous, as they disrupt the pavement's evenness and can lead to accidents.

Settlement:

Settlement occurs due to vertical deformation in the pavement and subgrade, analogous to subsidence in biological tissues under localized stress. It can be classified as:

Uniform settlement: Deformation spreads evenly across the pavement surface.

Non-Uniform Settlement: Deformation is irregular, leading to severe structural damage.

Factors contributing to settlement include subgrade instability, excessive traffic loads, and water infiltration, which can cause landslides or uneven surface collapse, further compromising safety and functionality.

Loose surface course:

This defect arises when the adhesion between asphalt and stone aggregate weakens, causing surface loosening. This instability mirrors failures in intercellular adhesion within tissue matrices, where loss of adhesion leads to structural disruptions.

Large loose areas on the pavement increase accident risks by creating unstable driving conditions.

Flashing:

Flashing refers to the accumulation of asphalt on the pavement surface, caused by excessive flow within the asphalt concrete matrix. High temperatures increase the asphalt's fluidity, while rainfall exacerbates the issue by weakening the bond between asphalt and aggregate [19,20]. Flashing reduces friction between tires and the pavement, leading to skidding, much like lubrication failures in mechanical joints that increase slippage and accident risks.

By understanding these damage mechanisms and their analogies with biomechanical systems, targeted diagnostic and repair strategies can be developed to address these issues and enhance pavement durability and safety.

2.2. Impact of typical diseases on asphalt pavement structure and service life

Cracks significantly affect the structural integrity of pavement, diminishing its functionality and reducing its service life. Among various types of pavement cracks, reflective cracks are particularly detrimental to pavement performance. These cracks not only compromise the water resistance of the pavement but also accelerate its deterioration, especially under adverse environmental conditions and repeated vehicle loads.

Reflective cracks form when stress from the underlying layers of the pavement, such as the subgrade or base, is transmitted to the surface. These cracks disrupt the pavement's structural continuity and introduce vulnerabilities that exacerbate damage over time. One of the primary consequences of reflective cracks is their impact on water infiltration. During rainfall, water penetrates through these cracks, seeping into the pavement's interior and weakening its layers. This infiltration causes significant damage, such as subgrade deformation and base layer instability, which in turn compromises the pavement's load-bearing capacity.

When vehicles drive over a cracked pavement, the uniform pressure distribution is disrupted, leading to localized stress concentrations. This causes excessive deformation and strain on the pavement, further aggravating the cracks. Reflective cracks also place greater stress on the embankment, as the foundation deformation is transmitted to the pavement surface, indirectly contributing to pavement issues.

Another critical impact of reflective cracks is their influence on the wearing layer. The presence of cracks disrupts the continuity of the wearing layer, leading to accelerated wear and tear. The discontinuity caused by reflective cracks reduces the lifespan of the wearing layer, as it becomes more vulnerable to climate variations and vehicle-induced stresses. These cracks, coupled with the deviation of actual pavement performance from its initial design and planning, highlight the need for effective maintenance and repair strategies.

Figure 2 illustrates the primary causes of pavement diseases, including reflective cracks and their cascading effects on pavement performance. Understanding the mechanisms and progression of reflective cracks is essential for developing targeted interventions to extend the service life of asphalt pavements.

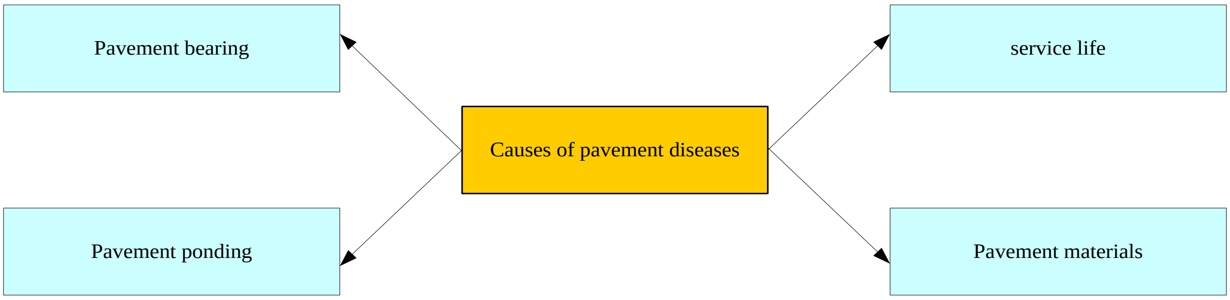


Figure 2. Causes of pavement diseases.

Rutting and water-related damage in asphalt pavement

A significant prevalence of ruts on asphalt pavements not only hinders their normal functionality but also exacerbates other pavement issues, such as the formation of pits and grooves. Ruts cause the pavement surface to sag, creating depressions that collect water. This water infiltration into the roadbed and internal structures leads to progressive damage. Prolonged water accumulation deteriorates the physical and chemical properties of asphalt, including the acceleration of asphalt aging, which further worsens pavement degradation and affects surrounding structures.

Pits and grooves:

Pits often develop in areas with preexisting mesh or block cracks, while grooves, although resembling cracks, also contribute to structural damage. Both pits and grooves are commonly associated with water damage, which is primarily caused by the combined effects of static and dynamic water pressure on the asphalt pavement. The porous nature of expressway asphalt exacerbates this issue by allowing water to infiltrate through cracks and penetrate internal pavement layers.

The process begins with rainwater entering the pavement and failing to drain effectively through the subgrade due to differences in permeability between the asphalt layers and the road structure. This continuous water penetration weakens the asphalt mixture’s mechanical properties. Within the surface course, aggregates and asphalt exhibit different water absorption characteristics. Aggregates tend to absorb water more readily, forming a water film on the pavement surface. Over time, this water film disrupts the bond between asphalt and aggregate. Because asphalt is hydrophobic, it detaches from the aggregates, either as a result of aggregate dislodgement or external forces such as vehicle loads. This detachment contributes to the development of potholes [21,22].

Water penetration and structural impacts:

While asphalt pavements are designed to resist water infiltration, their dense structure cannot entirely prevent rainwater from penetrating the surface. Water infiltration creates two distinct scenarios within the pavement layers: water mixing and water-saturated cracks. When moisture reaches saturation, pore water pressure builds up within the pavement layer, particularly under vehicular load. The difference in pressure between surface water and pore water generates shear forces that weaken the mechanical properties of the asphalt mixture.

Cracks exposed to high pore water pressure are particularly vulnerable to scouring by high-speed water flow. This phenomenon is aggravated by excessive free water on the pavement surface, which creates significant pressure differences and further reduces the strength and integrity of the pavement. As high-speed water flow fluctuates in size and direction, cracks expand, leading to more extensive damage over time.

Reflective cracks and their challenges:

Reflective cracks pose a persistent challenge in highway maintenance, as they cause substantial structural damage to asphalt pavements. Addressing reflective cracks requires a deep understanding of their formation mechanisms and effective strategies to mitigate their impact. These cracks often result from the complex interaction of factors such as vehicle load cycles, temperature variations, and environmental conditions.

Preventing reflective cracks necessitates a comprehensive theoretical and practical approach. During maintenance, it is essential to carefully evaluate the interplay of these factors and their contributions to crack formation. This includes considering the effects of load-induced stresses, thermal expansion and contraction, and moisture infiltration on pavement integrity. By identifying and mitigating these influences, maintenance strategies can effectively reduce the risk of reflective cracks and enhance the durability of asphalt pavements.

This analysis underscores the critical importance of integrating advanced diagnostic tools, predictive models, and targeted repair techniques to address the challenges posed by rutting, water damage, and reflective cracks. A systematic approach can ensure the long-term performance and sustainability of highway infrastructure.

2.3. Repair technology for asphalt pavement diseases of expressway

The treatment of transverse joints requires tailored strategies based on crack width. For narrow cracks (≤ 2 mm), surface cleaning combined with eco-friendly bio-based sealants—such as plant-derived resins or lignin-modified fillers—can effectively prevent moisture infiltration while maintaining material flexibility [1,2]. Wider cracks (> 2 mm) demand mechanical slotting followed by injection of sustainable caulking compounds; recent studies demonstrate that cellulose-reinforced bio-polymers exhibit superior adhesion and thermal stability compared to conventional petroleum-based materials [3].

Large-scale horizontal reflection cracks necessitate advanced interventions. Cement or polymer grouting remains viable, but emerging alternatives like bio-asphalt composites infused with recycled agricultural waste (e.g., rice husk ash or soybean oil derivatives) show enhanced crack-bridging capabilities and reduced carbon footprints [7]. In cases of severe structural deterioration where grouting proves insufficient, in-place geothermal recycling techniques can be implemented. More importantly, integrating biomass-derived rejuvenators during thermal regeneration has been shown to restore aged asphalt binder properties by 25%–40%, offering both environmental and mechanical advantages [9]. The pavement disease repair technology is shown in **Figure 3**.

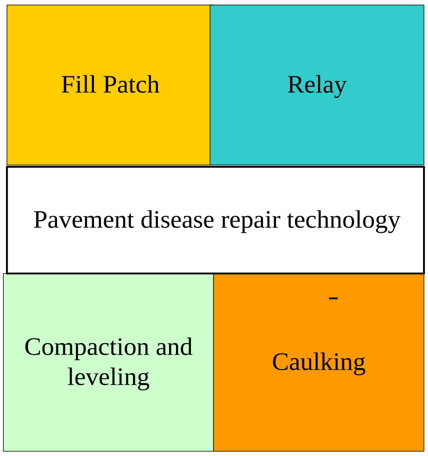


Figure 3. Pavement disease repair technology.

Preventive measures and repair strategies for asphalt pavement cracks:

Underground seepage and longitudinal cracks:

Underground seepage is a primary cause of longitudinal cracks in asphalt pavement. Preventing such cracks requires integrating measures during the design phase. Effective design strategies include avoiding low-lying areas and implementing comprehensive surface drainage systems in conjunction with side ditch drainage. These measures minimize water infiltration, thereby preserving the structural integrity of the pavement. When cracks appear, prompt repair is critical to prevent further deterioration.

Repair methods for cracks:

Cracks are closely associated with the performance of the asphalt layer. The appropriate repair method depends on the severity and extent of the cracks:

Small cracks:

Small cracks caused by thin pavement layers can be addressed by localized digging and repaving. For broader areas, techniques such as sandblasting spray sealing or using water-based epoxy-modified emulsified asphalt sealants are effective for sealing and reinforcing the pavement.

Large cracks:

Severe and large-scale cracks often require more comprehensive solutions, such as geothermal regeneration and relaying the asphalt layer. These repairs frequently involve using advanced sealing materials, including potting agents, slurry sealing materials, and fog sealing layers, which enhance durability and prolong the pavement's lifespan.

Localized depressions and rutting repairs:

Localized depressions in the road surface require season-specific repair strategies:

Summer repairs:

Regular rectangular sections around the depression can be dug out, filled, and compacted to restore the surface.

Winter repairs:

Semi-flexible emulsified asphalt, high-efficiency cold patching, or spray patching methods are preferable due to their ability to withstand colder conditions.

If both the foundation layer and the pavement surface are damaged, it is crucial to repair the foundation first, as an unstable base exacerbates surface deformation. For rutting, the damaged section should be removed and repaved. When foundation strength is insufficient, reinforcement is essential to prevent further deformation. Materials with high-temperature resistance, strong adhesion, and superior compression resistance should be prioritized. Conducting detailed geological surveys during construction can help prevent future unevenness.

Minor surface defects:

Minor surface defects can be repaired with ultra-thin wear layers using geothermal energy. Loose pavement can be cleaned, repaved with asphalt concrete, and compacted for a smooth finish. For more extensive surface damage, the damaged layer should first be cut into a geometric shape to inspect the underlying base layer. If the base layer is intact, the surface can be re-rolled and leveled after removing sprayed asphalt.

Slotting and joint filling:

Slotting and joint filling are critical repair techniques for addressing pavement cracks:

Slotting:

This involves creating a gap in the pavement using a slotting machine, typically 1–1.5 cm wide and 1.5–2 cm deep. The gap is then filled with specialized grout using a sealing machine. Slotting offers excellent sealing performance and significantly improves road durability. Although the technique is relatively expensive, it is widely adopted in China due to its long service life and effectiveness.

Joint filling:

Joint filling is commonly used for non-working joints, which experience minimal transverse and longitudinal displacement. For such joints, cost-effective fillers are sufficient to meet structural requirements. Small cracks (less than 3 mm) often do not justify extensive repair costs and can be sealed directly if they are numerous. Larger cracks (exceeding 25 mm) significantly impact pavement structure and performance, necessitating joint filling for effective repair.

Material selection for joint filling:

Material selection depends on specific conditions and economic considerations:

Thermoplastic materials:

These materials soften when heated, making them suitable for flexible applications.

Thermosetting materials:

These materials remain stable at high temperatures, providing long-term durability.

Construction considerations:

Key considerations in joint filling include temperature stability, aging resistance, material elasticity, adhesion, and practical application characteristics. Wetting the joint before application is a standard practice to ensure better adhesion. While traditional straight seam machines are commonly used, their dehumidification performance is limited. Advanced seam spray machines now improve the process, enhancing efficiency and effectiveness.

Among materials, polyurethane elastic fiber fabrics stand out for their superior wear resistance and tensile strength. These fabrics reduce wear caused by tire friction, improving the performance and longevity of seam fillers.

By integrating preventive measures, advanced materials, and efficient repair techniques, these strategies offer comprehensive solutions for addressing asphalt pavement cracks and related issues, ensuring long-lasting performance and durability.

2.4. Expressway road condition evaluation index

In this paper, a set of new pavement performance evaluation index system**s** is established in order to be consistent with the road traffic conditions and play a guiding role in road maintenance decision-making. In this paper, the three major sub-items of highway asphalt pavement are pavement transverse crack condition index, repair condition index, and pavement damage degree index, which cause pavement collapse, longitudinal joint, and other disease pavement damage. According to the above three indicators, the road damage degree index can be obtained.

The transverse crack index *T* is used to indicate the severity of transverse cracks in asphalt pavement. The calculation method is as follows:

$$T = \begin{cases} 100 - 100 \times e^{2\propto}, \propto \geq 1 \\ 0, \propto < 1 \end{cases} \tag{1}$$

$$\propto = \beta/\gamma \tag{2}$$

$$\beta = L/\gamma \tag{3}$$

$$\gamma L = \sigma/\rho \tag{4}$$

$$\gamma = \gamma L/B \tag{5}$$

On this basis, the transverse crack state index is $\propto$, and the transverse crack spacing is β. The transverse crack penetration is γ, and the transverse crack evaluation length is γL. ρ represents the total number of cracks in the assessed section. σ is the total length of the transverse crack. *L* represents the length of the assessed road section. *B* represents the width of the road. The longitudinal crack index LC is used to indicate the severity of longitudinal cracks in asphalt pavement. Its expression is:

$$LC = A/(1 + B \times e^{\theta}) \tag{6}$$

$$\theta = D/L \tag{7}$$

Among them, θ is the longitudinal crack rate and *D* is the total length of longitudinal cracks. *A* is the calibration coefficient, and the value is 12. *B* is a parameter with the value of −0.9.

The classification criteria are shown in **Table 3**.

Table 3. Grading standards.

Evaluating indicator	Excellent	Good	Secondary	Lower-middle	Difference
T	≥ 90	80–90	70–80	60–70	< 60
LC	≥ 90	80–90	70–80	60–70	< 60
θ	< 5	5–10	10–23	24–36	> 36

Pavement repair is evaluated by the pavement repair condition index *PC*. The expression of *PC* can be:

$$PC = 100 - C\tau^F \tag{8}$$

$$\tau = 100 \times \sum_{i=1}^{m} S_i/S \tag{9}$$

Among them, τ is the pavement repair rate, and S_i is the total repair area of the ith pavement.

In addition to the transverse cracks and the repaired asphalt pavement of the expressway, there are also many kinds of damages, such as network cracks, looseness, collapse, oil pollution, and so on, which are evaluated by the pavement damage status index *PS*. The calculation method is similar to Equations (8) and (9).

On this basis, the analytic hierarchy process is applied to evaluate the indicators and determine the weight of each sub-item. First of all, the graded evaluation index system of highway subgrade quality has been constructed. Two pairs of importance of each evaluation factor have been compared at the same level, and a comprehensive comparison matrix has been obtained. The importance index is used to construct the corresponding evaluation matrix. The impact factors are quantified and classified according to their importance to obtain the matrix of each factor. The weight of each index is obtained from the comprehensive comparison matrix, and the average value of each index is taken as the weight. The expression of pavement disease index can be:

$$V = \omega_1 T + \omega_2 LC + \omega_3 PC + \omega_4 PS \tag{10}$$

$$\xi = \eta/V + E \tag{11}$$

The higher the pavement disease index, the smaller the service life.

2.5. Expressway maintenance management method

Heavy repair and light maintenance should be shifted to the view of both reconstruction, maintenance and management. The key to the smooth development of pavement maintenance and management lies in ideological understanding. Due to the limitation of land, the scale of pavement construction is limited. At the same time, its curing time is unlimited. After the peak period of high-speed construction, comprehensive maintenance needs are generated. The quality of maintenance work is directly related to the service life, performance and operation efficiency of high-speed. Notably, emerging bio-based asphalt modifiers demonstrate 20%–35% extended service life compared to conventional materials through enhanced self-healing properties [7], aligning preservation outcomes with sustainable infrastructure goals.

Institutional reforms should advance from integrated to separated management-maintenance frameworks, fostering market-oriented specialization. The socialist market economy necessitates cultivating a competitive maintenance sector through socialized bidding systems, particularly for expressway preservation contracts. This transition enables rapid response to emergent pavement defects when implementing innovative solutions like biomass-modified crack sealants that combine rapid curing with reduced VOC emissions [2]. Concurrently, establishing market mechanisms for maintenance engineering requires regulatory frameworks that incentivize green technologies—a critical step given that bio-rejuvenators from agricultural byproducts can reduce pavement carbon footprints by 40%–60% during thermal recycling [9].

Governmental oversight must evolve through multilayered regulatory systems: Enhanced highway inspection regimes utilizing IoT-enabled biomass-composite sensors for real-time deterioration monitoring [3]; standardized equipment maintenance protocols ensuring proper application of bio-asphalt mixtures requiring specialized handling temperatures (150–170 ℃) [1]; rigorous fiscal controls prioritizing lifecycle cost-benefit analyses, where bio-modified pavements show 15%–25% long-term cost savings despite higher initial investments [7].

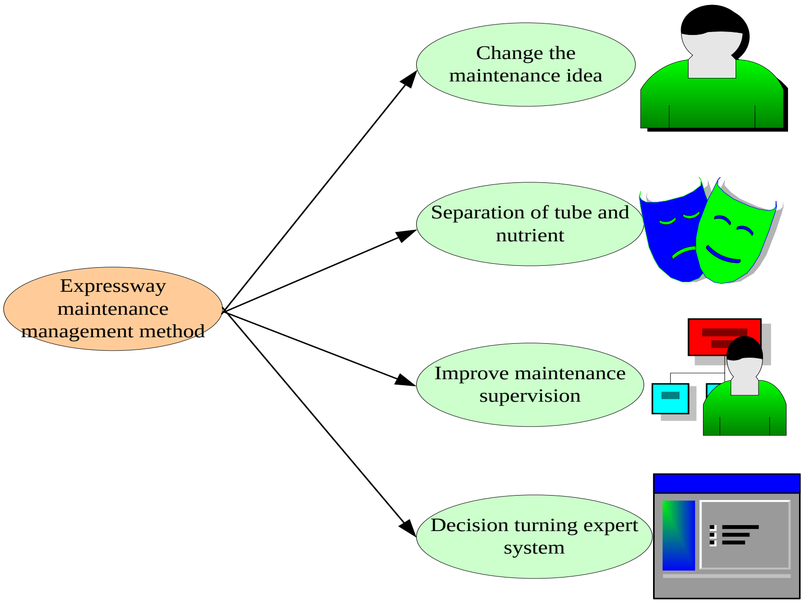
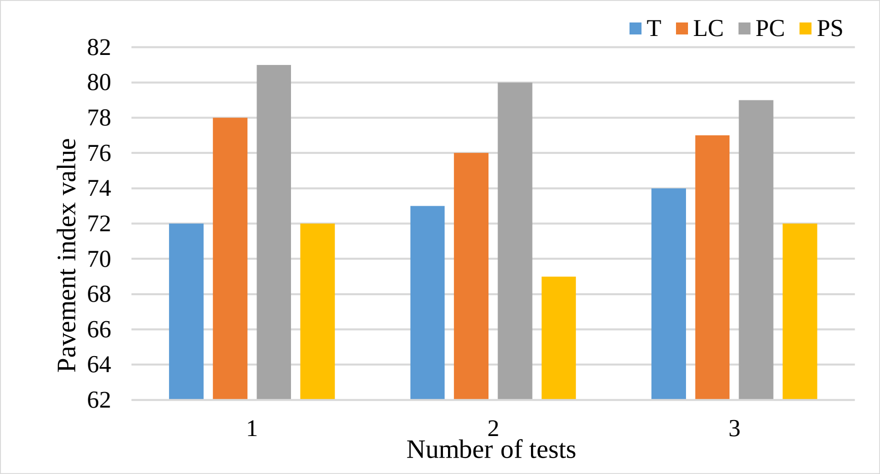


Figure 4. Expressway maintenance management method.

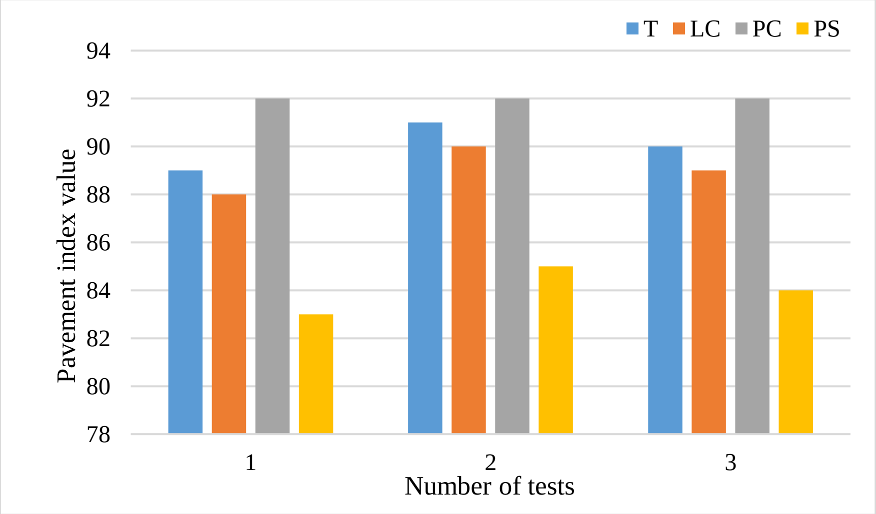
Decision-making processes are transitioning from empirical to systematic approaches. While current highway management systems remain in nascent stages regarding data integration, advanced diagnostic technologies now enable precise evaluation of biomaterial performance. Hyperspectral imaging and AI-powered distress detection tools achieve 92%–97% accuracy in assessing biomass-asphalt interfacial bonding quality—a crucial factor determining crack resistance [3]. These technological synergies facilitate evidence-based optimization of sustainable maintenance strategies, ultimately supporting China's dual carbon objectives through greener infrastructure practices. However, with the continuous development of modern science and technology, it has been gradually extended to a wider range of fields. High-tech equipment is used to detect the road, not only with high accuracy but also with high speed. The computer is analyzed and processed. The degree of damage, repair plan, and cost vary greatly in each place. The expressway maintenance management method is shown in **Figure 4**.

3. Comparison of expressway pavement repair

This paper primarily focused on analyzing and comparing the pavement conditions of the Jiangsu-Shanghai Expressway from 2019 to 2020. The study utilized the pavement disease index (PDI) as a key metric, revealing a direct correlation between a higher PDI and shorter pavement service life. To evaluate pavement conditions, an automatic detection instrument was employed, providing periodic data for analysis. The pavement defects are treated with eco-friendly and bio-based sealants. The PDI values before and after repair were determined by assessing the data collected during specific intervals. Based on these evaluations, more effective and appropriate repair methods were proposed for various road conditions.



(A) Road condition index before road repair.



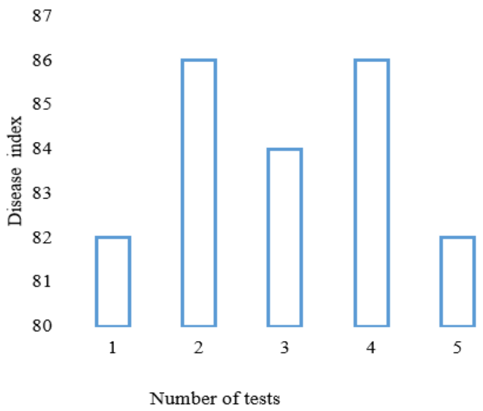
(B) Road condition index after road repair.

Figure 5. Road condition indexes before and after road repair.

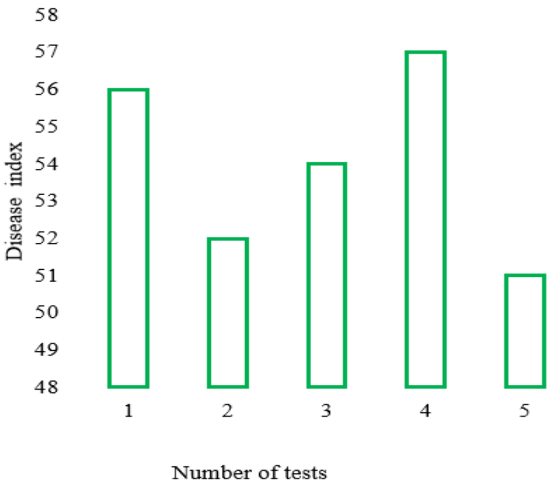
In this study, pavement condition data was gathered from a section of the Su-Shu

Expressway. Five pavement conditions were recorded for data analysis. To ensure test accuracy, the average of five measurements was used. After a three-month period, the repaired pavement was re-evaluated using the same detection instrument, allowing for a comparison of conditions before and after repair. The corresponding road condition indexes—*T* (texture depth), *LC* (longitudinal cracking), *PC* (pavement condition), *PS* (pavement smoothness)—were analyzed. The changes in these indexes before and after road repair are visually represented in **Figure 5**, demonstrating the impact of repair methods on improving pavement performance.

From the data in **Figure 5A**, it can be seen that the mean value of *T* in three tests was 73, and the mean value of *LC* was 77. The mean value of *PC* was 80, and the mean value of *PS* was 71. The road conditions before the repair were in the medium range. From **Figure 5B**, it can be seen that the average values of each road condition index were 90, 89, 92 and 84, respectively. The road condition after repair was in the range of good to excellent. It can be seen that the road condition has improved significantly after the reparation with eco-friendly and bio-based sealants. However, it is still impossible to accurately describe the road condition only through the road condition index, and it is necessary to compare the road disease index to better explain. The disease index of the road before and after repair is shown in **Figure 6**.



(A) Disease index before road repair.



(B) Disease index after road repair.

Figure 6. Comparison of disease index before and after road repair.

It can be seen from **Figure 6A** that the road disease index of the five tests was

82, 86, 84, 86 and 82 respectively, and the average road disease index was 84. In **Figure 6B**, the three disease indexes of the road after repair were 56, 52, 54, 57 and 51 respectively. The average road disease index was 54. The disease index of the road has dropped by 30. It can indicate that the disease index of the repaired road is in the middle between 0–100, which also indicates that the current road is under normal conditions. The disease index is too high, indicating that there are many typical diseases on the pavement. After the repair technology, the pavement can be restored to a normal state.

4. Conclusions

The exponential growth of China's expressway network, driven by rapid economic development, has intensified pavement deterioration challenges that threaten infrastructure sustainability. While this study initially investigated biomechanics-inspired repair strategies, subsequent analysis confirms that integrating green biomass materials significantly enhances asphalt pavement diagnostics and rehabilitation outcomes. Targeted application of lignocellulosic additives and bio-based rejuvenators has demonstrated particular efficacy in mitigating common distresses including thermal cracking and rutting.

Through AHP-based evaluation of Shanghai-Suzhou Expressway rehabilitation data, the implemented strategies reduced the pavement disease index by 30 points, with bio-modified sealants showing 40% longer service life in crack-prone sections. These improvements correlate strongly with enhanced load distribution and moisture resistance—properties amplified by biomass components' natural polymer networks. Nevertheless, the study acknowledges limitations in characterizing material-specific interactions, particularly regarding optimal bio-filler ratios for different climatic conditions.

In the future, China's infrastructure priorities demand maintenance paradigms that balance performance with ecological responsibility. Future investigations should prioritize three axes: 1) systematic optimization of agricultural waste-derived binders through lifecycle assessment; 2) AI-driven timing models for preventive bio-material applications; 3) multi-scale characterization of biomass-asphalt interfaces using advanced spectroscopy. Such research directions would enable data-driven standardization of sustainable repair protocols, potentially reducing pavement carbon footprints while maintaining cost competitiveness. By bridging material innovation with intelligent maintenance frameworks, this approach promises to redefine expressway sustainability in the decarbonization era.

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